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FOREWORD

From May 13 to 14, 2026, Latvia University of Life Sciences and Technologies hosted the 32nd Annual International Scientific Conference 'Research for Rural Development,' bringing together researchers, experts, and practitioners to discuss current scientific developments and practical solutions for the sustainable development of rural areas.

This year, a total of 139 research contributions were presented, including 88 in-person oral presentations, 23 in-person poster presentations, 24 online oral presentations, and 4 online poster presentations. Registered participants represented 14 countries. A total of 158 participants registered to attend the conference in person, while a further 28 participants took part in the online sessions.

We believe that these Proceedings will serve as a valuable reference for researchers worldwide and will stimulate further research in agriculture, forestry, food and veterinary sciences, engineering, information and communication technologies, environmental sciences, economics, social sciences, and education.

We also sincerely thank all section moderators for their dedication and professionalism, which contributed to productive and meaningful discussions throughout the sessions: A. Spage, S. Ancans, V. Tetere, E. Dubrovskis, G. Mazure, U. Skadins, I. Straupe, S. Vasilevska, L. Licite-Kurbe, I. Grinfelde, I. Stokmane, P. Abolins, T. Rubina, J. Kaneps, J. Pilecka-Ulcugaceva, K. Amatnieks, and Z. Vitolina. We extend our sincere thanks to the conference organizing team and all our colleagues whose dedicated efforts made this event a success.

The 'Research for Rural Development' conference continues to serve as an important platform for international collaboration and scientific exchange, supporting innovation and sustainability in rural regions.

We look forward to welcoming you to the Latvia University of Life Sciences and Technologies next year for the 33rd Annual International Scientific Conference 'Research for Rural Development 2027', which will take place from May 12 to 14, 2027.

Natalija Sergejeva
Chairperson
Annual 32nd International Scientific Conference
'Research for Rural Development 2026'

CONTENTS

AGRICULTURAL SCIENCES

GENETIC ANALYSIS OF LATVIAN DARK HEAD OLD TYPE BREEDING RAMS
Dace Barzdina, Daina Kairisa 14

BLACK SOLDIER FLY LARVAL MEAL AS A PROTEIN SOURCE IN PIG NUTRITION: A REVIEW
Patrīcija Paula Pauliņa, Lilija Degola 22

EGG PRODUCTION ANALYSIS IN AUSTRALORP HENS
Didzis Dreimanis, Daina Jonkus, Līga Paura 31

ASSESSMENT OF UAV-DERIVED VEGETATION INDICES FOR EARLY-GENERATION SELECTION IN SPRING WHEAT
Zaiga Jansone, Māra Bleidere, Gundega Putniece 38

PATHOGENICITY OF TWO ALTERNARIA SPECIES ON POTATO AND THEIR COMPATIBILITY WITH A BACILLUS SUBTILIS-BASED PRODUCT
Linda Upeniece, Gunita Bimšteine, Veneranda Stramkale 45

A REVIEW: THE INFLUENCE OF VARIOUS FACTORS ON THE COMPOSITION AND QUALITY OF STARCH IN POTATO TUBERS
Inese Taškova, Ina Alsiņa 52

THE OCCURRENCE OF TOMATO DISEASES CAUSED BY ALTERNARIA SPP. AND STEMPHYLIUM SPP. IN THE BALTIC REGION
Lilija Dučkena, Nabahat Bessadat, Nelly Bataillé-Simoneau, Franck Bastide, Bruno Hamon, Mati Koppel, Kaire Loit, Neringa Rasiukevičiūtė, Gunita Bimšteine, Philippe Simoneau 59

THE IMPACT OF THERMOREFLECTIVE SURFACES ON THE OVERWINTERING OF APIS MELLIFERA CARNICA: PRELIMINARY STUDY
Pavels Avens, Janis Gailis, Ulla Milbreta. 67

TOWARDS SUSTAINABLE LIVESTOCK: CALCULATED AND ON-FARM MEASURED METHANE VALUES IN A HIGH-YIELDING DAIRY HERD
Ilga Sematovica, Ilze Vike, Laima Berzina 74

MANAGEMENT OF BIOMASS AND ENERGY POTENTIAL OF SWITCHGRASS (PANICUM VIRGATUM L.) AS AFFECTED BY SOWING DATE AND SEED BURIAL DEPTH
Ulyana Nedilska, Serhii Yermakov, Oleg Kucher, Volodymyr Kryzhanivskyi. 79

FORESTRY

DO FLOWERING PLANTS CONTRIBUTE TO BUTTERFLY DIVERSITY ALONG THE FOREST ROADS IN LATVIA?
Dagmāra Čakstiņa, Santa Ieviņa, Līga Pentjuša, Zane Lībiete, Linda Gerra-Inohosa 85

STAND DENSITY EFFECTS ON GROWTH AND STEM QUALITY OF HYBRID LARCH IN LITHUANIA
Loreta Semaškienė, Sinilga Černulienė 91

INDOOR SEED PRODUCTION OF SILVER BIRCH (BETULA PENDULA ROTH): CURRENT KNOWLEDGE AND RESEARCH NEEDS
Aldis Sproģis, Alise Bleive, Kaspars Liepiņš 96

EFFECT OF ALNUS GLUTINOSA (L.) GAERTN. AND BETULA PENDULA ROTH. PLANTATIONS ON GROUND COVER PLANT DIVERSITY
Inga Straupe, Sintija Ozola, Baiba Jansone, Āris Jansons 104

OCCURRENCE PATTERNS OF KEY NON-TIMBER FOREST PRODUCTS: EVIDENCE FROM THE NATIONAL FOREST INVENTORY IN LATVIA
Agita Treimane, Jānis Donis, Ilze Barone, Zane Lībiete 109

SNOW, WATER, AND TERRAIN AS DRIVERS OF FOREST SCENIC BEAUTY
Zane Lībiete, Edgars Jūrmalis 116

REDUCTION OF R:FR RATIO MODULATES SHOOT ARCHITECTURE OF BETULA PENDULA IN VITRO WITHOUT IMPAIRING PHOTOSYNTHESIS
Toms Kondratovics, Ina Alsina, Arnis Gailis 122

CASE STUDY OF BIRD'S-FOOT TREFOIL (LOTUS CORNICULATUS), WOOD FIBER, PEAT FOR SAND AND GRAVEL QUARRY RECLAMATION
Viktorija Vendina, Dagnija Lazdiņa 129

VETERINARY MEDICINE

MANUAL PIPETTING: A MULTI-SECTOR STUDY WITH DRY-VERIFICATION TECHNOLOGY (ATMOS-1)
Avo Karus 136

FOOD SAFETY

COMPARATIVE ANTIBACTERIAL AND BIOFILM-INHIBITORY ACTIVITY OF LACTOBACILLUS HELVETICUS CELL-FREE AND HEAT-INACTIVATED NON-FILTERED SUPERNATANTS
Gundega Gulbe, Agnese Brūvere, Anda Valdovska 140

FOOD SCIENCE

THE EFFECT OF FREEZE-DRYING ON THE PHENOLIC AND ANTHOCYANIN CONTENT IN BERRY PRESS RESIDUES
Jelena Pisarjonoka, Anete Keke 148

AGRICULTURAL ENGINEERING

HIGH-POWER CHARGING SOLUTIONS FOR ELECTRIC TRANSPORT: REVIEW OF EXISTING TECHNOLOGIES AND APPROACHES
Mārtiņš Tisenkopfs, Aigars Laizāns 156

A LINEAR PROGRAMMING APPROACH TO LAND AND IRRIGATION WATER ALLOCATION FOR PRIORITY CROPS IN RWANDA
Emmanuel Hakiruwizera, Yusuf Ucar, Niragire Theophile 166

BELL PEPPER RESPONSE TO MULCH TYPES UNDER DIFFERENT IRRIGATION STRATEGIES
Emmanuel Hakiruwizera, Yusuf Ucar 174

THE POTENTIAL OF ROBOTISATION FOR STRAWBERRY CULTIVATION IN OPEN FIELDS: A REVIEW
Artūrs Feldmanis, Vilnis Pīrs, Kārlis Banis 179

DIVERSIFYING ENERGY FLOWS IN THE EU: STRUCTURAL CONSTRAINTS AND THE LATVIAN CASE
Ivans Zotovs, Alina Zotova, Liene Kancevica, Aigars Laizans 188

CONSTRUCTION AND GEODESY

IMPACT OF PRATT TRUSS MEMBER SIZING ON OPTIMAL SOLUTIONS
Arturs Neiburgs 197

COMPARISON OF A LATVIAN REGIONAL GNSS-BASED IONOSPHERE TIME SERIES WITH GLOBAL IONOSPHERE MAPS
Atis Vallis, Armands Celms, Jānis Zvirgzds, Jānis Kaminskis, Jēkabs Vallis 205

APPLICATION OF THE LBTU METHOD FOR DEFORMATION MONITORING OF A TUNNEL DURING CONSTRUCTION
Edgars Kraskevičs, Armands Celms 210

DEVELOPMENT OF STRATEGIC IMPLEMENTATION FRAMEWORK FOR CIRCULAR MODULAR CONSTRUCTION SYSTEMS IN INDIAN REAL ESTATE DEVELOPMENT COMPANIES
Soniya Mohankumar, Janis Zvirgzdins **215**

IMPACT OF VOC EMISSIONS FROM RECYCLED BUILDING MATERIALS ON INDOOR ENVIRONMENTAL QUALITY
Andris Stankevics, Sandra Gusta **223**

THE ROLE OF KNOWLEDGE-BASED TECHNOLOGIES AND INNOVATIONS IN THE SUSTAINABLE DEVELOPMENT OF THE LATVIAN CONSTRUCTION
Inese Biuksane **229**

A LITERATURE REVIEW OF STEEL FIBRE REINFORCED CONCRETE BEAMS FAILING IN SHEAR
Venkata Siva Kumar Anumolu **234**

EXPERIMENTAL INVESTIGATION OF BUCKLING STABILITY OF NON-COMPOSITE-SECTION MULTI-LAYER PANELS UNDER AXIAL COMPRESSION
Dana Puzanova, Ulvis Skadins **241**

IMPACT OF UNIFORMLY DISTRIBUTED LOAD TYPES ON DEFLECTION OF SFRC FLAT SLABS
Solvita Šņore, Ulvis Skadiņš **247**

ENVIRONMENTAL ENGINEERING

LONG-TERM CHANGES IN ARABLE LAND, MEADOWS AND NATURAL PASTURES, ORCHARDS IN LITHUANIA
Giedrė Ivavičiūtė **253**

MOSS-BASED VERTICAL BARRIERS AS HYBRID INFRASTRUCTURES FOR URBAN PM MONITORING AND MITIGATION
Edgars Karklins **263**

VEGETATIVE PROPAGATION OF BRYOPHYTES FOR URBAN DEPLOYMENT AND ECOSYSTEM SERVICES PROVISION
Juta Karklina **268**

IRRIGATION PRIORITIZATION MODEL FOR DROUGHT RESILIENCE: CROP RANKING AND WATER SAVING SCENARIOS
Vilda Grybauskiene, Gitana Vyciene, Inga Grinfelde, Ulaş Şenyiğit **273**

A COMPARATIVE ASSESSMENT OF FARM-LEVEL GREENHOUSE GAS EMISSION ESTIMATES USING DECARBFARM AND ESTABLISHED GHG TOOLS
Katrina Muizniece, Inga Grinfelde, Jovita Pilecka-Ulcugaceva **279**

SPATIAL OCCURRENCE OF PFOS AND PFOA IN THE DAUGAVA AND LIELUPE RIVER BASINS (LATVIA)
Jana Grave, Inga Grinfelde, Jovita Pilecka-Ulcugaceva **285**

WATER BASIN GOVERNANCE CAPACITY DEVELOPMENTS: PARTICIPATORY MANAGEMENT PRACTICE ENHANCEMENT
Raimonds Ernsteins, Toms Bringulis, Karlis Konkovs, Maris Ozolins, Arturs Skute **293**

LOCAL WATER BASIN GOVERNANCE DEVELOPMENTS IN LATVIA: COMPLEMENTARY TRIPPLE GOVERNANCE DIMENSIONS FRAMEWORK
Raimonds Ernsteins, Toms Bringulis, Maris Ozolins, Karlis Konkovs, Arturs Skute **303**

GOVERNANCE FRAMEWORK FOR ENERGY EFFICIENT HOUSING RENOVATION PROCESS: MULTI-APARTMENT BUILDING WITH COMPLEMENTARY ROOF-TOP SOLAR TECHNOLOGIES
Raimonds Ernsteins, Ivars Kudrenickis, Liga Biezina, Rasa Ikstena **319**

POLICY ARRANGEMENTS AND PRACTICE IMPLEMENTATION STUDIES TOWARDS NECESSARY HARMONISATION OF WATER AND AGRICULTURAL GOVERNANCE
Toms Bringulis, Raimonds Ernsteins, Erika Lagzdina, Arturs Skute **335**

LAND USE PLANNING

DYNAMICS OF BUILT-UP AREA DEVELOPMENT IN LITHUANIA IN 2005-2025
Giedrė Ivavičiūtė 348

AGRICULTURAL LAND CHANGE IN LITHUANIA AND ITS COUNTIES (2005–2025)
Giedrė Ivavičiūtė 357

GREENHOUSE GAS EMISSION REDUCTION POTENTIAL ASSESSMENT FROM LAND-USE CHANGE IN AGRICULTURE
Kristiāna Griķe, Raimonds Kasparinskis 366

LANDSCAPE ARCHITECTURE

THERAPEUTIC LANDSCAPES AS A PUBLIC HEALTH RESOURCE
Kitija Graudiņa, Ilze Stokmane 375

INFORMATION AND COMMUNICATION TECHNOLOGIES

FROM PAPER TO PIXELS: DIGITAL DELEGATE BADGES AND CONFERENCE COMPETITIVENESS
Ēriks Lingebērziņš, Agita Doniņa 384

UNEVEN DIFFUSION: THE SECTORAL CONTOURS OF DATA CAPITALISM IN A SMALL OPEN ECONOMY
Ritvars Metra 390

IOT-BASED AUTONOMOUS MONITORING SYSTEM FOR REAL-TIME WASP DETECTION AT BEEHIVE ENTRANCES
Kirishanth Manivannan, Aleksejs Zacepins 396

ARTIFICIAL INTELLIGENCE AND THE WORK ENVIRONMENT: CHALLENGES AND SOLUTIONS FOR HUMAN CAPITAL DEVELOPMENT
Simona Ozoliņa-Ugore, Elīna Pentjuša, Anita Straujuma, Elīna Gaile-Sarkane 405

AI-BASED IMAGE CLASSIFICATION FOR HEN EGG FERTILITY DETECTION
Sausthene Landry Tsiguia Tetangmo, Liga Paura 414

TOURISM RECOMMENDER SYSTEMS AI HYBRID FILTERING CONTEXT-AWARE ADAPTATION SOCIAL MEDIA TRENDS USER SATISFACTION
Pradeep Sharma, Tatjana Rubina 421

AGRARIAN ECONOMICS

FINANCIAL AND ECONOMIC IMPACT OF SOLE PROPRIETORS' ACTIVITIES ON THE DEVELOPMENT OF RURAL TERRITORIAL COMMUNITIES
Yuliia Cheban, Olha Luhova. 429

ADAPTIVE GOVERNANCE MODELS FOR RURAL DEVELOPMENT IN SOUTHERN UKRAINE DURING POST-WAR RECOVERY
Maryna Dubinina, Svitlana Syrtseva 437

CHANGES IN EXPORTS AND MARKET CONCENTRATION IN THE BEEF CATTLE INDUSTRY IN LATVIA
Evija Skujiņa, Irina Pilvere 445

THE IMPACT OF THE RURAL DEVELOPMENT PROGRAMME SUPPORT ON AMMONIA EMISSIONS FROM AGRICULTURE
Elita Benga, Juris Hāzners, Anita Auziņa 454

BIOFUEL EXPANSION AND AGRICULTURAL LAND USE: ASSESSING FOOD–FUEL COMPETITION IN POLAND
Ludwik Wicki, Aleksandra Wicka 460

ANALYSIS OF THE TAX BURDEN IN AGRICULTURAL FARMS OF VARIOUS SPECIALIZATIONS, A CASE STUDY OF LATVIA
Inguna Leibus, Agita Bicevska 468

RETHINKING HUMAN CAPITAL INDICATORS IN REGIONAL ANALYSIS BASED ON EVIDENCE FROM LATVIA
Ģirts Veigners, Andra Zvirbule 475

CAP SUPPORT AND BALANCED AGRICULTURAL DEVELOPMENT IN LATVIA: EVIDENCE FROM EXPERT EVALUATIONS AND FARM-LEVEL DATA
Jana Gurska, Irina Pilvere 481

THE ROLE OF PUBLIC-PRIVATE PARTNERSHIPS IN REGIONAL DEVELOPMENT AND SUSTAINABILITY: A REVIEW OF THE THEORETICAL FRAMEWORK, FUTURE PROSPECTS, AND CHALLENGES IN THE LITERATURE
Peteris Abolins, Andra Zvirbule, Liga Jankova, Kristine Rendniece-Petrevica, Inga Megne 488

ANALYSIS OF THE INSTITUTIONAL ENVIRONMENT OF PUBLIC-PRIVATE PARTNERSHIPS IN THE CONTEXT OF REGIONAL DEVELOPMENT AND SUSTAINABILITY
Peteris Abolins, Andra Zvirbule, Liga Jankova, Kristine Rendniece-Petrevica, Maira Lescevica 494

SYNERGY OF RURAL AREA REVITALIZATION AND AGRICULTURAL PRODUCTION DEVELOPMENT IN THE CONTEXT OF WAR AND POST-WAR CHALLENGES IN UKRAINE: MANAGERIAL ASPECT
Halyna Matskiv, Hanna Zhosan, Iryna Romaniuk 500

CONVERGING TRENDS IN AGRICULTURAL PERFORMANCE BETWEEN WESTERN AND EASTERN EUROPE
Sandris Ancans 509

LEGAL FRAMEWORK FOR REGULATING FAIR AND RESPONSIBLE MARKETING COMMUNICATION IN LATVIA'S AGRICULTURAL PRODUCT MARKET
Ksenija Furmanova, Gunta Freimane 515

THE THEORETHICAL ASPECTS OF AGRICULTURAL LOGISTICS
Annija Marta Jurgevica, Liga Jankova 520

HIERARCHICAL STRUCTURING OF SUSTAINABILITY - ORIENTED ECONOMIC CONCEPTS
Maira Leščevica, Zane Gusta 526

BIOMETHANE PRODUCTION FROM AGRICULTURAL BY-PRODUCTS: SUPPORTING THE DEVELOPMENT OF RURAL AREAS IN LATVIA
Davide Iannantuono, Sandija Zeverte-Rivza, Kaspars Naglis-Liepa 534

DEFINING THE PRIORITY RESEARCH AREAS IN DIGITAL TECHNOLOGIES, ARTIFICIAL INTELLIGENCE OF UKRAINE BY DELPHI SURVEY
Anton Koretsky, Denys Zhernovyi, Vitaliya Klimenkova 541

SHEEP MEAT PRODUCTION POTENTIAL IN LATVIA
Matiss Bicevskis, Agita Bicevska, Dina Popluga 550

TRENDS IN THE POLISH AGRICULTURAL LAND MARKET BETWEEN 2015 AND 2024
Alina Danilowska 558

VEGANISM IN THE CONTEXT OF SUSTAINABLE FOOD SYSTEMS: GLOBAL TRENDS AND THE LATVIAN CASE
Anastasija Zemcova, Sandija Zēverte-Rivža 565

DIGITALISATION OF THE DEVELOPMENT OF SUBJECTS OF REGIONAL AGRARIAN ECONOMY
Natalya Sirenko, Kateryna Tishechkina, Kateryna Mikulyak 572

INSTITUTIONAL CAPACITY AND THE EMERGENCE OF BIOREGIONAL INITIATIVES IN RURAL LATVIA: A GOVERNANCE PERSPECTIVE
Inga Megne, Kaspars Naglis-Liepa, Pēteris Āboliņš 580

IDENTIFYING UKRAINE'S RESEARCH PRIORITIES IN EFFICIENCY AND SAFETY OF ENERGY BY TECHNOLOGY FORESIGHT
Anton Koretskyi, Kaspars Naglis-Liepa, Tetiana Velenteichyk, Denys Zhernovyi, Serhii Taran, Yuri Khomenko 589

THE CONTRIBUTION OF AGRICULTURAL MARKETING COOPERATIVES TO THE SUSTAINABLE DEVELOPMENT GOALS: EVIDENCE FROM TÜRKIYE
Bakiye Kilic Topuz, Mücahit Bulut 597

SOCIAL SCIENCES

INTERREGIONAL TOURISM SPILLOVERS AND REGIONAL DEVELOPMENT: A SPATIAL NETWORK APPROACH
Rajkumar Jayaraj 606

FROM GLOBAL ISSUES TO LOCAL AGENCY: SOCIAL WORK FOR COMMUNITY RESILIENCE IN RURAL MUNICIPALITIES IN LATVIA
Baiba Bela.....613

EMBEDDING CULTURE IN SUSTAINABLE RURAL PLACE-MAKING: EVIDENCE FROM REGIONAL PLANNING STRATEGIES IN LATVIA
Dina Bite, Liene Kairiša 620

REGULATORY FRAMEWORK OF PUBLIC ADMINISTRATION SERVICES GOVERNANCE IN LATVIA: TOWARDS GOOD GOVERNANCE
Lilita Gurnasa, Gunita Mazure 628

SUSTAINABLE WORKFORCE DEVELOPMENT IN EUROPE: HR STRATEGIES FOR SUPPORTING GENERATION Z IN RURAL AND REGIONAL LABOUR MARKETS
Shruti Gupta, Andra Zvirbule 636

RURAL IDYLL AND RURAL PENALTY: THE PERSPECTIVE OF FAMILIES WITH CHILDREN
Jolanta Millere, Signe Dobelniece 643

BROADER ECONOMIC IMPACTS EVIDENCE OF GENOMICS IN BEEF CATTLE PRODUCTION SYSTEMS
Sandra Helmute, Gunita Mazure.....650

URBANIZATION AND DEMOGRAPHIC CHALLENGES OF FUNDING EDUCATIONAL INSTITUTIONS IN MUNICIPALITIES IN LATVIA
Modrite Pelse, Elina Laine Melbarde 658

THE IMPACT OF HUMAN LIFE CYCLE STAGES ON INDIVIDUALS' SUSTAINABLE CONSUMPTION CHOICES
Liga Feldmane, Krista Patricija Zeibote.....665

REGIONAL DIFFERENCES IN FACTORS AFFECTING THE EMPLOYMENT OF THE SILVER GENERATION IN LATVIA
Lilita Seimuškāne, Biruta Sloka.....672

THE ROLE OF SOCIAL ENTERPRISES IN BUILDING SOCIAL CAPITAL IN THE EDUCATION SECTOR IN ZEMGALE
Lasma Licite-Kurbe, Amanda Silina, Baiba Blomniece-Jurane.....678

A SYSTEMIC MODEL OF TECHNOLOGY TRANSFER AND COMMERCIALISATION IN LATVIAN SCIENTIFIC INSTITUTIONS
Liga Braslina, Anda Batraga, Jelena Salkovska, Didzis Rutitis, Davids Stebelis, Solvita Kostjukova, Marta Kontina, Girts Braslins, Laima Braslina.....686

ANALYSIS OF THE INSTITUTIONAL FRAMEWORK FOR HUMAN CAPITAL DEVELOPMENT IN THE BALTIC SEA REGION
Marina Romele, Kaspars Naglis-Liepa 694

SUSTAINABLE FOOD PACKAGING INDICATORS
Laura Martinsone-Ozoliņa, Dina Popluga 700

ENVIRONMENTAL PRACTICES IN TOURISM AND TOURISTS' PRO-ENVIRONMENTAL BEHAVIOUR AS DRIVERS OF SUSTAINABLE RURAL DEVELOPMENT IN UKRAINE
Iryna Kyryliuk, Nataliia Barvinok, Viktoriia Krasnomovets, Oksana Lytvyn, Valentina Demko 707

SUSTAINABILITY COMMUNICATION: FROM SMALL ENTERPRISES TO STRONG COMMUNITIES IN THE REGIONS OF LATVIA
Ilze Vike, Ginta Kronberga 715

POWER RELATIONS IN SENIOR CARE: COMMUNITY BASED AND LONG-TERM CARE SOLUTIONS
Endija Rezgale-Straidoma, Līga Rasnača 722

INSTITUTIONAL AND REGIONAL INEQUALITY IN LONG-TERM SOCIAL CARE PROVISION IN LATVIA: IMPLICATIONS FOR RURAL DEVELOPMENT
Jana Muizniece, Lilita Seimuskane 730

SOCIAL IMPLICATIONS OF THE SILVER ECONOMY IN RURAL REGIONS OF LATVIA
Signe Dobelniece, Ginta Kronberga 737

NGOS IN RURAL SOCIO-ECONOMIC DEVELOPMENT: COMMUNITY RESILIENCE AND SOCIAL INFRASTRUCTURE
Krista Alksne, Anita Straujuma 744

SOCIAL ACCEPTANCE OF POWER GENERATION POSSIBILITIES
Olafs Slutins, Sandija Zeverte-Rivza, Laila Zemīte 752

INCENTIVE-BASED AND EQUALIZATION-BASED APPROACHES TO MITIGATING REGIONAL INEQUALITY
Anna Velickina, Modrite Pelse 759

ENERGY SECURITY RESEARCH IN THE BALTIC STATES: FUNDING AND COORDINATION
Sandra Vasilevska 766

DIGITALISATION AND TOURISM POLICY IN LATVIA: IMPLICATIONS FOR RURAL TOURISM DEVELOPMENT
Inita Kindzule-Millere, Sandija Zēverte-Rivža 773

UNDERSTANDING GREEN FINANCE: DEFINITIONS AND CONCEPTUAL DEVELOPMENT
Eliza Elza Lipsane, Gunita Mazure 780

COMPETITIVENESS DETERMINANTS OF CATERING ENTERPRISES IN REGIONAL TOWNS OF LATVIA: THE CASE OF TALSI AND TUKUMS
Kitija Kirila, Gita Krumina-Zemture, Ilva Peka, Niklavs Libergs 786

GENERATIONAL SUCCESSION IN SMALL FARMS AND FARMING RESILIENCE IN LATVIA
Aija Zobena 794

SOCIAL ENTERPRISES IN LATVIA: AN UNTAPPED RESOURCE FOR COMMUNITY SOCIAL WORK IN RURAL AREAS
Liesma Ose 800

POLITICAL DIMENSION FOR PUBLIC ENGAGEMENT IN REGIONAL DEVELOPMENT AND RESILIENCE
Jeļena Šaicāne, Līga Proškina 807

EDUCATION

EMPIRICAL RESULTS OF MENTORSHIP IMPACT ON ACADEMIC PROGRESS AND ATTITUDES OF VETERINARY MEDICINE PRECLINICAL STUDIES
Virge Karus, Hanna Belinska, Kärt-Carmen Konsa, Avo Karus 814

ARTIFICIAL INTELLIGENCE IN HIGHER EDUCATION: A CROSS-DISCIPLINARY SURVEY STUDY
Natalja Vronska, Olafs Vronskis 818

VOCATIONAL AGRICULTURAL EDUCATION AND LABOUR MARKET DYNAMICS: IMPLICATIONS FOR SUSTAINABLE REGIONAL DEVELOPMENT AND ECONOMIC GROWTH
Iveta Leitlante **825**

CIVIL PROTECTION DISASTER PREPAREDNESS OF LATVIA`S REGIONS
Uldis Karlsons, Dace Brizga, Uldis Spulle **830**

TIMETABLE PLANNING AND OPTIMIZATION IN LATVIAN SCHOOLS: EMPIRICAL EVIDENCE FROM A NATIONAL SURVEY ON DIGITALIZATION, WORKLOAD, AND ORGANISATIONAL CONSTRAINTS
Katrina Kellerte, Liga Braslina, Anda Batraga **834**

KEY COMPETENCIES FOR REWRITING THE NARRATIVE ON GENDER-BASED VIOLENCE IN RURAL AREAS FOR SUSTAINABLE SOCIAL DEVELOPMENT
Anna Vintere, Antonia Castellani, Andreas Ahrens, Jelena Zascerinska **840**

DIGITAL COLLABORATIVE TOOLS IN ENGLISH LANGUAGE TEACHING AT REGIONAL HIGHER EDUCATION INSTITUTIONS
Olena Kan **846**

THE DIGITAL SKILLS GAP IN GEODESY AND LAND MANAGEMENT: AN ANALYSIS OF THE CURRICULUM AT UKRAINIAN AGRICULTURAL UNIVERSITIES
Oleksandr Kovalenko **853**

KINSHIP CARE FAMILIES IN RURAL REGIONS: AN ACTOR-NETWORK PERSPECTIVE
Aiga Romāne-Meiere **861**

LINKING MATHEMATICS EDUCATION WITH REAL-LIFE APPLICATIONS FOR SUSTAINABLE RURAL DEVELOPMENT
Liene Briede, Oksana Labanova, Elena Safiulina, Inna Samuilik, Leif Hammar, Elena Ligere **869**

GENETIC ANALYSIS OF LATVIAN DARK HEAD OLD TYPE BREEDING RAMS

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Abstract
To ensure genetic diversity of sheep production, local sheep breeds are included in genetic resource conservation programs, which increases their unique characteristics. The Latvian Dark Head old type (LTvt) sheep breed is an excellent example of how important it is to preserve genetic diversity among farm animals. The aim of the study is to evaluate the genetic diversity of LTvt breeding rams. The study included 126 LTvt breeding rams, which were genetically analysed by their year of birth (2002–2021) and paternal (ram) genealogical line, it is seven. Since 2012, the Latvian Sheep Breeders Association (LAAA) has been determining deoxyribonucleic acid (DNA) profiles by microsatellite loci lengths at the Eurofins Genomic laboratory in Germany. Fourteen microsatellite loci were used for DNA profiling. The results show that greater genetic diversity was obtained in indicators such as the number of different alleles (8.86 ± 0.601), the number of effective alleles (4.55 ± 0.476), Shannon's information index (1.66 ± 0.104) and expected heterozygosity (0.74 ± 0.037) in the group of breeding rams born between 2012 and 2016. The inbreeding coefficient values were close to zero, which indicates the absence of inbreeding. The analysed F-statistics values were negative in most loci, which indicates the excess of heterozygous genotypes in the studied population. Genetic differentiation between ram lines selected in the LTvt population was low (0.006–0.074), indicating low genetic diversity. Analysis of molecular variance showed that most of the genetic variation was between alleles within individual (93%).
Keywords: microsatellite loci, allele, genotype, genetic diversity, and variation.

Introduction

The conservation of sheep genetic resources is particularly important. Their variation is characterised by the compatibility of biodiversity conservation with sustainable agriculture, providing food for the population. Sheep genetic resources include genetic diversity that promotes their unique characteristics, such as disease resistance, ability to adapt to changing climatic conditions, and diverse productivity. Continuous cooperation at national, regional, and global levels is essential to ensure the sustainability and resilience of sheep breeds for future generations.

Although awareness of the importance of conserving animal genetic resources increases each year, their decline persists. Genetic diversity provides an opportunity to obtain or improve the disease resistance of farm animals (Jovanovic et al., 2009). Highly resilient local sheep breeds worldwide are capable of surviving extreme climatic conditions. Such breeds are easy to rear and use for small land management systems, as they require less investment in terms of costs and labour, and can lead to significant developments in sheep breeding (Molotsi et al., 2017).

Comparative genetic analysis shows that although the Latvian Dark Head sheep has similar genetic markers to other Northern European sheep breeds, it also has different genetic characteristics. Studies in the Baltic region using microsatellite loci and mitochondrial DNA have revealed both common ancestors and unique genetic diversity within this breed (Larsson et al., 2024).

The selection of the Latvian Dark Head breed is historically based on sheep breeding by ram lines. In 2014, seven breeding ram lines of this breed were identified: Skaris 0008; Edžiņš 0365; Sīgars 0005; Apollons 0302; Sīmanis 0195; Irbis 0125 and Ikars 0121. A systematic survey of the genetic resources of the Latvian Dark Head sheep breed was started in 2004. The animals had to comply with the criteria set out in the Latvian Dark Head sheep breed conservation program. In order to include typical LTvt animals in the genetic resource program in the future, a new breeding program for the Latvian Dark Head old type sheep breed was developed in 2019 (Latvjas Aitu…, 2024). In addition to all animal performance test evaluations, it introduced an evaluation based on wool growth on the head, belly, and legs.

The preservation of the Latvian Dark Head sheep includes two strategic methods. *In situ*: using support and education programs to encourage farmers to breed local animal breeds (including sheep), and *ex situ*: establishing Gene banks and cryopreserving genetic material with the aim of preserving biological material for future use. The aim of Gene bank is to preserve part of the Latvian Dark Head sheep breed as a gene reserve, without introducing other non-related breeds in future generations, and to use it as a 'mother' breed for sheep crossbreeding, as it improves fertility and milk production and is characterized by good maternal traits, a strong constitution, resistance to disease, and suitability for local conditions (Gene Bank, 2021).

Sheep farms often rely on just a few breeding rams, which can lead to a decrease in genetic diversity within ram lines as certain alleles are lost. Breeds originating from a small number of individuals often exhibit low genetic diversity. If a breeding flock initially relies on a single ram, the genetic profile of the offspring is heavily restricted by the father's limited allele pool. The loss of alleles in a population often indicates genetic drift. This is, especially true in small populations where alleles can be randomly lost by chance, particularly when the number of individuals of one sex is limited. Consequently, even neutral or beneficial alleles may fail to be passed on to offspring purely through random sampling. The loss of alleles can also result from deliberate selection goals. For example, if an individual carries alleles associated with undesirable trait like low fertility, those alleles will be passed on to subsequent generations less frequently or

eliminated entirely (David et al., 2018; Karsli et al., 2020; Ocampo et al., 2016; Tapio et al., 2010).

Materials and Methods

Microsatellite loci, or more exactly, genotype distribution, are used in population genetic calculations to determine the level of relationship between breeds, groups, and individuals (Wagner et al., 2006).

Supported by funding from the Latvian Ministry of Agriculture, the LAAA has conducted DNA profiling since 2012 using microsatellite markers based on allele fragment length analysis at Eurofins Genomics (Germany). DNA profiling allows the origin of an animal to be accurately determined and verified. During this process, the laboratory uses 14 microsatellite loci for DNA profiling, see Table 1. All of the listed microsatellite markers are widely used in sheep genetic research in analyses of allele diversity, population structure, and Hardy-Weinberg equilibrium (HWE) (Al-Atiyat et al., 2018; Saberivand et al., 2010).

Table 1

Characterization of DNA profile microsatellite loci and alleles with chromosomal localization

Microsatellite loci	Size range, bp	Primer sequences (5′ – 3′) F – forward, R – reverse	The chromosome	Expected length, bp	Allele repetition
OarFCB128	94 – 126	F: ATTAAAGCATCTTCTCTTTATTTCCTCGC R: CAGCTGAGCAACTAAGACATACATGCG	2	105	TG9
TGLA53	140 – 160	F: ATCTTCACATGATATTACAGCAGA R: GCTTTCAGAAATAGTTTGCATTCA	12	141	TG12
D5S2	186 – 196	F: GAGACCTCAGGGTTGTTGGTCAG R: TACTCGTAGGGCAGGCTGCCTG	3	194	GT16
BP33	247 – 279	F: AGGCCTCTGAATTCCTCTCC R: AACCAGCAGTCTTGCTCTCTC	18	271	AC23
MAF65	89 – 139	F: AAAGGCCAGAGTATGCAATTAGGAG R: CCACTCCTCCTGAGAATATAACATG	15	124	GT11
McM527	134 – 180	F: GTCCATTGCCTCAAATCAATTC R: GTTTCTTAAACCACTTGACTACTCCCCAA	5	164	TG16
DRB2	227 – 289	F: CTGCCAATGCAGGAGACACAAGA R: GTCTGTCTCCTGTCTTGTCTCAT	20	300	AC29
OarFCB20	87 – 129	F: GGAAAACCCCCATATATACCTATAC R: AAATGTTGTTTAAGATTCCATACATGTG	2	95	TG15
INRA49	134 – 164	F: TCCACAATCACACAGGCCA R: TGTATTAGTTTGTGTTCTTTGGC	1	135	AC8
CSRD247	209 – 283	F: GGACTTGCCAGACTCTGCAAT R: CAGCTGTGGTTTGTATTAGTCAGG	14	244	CA28
MMP9	183 – 204	F: CTTGCCTTCTCATGCTGGGACT R: GTGAGGCTGGCACTTGGTCTGGCT	13	220	AC20
OarCP49T	78 – 106	F: CAGACACGGCTTAGCAACTAAACGC R: GTGGGGATGAATATTCCTTCATAAGG	17	87	CA17
INRA172	122 – 168	F: CCAGGGCAGTAAAATGCATAACTG R: GGCTTTGCTAGCCTCTGCAAAC	22	152	GT21
BP28	209 – 241	F: CCTCCACAACACCATCCTTC R: AGGTGACAGGTGGGAGGGC	24	221	TG21

In laboratory analyses, each sample is (1) subjected to DNA extraction, (2) a multiple polymerase chain reaction is performed with appropriate primers to synthesize the region of the genome of interest, and (3) the length of the synthesized fragment is determined using a capillary electrophoresis sequencer. The laboratory provided information on the fragment lengths of each sample in all 14 loci. Information on the possible number of nucleotides repeats in the microsatellite loci according to the determined fragment length was found on the website of the University of California Regents' International Sheep Genome Consortium (Archibald et al., 2010). Using the primer sequence, the corresponding location in the sheep genome and the number of repeats at the fragment length in the database were determined. Furthermore, the locations of microsatellites loci on the chromosome were verified. The genetic analysis of the LTvt breeding ram population included in the study was performed according to their year of birth and affiliation to the paternal (ram) genealogical line, see Table 2. In total, data on 126 breeding rams born between 2002 and 2021 were analysed, dividing this period into four-year intervals. In Latvia, Apolons 0302 (46) and Skaris 0008 (27) lines of breeding rams are more commonly used on sheep breeding farms. Less represented rams are from the Edžiņš 0365 and Ikars 0121 lines.

Table 2
Number of breeding rams by year of birth and affiliation to the father (rams) line

Ram line	Ram count by birth year				Total in rams' line
	2002–2006	2007–2011	2012–2016	2017–2021	
Apolons0302	2	9	25	10	46
Edžiņš0365	0	0	0	5	5
Ikars0121	0	1	4	4	9
Irbis0125	0	2	6	5	13
Sīgars0005	1	3	8	1	13
Sīmanis0195	0	2	8	3	13
Skaris0008	1	9	7	10	27
Total by period	4	26	58	38	126

More breeding rams were included in the LTvt breeding program from 2012 to 2016 (58), but breeding rams (5) from the Edžiņš 0365 line were only included in the LTvt breeding program from 2017 to 2021. For the genetic analysis of the population, the following statistical methods were used to calculate allele frequency, heterozygosity, Wright's F–statistic (Wright, 1978), Nei's genetic distance, and the Hardy-Weinberg equilibrium test.

Population genetic diversity was characterized by several indicators that reflect allele diversity and genotype distribution. Population genetics is based on the calculation of HWE equilibrium, which indicates a constant allele and genotype frequency in a population from generation to generation, provided there are no allele mutations, migration, selection, inbreeding, or random genetic drift. The GenAlEx 6.5 software package was used to analyse genetic diversity and population structure in the animals included in the study, dividing them by birth year according to their ram line. Based on genotype and allele frequencies (N), the number of different alleles (Na), the effective number of alleles (Ne), and the observed (Ho) and expected (He) heterozygosity were calculated. Different inbreeding coefficients (F) were calculated and analysed. These help to understand the genetic structure of populations, identify the degree of inbreeding, and determine how genetic variation is distributed at the level of individual relative to its subpopulation (Fis), inbreeding coefficient among populations by year of birth (Fst), and the overall inbreeding coefficient entire population (Fit). Principal Coordinates Analysis (PCoA) was based on and calculated using standard genetic distance (Nei). The number of different alleles (Na) provides a general overview of genotype polymorphism, reflecting how many different alleles exist in a single locus. This is the basis for calculating the effective number of alleles and heterozygosity. The effective number of alleles (Ne) shows the most common alleles based on their frequency. The closer this value is to the Na, the more evenly the alleles were distributed. However, if Ne is much smaller than Na, it means that some alleles dominate, while others are very rare. Shannon's information index (I) compares genetic diversity between populations. Its value indicates the frequency of alleles, if there is one dominant allele in a locus, then I will be lower, but if all of them are common, then I will be higher. To assess the extent to which the number of heterozygous genotypes (Ho, He) in a population has decreased due to random crossing, the inbreeding coefficient (F) is calculated (Peakall & Smouse, 2009).

The aim of the study was to evaluate the genetic diversity of Latvian Dark Head old type breeding rams.

Results and Discussion

By analysing the number of alleles present in 14 loci, it was concluded that a total of 136 alleles were observed in the LTvt breeding ram population. Polymorphic genotypes were observed in 14 loci in all 7 breeding ram lines. In some loci, unique alleles were also observed, which characterize the breeding rams belonging to a certain line, for example, in loci 'OarFCB128' (allele 126), 'OarFCB20' (allele 129), 'MAF65' (allele 117), 'MAF65' (allele 123), 'MMP9' (allele 181) and 'BP28' (allele 215). Analysis of the HWE parameter showed that the LTvt breeding ram population was in equilibrium.

The evaluation of the genetic diversity parameters of breeding rams in the LTvt population by year of birth is shown in Table 3.

Over the course of the study, a total of 126 breeding rams were analysed, including their 136 alleles and 795 genotypes. Of these genotypes, 657 were heterozygous and 138 were homozygous. This confirms that the LTvt population has good genetic diversity, and it means high heterozygosity and no obvious inbreeding. Genetic diversity indices differ significantly between the birth year groups of breeding rams ($p<0.05$) by Na, I and He.

Table 3

Evaluation of genetic diversity parameters of rams in the LTvt population by birth years

Birth year of the rams	N	Na	Ne	I	Ho	He	F
		$\bar{x} \pm S\bar{x}$					
2000. – 2006.	4	3.79 ± 0.318[a]	2.96 ± 0.273	1.13 ± 0.111[a]	0.70 ± 0.075	0.60 ± 0.054[a]	–0.05 ± 0.035
2007. – 2011.	26	7.50 ± 0.693[b]	4.43 ± 0.451	1.58 ± 0.119[b]	0.70 ± 0.053	0.72 ± 0.048[ab]	0.01 ± 0.046
2012. – 2016.	58	8.86 ± 0.601[b]	4.55 ± 0.476	1.66 ± 0.104[b]	0.71 ± 0.044	0.74 ± 0.037[b]	0.03 ± 0.033
2017. – 2021.	38	7.57 ± 0.677[b]	4.33 ± 0.474	1.59 ± 0.104[b]	0.70 ± 0.037	0.72 ± 0.037[ab]	0.02 ± 0.032
Along/ Mean	126	6.93 ± 0.385	4.07 ± 0.225	1.49 ± 0.060	0.70 ± 0.026	0.70 ± 0.023	–0.02 ± 0.024

Na – number of alleles, Ne – number of effective alleles, I – Shannon's information index, Ho – observed heterozygosity, He – expected heterozygosity, F – inbreeding coefficient.

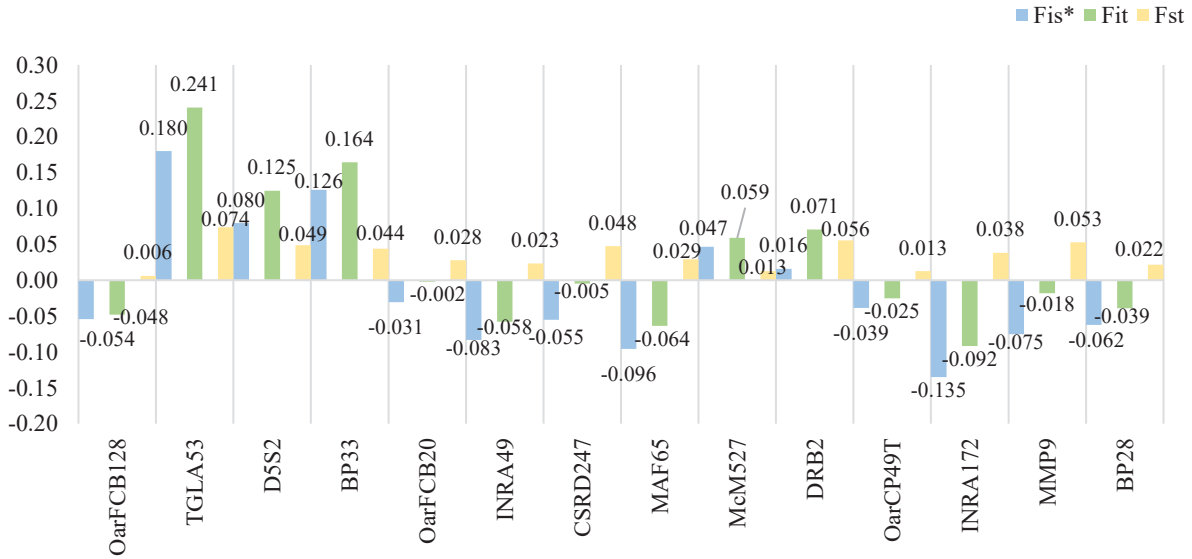
Different superscript letters within a column indicate statistically significant differences ($p<0.05$).

The group of rams born from 2000 to 2006 exhibited the lowest Na (3.79 ± 0.318), Ne (2.96 ± 0.273) and I (1.13 ± 0.111) values. This indicates reduced allelic richness, low effective allele diversity and low overall genetic diversity. However, because this group contained only four animals, and these results should be interpreted with caution. The highest Na (8.86 ± 0.601), Ne (4.55 ± 0.476), I (1.66 ± 0.104) and He (0.74 ± 0.037) values were observed in the group of breeding rams born between 2012 and 2016, indicating genotype polymorphism and higher genetic diversity, where the breeding rams in this group are genetically more diverse. The observed heterozygosity (Ho) was similar in all groups (0.70–0.71) and did not differ significantly ($p>0.05$) between studied groups. In a Lithuanian study, which also studied Latvian Dark Head breed sheep, the expected heterozygosity (He) (0.698 ± 0.173) was lower than the observed heterozygosity (Ho) (0.712 ± 0.143), which can be explained that the breed has been highly selected in flocks (Grigaliūnaite et al., 2003). The low inbreeding coefficient (F) values indicate that there is no significant inbreeding among the breeding ram groups by birth year. Consequently, no significant deficit of heterozygous genotypes was observed, suggesting that the LTvt breeding ram population is in equilibrium. The negative F value (-0.05 ± 0.035; -0.02 ± 0.024) indicates a slight excess of heterozygote genotypes, while a positive F value (0.01 ± 0.046; 0.03 ± 0.033; 0.02 ± 0.032) indicates a slight deficit of heterozygote genotypes.

Genetic differences between populations and the level of inbreeding are described by F-statistics (Fis, Fit, and Fst). They provide insight into the distribution of genetic diversity at different levels and allow us to characterize genetic differences between individuals, lines, and the population as a whole. The Fis, Fit, and Fst values of genetic differences that characterize the genetic structure of the LTvt population of breeding rams in all 14 loci can be seen in Figure 1.

Figure 1

Distribution of Fis, Fst and Fit values by loci in the ram LTvt population



**Fis – level of inbreeding within a population; Fit – total level of inbreeding across all populations; Fst – genetic differentiation between populations.*

In the LTvt breeding population, heterozygous genotypes exceeded homozygous genotypes in most loci, which was characterized by negative Fis values (from -0.135 to -0.031), but in three loci, 'TGLA53' (0.180), 'D5S2' (0.080) and 'BP33' (0.126), it is positive, where a deficit of heterozygous genotypes is observed. This is often observed in small populations or when animals with specific genotypes have been selected during the selection process. The total heterozygous genotype deficit (Fit) in the LTvt breeding ram population is slightly lower than expected, depending on the year of birth.

In the LTvt breeding poplulation rams' population, the total inbreeding coefficient (Fit) is slightly lower than the level of inbreeding within a population (Fis). The highest Fit values were observed at loci 'TGLA53' (0.241), 'BP33' (0.164) and 'DRB2' (0.071), indicating a persistent deficit of heterozygous genotypes across birth years. Conversely, 8 of the 14 analysed loci exhibited negative Fit values, indicating an excess across the ram groups of birth year.

The total genetic difference in the LTvt breeding ram population by year of birth is determined by the Fst value. If the Fst value is between 0.00 and 0.05, it is low. If it is between 0.06 and 0.15, it is medium, and if the Fst value is more than 0.16, there is a large difference between the animals in the population (Peakall & Smouse, 2009). In most loci, the Fst value varies from 0.01 to 0.07, for example, the lowest value is in the locus 'OarFCB128' (0.006), but the highest is in the locus 'TGLA53' (0.074). This means that the LTvt breeding ram population is genetically similar depending on the animal's year of birth, but there are slight differences in genetic diversity in some loci.

Research conducted by various international authors on local sheep breeds indicates that these populations typically exhibit significant allele diversity. A high number of heterozygous genotypes is often observed, indicating that there is no significant decrease in genetic diversity within breeds. The Fis values of the breeds studied by the authors ranged from 0.110 to 0.752, and negative values were also observed. When describing Fst values, the authors note that in most cases they are low (0.028–0.319), and there is a certain genetic difference between these breeds. In these mentioned studies, the total inbreeding level in relation to the entire population (Fit) ranged from 0.246 to 0.751, and therefore signs of inbreeding or frequent selection were observed in individual loci (Arora et al., 2011; Baumung et al., 2006; Ghazy et al., 2013; Hoda et al., 2009; Hoda & Ajmone, 2012; Kusza et al., 2010; Mukesh et al., 2006; Yilmaz et al., 2014). To evaluate the distribution of genetic diversity at different levels, molecular variance analysis (AMOVA) was performed (Peakall & Smouse, 2009). This helps to understand the extent to which genetic differences exist within the population and between individuals in the population. Molecular variance analysis for the whole LTvt breeding ram population by year of birth can be seen in Table 4.

Table 4

Analysis of molecular variance in ram LTvt population by birth year

Source	df	SS	MS	σ^2	%SS
Among line	3	22.86	7.62	0.04	1
Among individual	122	668.97	5.48	0.31	6
Within individual	126	613.00	4.87	4.87	93
Total	251	1304.83	…	5.21	100

df – degrees of freedom, SS – sum of squares, MS – mean square, σ^2 – estimated variance, %SS – Percentage distribution of variation.

When analysing genetic variation among all breeding ram lines depending on their year of birth, these ram lines are genetically similar across years and show slight variation, as indicated by the percentage distribution of variation (%SS) value (1%). Genetic variation between certain breeding ram lines among individual is 6%, where different individuals in the same population are genetically different, but this variation is not wide. When analysing the genetic variation between alleles within individual, this value is higher – 93%, which can be explained by the heterozygosity of the individual, where different alleles are found in the same locus. In a study carried out in Italy with a single sheep breed kept in different regions, these values were similar to the data from our study, as the highest genetic variation between individual alleles was 94.21% (Ceccobelli et al., 2016).

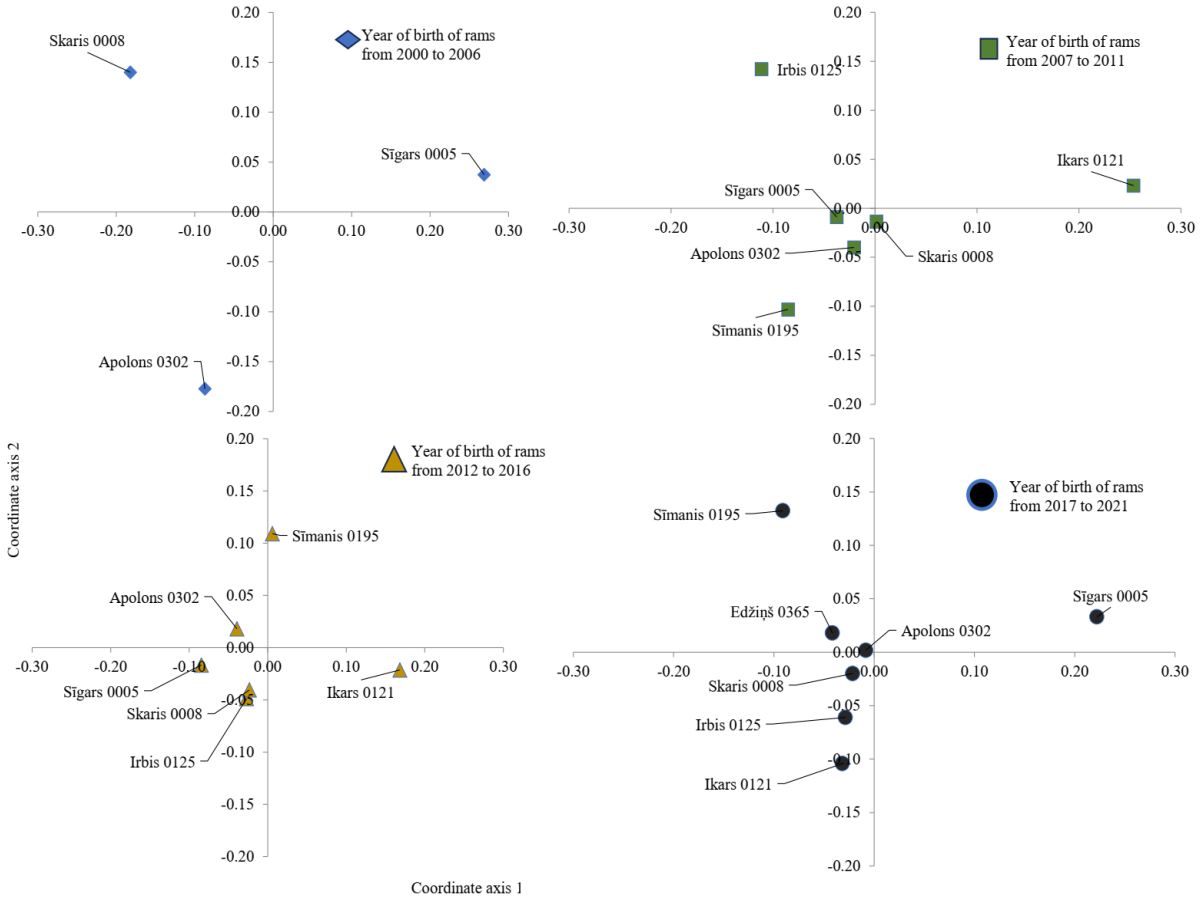
Principal coordinate analysis (PCoA) shows how animals are grouped according to similar or different alleles within a population. The position of breeding rams from a specific line within each LTvt population on the respective axis is indicated by positive or negative numbers. These determine which side of the axis (positive or negative direction) the animals from a specific line are located on. Animals with similar values are closer to each other, while those with opposite values are more different. PCoA analysis was performed for breeding rams of each line depending on their year of birth (Figure 2).

Analysis of the principal coordinates shows that the year of birth of breeding rams is not the main factor in genetic differences, but that the highest allele diversity is at the individual level. Several animals from breeding lines are located on one side of the coordinate axis, for example, animals from the Apolons 0302, Skaris 0008, and Irbis 0125 lines. The animals in these breeding ram lines are genetically similar. However, there are animals in breeding ram lines such as Ikars

0121, Sīmanis 0195, and Sīgars 0005 that are more separated from the main coordinate axis. This indicates a longer genetic distance, which is based on changes in allele frequencies in a certain individual in the year of birth of a certain breeding ram, where these alleles can disappear and reappear when mating with an ewe that may or may not have these alleles. In a study carried out in the Baltic States with local sheep breeds, the genetic characteristics of the Latvian Dark Head sheep breed were similar to the average characteristics of all breeds studied. Animals of the Latvian Dark Head breed formed the most homogeneous group, as the individuals in the group were genetically similar to each other, which can be explained by the extensive selection work carried out during the development of the breed (Tapio et al., 2005).

Figure 2

Genetic relationships among ram birth year and line in LTvt population revealed by PCoA



Conclusions

1. Breeding rams born between 2000 and 2006 had lower genetic diversity, whereas breeding rams born between 2012 and 2016 had higher genetic diversity.
2. Genetic diversity and inbreeding levels in the LTvt breeding ram population showed that most loci had an excess of heterozygous genotypes rather than a deficit, and that there was low to medium genetic variation between breeding ram lines.
3. Molecular variance analysis confirmed that LTvt breeding ram lines are very similar to each other, with the highest genetic variability occurring among the animals themselves.
4. Principal coordinate analysis reflected a similar genetic structure among LTvt ram lines, with slight changes in genetic distance observed across ram birth year periods.
5. The observed heterozygosity in all breeding ram groups by year of birth was similar, the inbreeding coefficient was close to zero, and no significant inbreeding between LTvt breeding ram lines was confirmed.

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BLACK SOLDIER FLY LARVAL MEAL AS A PROTEIN SOURCE IN PIG NUTRITION: A REVIEW

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Abstract
This review is based on the analysis of recent scientific literature on black soldier fly larvae (BSFL) production, processing and application in pig nutrition. The increasing demand for sustainable protein sources in animal nutrition has stimulated growing interest in insects, particularly black soldier fly (*Hermetia illucens*) larvae, as an alternative feed ingredient. The literature shows that these larvae efficiently convert various organic substrates into high quality biomass, making their production compatible with circular economy principles and supporting sustainable feed systems. BSFL are commonly harvested at the late larval or prepupal stage and processed through thermal treatment, drying and grinding to obtain larvae meal. Depending on processing techniques, both full-fat and defatted meals can be produced. Defatting significantly increases the relative protein content while reducing lipid levels, improving nutritional consistency and storage stability. Chemical analyses show that larvae meal contains high levels of crude protein, often exceeding 45–55% of dry matter, together with valuable lipids. The lipid fraction is characterized by medium-chain fatty acids, particularly lauric acid, which is associated with antimicrobial properties. Processing methods strongly influence the nutritional quality of larvae meals. Drying techniques and blanching conditions affect nutrient availability, protein structure and digestibility. In vitro studies demonstrate that appropriate processing strategies can enhance nutrient utilization of BSFL meals in monogastric animals such as pigs. BSFL meal represents a promising alternative protein source in swine nutrition, offering high nutritional value and the potential to partially replace conventional protein ingredients.
Keywords: black soldier fly larvae, insect protein, pig nutrition, sustainable feed.

Introduction

As the global population continues to grow, the need for animal products is also rising, creating challenges for livestock systems to improve both efficiency and sustainability. Pig production represents an important component of global meat production, and pork accounts for a large proportion of total meat consumption worldwide. However, feed costs represent the largest share of pig production expenses, often accounting for 60–70% of total production costs (Chia et al., 2021). Pig diets frequently contain soybean and fish meal, as these ingredients are good sources of nutrients and protein, but their increasing price and environmental impact have stimulated the search for alternative protein sources (Chia et al., 2021).

Conventional protein sources used in livestock feeding are associated with several sustainability challenges. For example, soybean cultivation is linked to deforestation, high water consumption and greenhouse gas emissions, while fish meal production is strongly influenced by marine resources that are already under pressure due to overfishing. These concerns have led researchers to investigate new feed ingredients that can support efficient animal production while reducing environmental impact (Kar et al., 2021).

Insects are increasingly recognized as a viable alternative to conventional protein sources for animal feed. They are known for their fast development, efficient feed use, and ability to transform organic waste into valuable biomass. Importantly, insect farming requires relatively small land areas and generates lower greenhouse gas emissions compared with conventional livestock production systems (Spranghers et al., 2018). Among the different insect species evaluated for feed applications, the black soldier fly (*Hermetia illucens*) has become more widely studied due to its favourable biological and nutritional characteristics (Spranghers et al., 2018).

Black soldier fly larvae (BSFL) are suitable for livestock diets due to their high content of crude protein, lipids and bioactive compounds. Moreover, the larvae can be produced using organic waste materials, helping to support waste recycling and supporting circular bioeconomy systems (Zhu et al., 2022). Despite the growing interest in insect-based feeds, additional studies are needed to better understand the nutritional properties of BSFL meal and its potential use in pig nutrition (Zhu et al., 2022).

However, despite the growing number of studies on insect feed ingredients, the reported results remain inconsistent, particularly regarding nutrient digestibility and long-term effects in pig production systems.

Therefore, the aim of this review is to summarise and analyse current scientific knowledge regarding BSFL production, processing methods, nutritional composition and their potential use as an alternative protein source in pig feeding systems.

Materials and Methods

This study employed a monographic approach to evaluate existing research on the use of BSFL meal in pig nutrition. The analysis was based on peer reviewed research articles, review papers and experimental studies focusing on insect production, nutrient composition and feeding trials in pigs.

Literature was collected using databases such as Scopus, Web of Science and Google Scholar using keywords 'black soldier fly', 'pig nutrition' and 'insect protein'. Studies were selected based on relevance, publication date and scientific quality. In total, 35 scientific publications were included in the analysis, of which all were experimental studies. The selected studies were

published between 2015 and 2025. The reviewed publications included studies conducted in different countries with advanced research programmes in animal production and feed technology. Particular attention was given to studies investigating the production of BSFL, their chemical composition and how their inclusion in pig diets affects growth performance, nutrient digestibility, gut health and meat quality.

Although a systematic review protocol (e.g., PRISMA) was not applied, efforts were made to include recent and relevant peer reviewed studies to ensure a comprehensive overview of the topic.

The results of these studies were synthesised to assess the current scientific understanding of the role of insect-based protein sources in swine feeding systems.

Results and Discussion

Production and biological characteristics of black soldier fly larvae

The black soldier fly (*Hermetia illucens*) is a saprophagous dipteran species capable of converting a wide range of organic substrates into nutrient-rich biomass suitable for feed production (Nguyen et al., 2015). The species undergoes complete metamorphosis, comprising egg, larval, pupal and adult stages. Depending on environmental conditions, eggs generally hatch within 4 days, larval development lasts approximately 13–16 days, the pupal stage requires around 14 days, and adults survive for approximately 5–8 days (Laursen et al., 2024). Adult flies are distributed across tropical, subtropical and temperate regions, while larval development and survival are strongly influenced by environmental conditions, particularly temperature and substrate composition (Chia et al., 2018).

The larval stage is characterized by rapid growth, with larvae typically reaching the prepupal stage within 15 – 22 days and exhibiting growth rates ranging from 0.0014 to 0.0056 g day^{-1}, depending on substrate (Bava et al., 2019; Nguyen et al., 2015). BSFL also demonstrate efficient utilization of organic materials, achieving waste reduction index (WRI) values of 3.01–4.90 and feed conversion efficiency (ECD) values of 0.25–0.36, while reducing organic waste mass by approximately 50% or more under suitable rearing conditions. BSFL have been successfully reared on diverse substrates, including poultry feed, kitchen waste, pig manure, fruit and vegetable waste, fish-processing residues, brewery by-products and distillers' grains (Bava et al., 2019; Nguyen et al., 2015). In a comparative study evaluating different organic waste streams, kitchen waste increased waste reduction by 67.9% relative to the control poultry feed and yielded the highest larval biomass (679.9 mg per three larvae), compared with approximately 580 mg per three larvae in the control group (Nguyen et al., 2015). Similarly, larvae fed maize distillers reached final weights of up to 1.97 g, while those reared on a control hen diet reached 2.29 g before the prepupal stage (Bava et al., 2019).

The nutritional composition of BSFL varies according to the substrate used during rearing. Crude protein concentrations ranging from 39.9 to 43.1% of dry matter (DM) have been reported in prepupae reared on chicken feed, vegetable waste, biogas digestate and restaurant waste (Spranghers et al., 2016). Likewise, larvae produced on different by-products contained between 37.2 and 52.3% crude protein on a DM basis, indicating considerable flexibility in nutrient composition depending on the feeding substrate (Tschirner & Simon, 2015). Due to their ability to efficiently transform low-value organic materials into protein- and lipid-rich biomass, BSFL have gained increasing attention as a sustainable ingredient for animal feeding systems (Oonincx et al., 2015).

BSFL can be reared on a wide range of organic substrates, including agricultural residues, food processing by products and livestock manure (Hao et al., 2023).

Beyond its nutritional value, BSFL production contributes to improved nutrient recycling and resource efficiency (Parodi et al., 2021). During manure bioconversion, BSFL were shown to recover and retain approximately 12.5% of the supplied dry matter, 13% of carbon, 25% of nitrogen, 14% of gross energy, 8.5% of phosphorus and 9% of potassium in larval biomass within a nine-day period, demonstrating their capacity to redirect nutrients from waste streams into valuable biological products (Parodi et al., 2021). This highlights the dual role of BSFL as both a feed ingredient and a biological tool for waste valorisation.

BSFL are widely recognized for their capacity to efficiently reduce organic waste. The effectiveness of this process depends on substrate composition. Larvae reared on tofu by-products achieved greater larval biomass, higher bioconversion rates and higher protein and lipid yields than larvae reared on food waste or vegetable substrates, indicating substantial differences in nutrient conversion efficiency among feedstocks (Hosseindoust et al., 2023). Similarly, prepupae reared on different organic substrates contained between 399 to 431 g kg^{-1} DM crude protein and lipid between 218 to 386 g kg^{-1} DM lipids, demonstrating the strong influence of substrate quality on biomass composition (Spranghers et al., 2016).

The growth and development of BSFL are strongly influenced by environmental conditions, particularly temperature. Larvae successfully completed development between 15 and 35 °C, whereas survival and growth performance declined substantially at lower temperatures (Shumo et al., 2019). Population growth was greatest at approximately 30 °C, where the intrinsic rate of increase reached 0.127 and population doubling time was reduced to 5.5 days, indicating highly suitable conditions for mass production (Chia et al., 2018). In addition, substrate characteristics interact with temperature effects, as larvae reared on brewers' spent grain exhibited greater tolerance to temperature fluctuations and produced more biomass than those reared on cattle manure (Shumo et al., 2019).

The larval stage plays a key biological role in organic matter decomposition and nutrient transformation. Rapid biomass accumulation is supported by extensive microbial activity within the digestive tract (Zhineng et al., 2021). Metagenomic analyses revealed that the BSFL intestine contains more than 11,000 bacterial species involved in polysaccharide metabolism, membrane transport, energy metabolism and nutrient conversion pathways (Zhineng et al., 2021). Furthermore, manure conversion studies identified *Proteobacteria*, *Firmicutes* and *Bacteroidetes* as the dominant bacterial phyla, while approximately 90 and 109 newly established bacterial genera were detected during chicken and swine manure conversion, respectively (Ao et al., 2020). Functional analyses suggested that these microbial communities contribute directly to amino acid metabolism and nutrient utilization efficiency, thereby supporting protein accumulation in larval biomass (Ao et al., 2020).

BSFL reared on tofu by-products produced the highest protein yield (1.45 kg per clutch) and lipid yield (1.23 kg per clutch), compared with 1.25 and 1.20 kg per clutch for food waste and 1.05 and 0.96 kg per clutch for vegetable substrates, respectively. In contrast, vegetable-based substrates resulted in the highest protein conversion rate (21.44%) and lipid conversion rate (25.55%), compared with 8.69% and 16.48% for tofu by-products, and 11.30% and 11.35% for food waste, respectively (Hosseindoust et al., 2023). Likewise, larvae reared on thermally pre-treated sewage sludge contained between 44 and 54% crude protein and between 21 and 25% lipids, while thermal pre-treatment at 90°C for 16 h increased protein and lipid yields by 69% and 71%, respectively, compared with untreated sludge. The larvae were reared for 15 days on the pre-treated substrate and subsequently harvested, inactivated, dried and proceseed into meal for protein and lipid analyses (Liew et al., 2023).

Processing of black soldier fly larvae into meal

After harvesting at the late larval or prepupal stage, typically after approximately 14–18 days of larval development under optimal rearing conditions (25 – 30°C), BSFL are processed into insect-derived feed ingredients suitable for livestock nutrition. Depending on the intended product, harvested larvae may be processed into full-fat BSFL meal, partially or fully defatted BSFL meal, or BSFL oil. Defatted meals are produced by removing part or most of the lipid fraction from dried larvae, thereby increasing the relative crude protein concentration, whereas the extracted lipid fraction can be further processed and used as BSFL oil in animal feeds. The processing methods applied to the larvae play critical role in determining the nutritional quality, safety and storage stability of the final product (Chia et al., 2018; Oh et al., 2024., Zozo et al., 2022).

The most common processing procedure includes several stages, such as washing, thermal treatment, drying and grinding. The processing of BSFL generally includes cleaning, blanching or thermal treatment to inactivate enzymes and microorganisms, grinding, drying (e.g., ove-, microwave- or freeze-drying), and milling (Zozo et al., 2022). Depending on the intended application, and additional defatting step may be applied. In solvent-based defatting, lipids are extracted using organic solvents such as hexane and isopropanol, followed by solvent removal and further grinding of the residual meal. Defatting reduces the fat content and increases the relative protein concentration, resulting in partially or fully defatted BSFL meal with improved storage stability and reduced risk of lipid oxidation (Zozo et al., 2022). Thermal treatment is commonly used to inactivate microorganisms and enzymes that could otherwise reduce product quality during storage. Drying methods may include microwave drying, hot-air drying and freeze drying, depending on the processing technology used (Son et al., 2023). For example, microwave drying has been performed at 80 °C for 32 minutes, whereas hot-air drying has been conducted at 60 °C for 17 hours. In addition, blanching in boiling water or in a 2% citric acid solution for 5 min is often applied before drying to reduce microbial contamination and inactivate enzymes. After drying, the larvae may be defatted by mechanical oil extraction and subsequently ground into a fine powder that can be incorporated into feed formulations (Son et al., 2023).

Processing conditions strongly influence nutrient availability and digestibility. For example, drying methods involving higher thermal exposure, such as infrared drying at 95 °C for 12 min, resulted in lower crude protein digestibility compared with hot-air drying at 65 °C for 24 h, microwave drying, or freeze drying (Oh et al., 2024; Son et al., 2023). Similarly, blanching prior to drying reduced nitrogen and amino acid digestibility compared with hot-air drying alone. Therefore, selecting appropriate processing techniques is essential to maintain the nutritional value of insect feed ingredients (Oh et al., 2024; Son et al., 2023).

Son et al. (2023) reported that hot air drying at 60 °C for 17 h improved nitrogen digestibility compared with microwave drying at 80 °C for 32 min, increasing the *in vitro* ileal disappearance of nitrogen from 84.4% to 86.7% ($p<0.05$). These findings demonstrate that thermal processing conditions can influence nutrient availability for pigs.

However, the reported results are not entirely consistent, which may be explained by differences in experimental conditions, including variation in BSFL inclusion levels, processing methods, animal age and duration of feeding trials. Notably, the nutritional composition of BSFL meal is influenced by rearing substrate, which may further contribute to variability in reported outcomes.

Chemical composition and nutritional value of black soldier fly larvae meal

The chemical composition of BSFL meal has been extensively investigated due to its potential as an alternative protein source in animal nutrition. The nutritional value of BSFL is largely determined by its

protein, lipid, amino acid and mineral composition, all of which can be influenced by rearing substrate and processing methods.

BSFL meal is characterized by a crude protein content ranging from approximately 40 to 56% on a dry matter basis, depending on larval age and rearing substrate, which is comparable to soybean meal (44–48% crude protein) and lower than fish meal (60–72% crude protein). In addition, BSFL contains substantial amounts of lipids and various bioactive compounds (Eke et al., 2025). In larvae reared on different food waste mixture, crude protein concentrations reached 44.5% DM, while lipid content remained close to 30% DM, confirming the ability of BSFL to convert organic residues into nutrient-rich biomass suitable for feed applications (Eke et al., 2025). Similarly, BSFL reared on agro-industrial by-products showed significant variation in chemical composition, with crude protein concentrations ranging from 22.9% to 39.6% DM depending on the rearing substrate (Meneguz et al., 2018).

The nutritional composition of BSFL meal is strongly affected by processing. Zozo et al. (2022) reported that full-fat BSFL flour contained 45.8% crude protein and 25.8% fat, whereas defatted BSFL flour contained 56.1% crude protein and only 4.8% fat. Defatting therefore increased protein concentration by approximately 10 percentage points while substantially reducing lipid content, improving the suitability of BSFL meal as a concentrated protein ingredient for monogastric diets (Zozo et al., 2022).

In addition to crude protein content, the nutritional value of BSFL meal depends on protein digestibility and amino acids availability. Chen et al. (2019) demonstrated that BSFL protein exhibited a slower nitrogen solubilisation rate during the initial stages of digestion than whey protein, although the release of low-molecular-weight peptides during pancreatic digestion was comparable. These findings suggest that BSFL protein may provide a more gradual supply of amino acids within the gastrointestinal tract (Chen et al., 2019).

BSFL lipids are characterized by a high proportion of medium-chain fatty acids, particularly lauric acid (C12:0), which may account for up to 60% of the total fatty acid profile. Spranghers et al. (2018) reported that extracted BSFL fat exhibited antimicrobial activity against *D-streptococci* under *in vitro* conditions, with approximately 2.2 log reductions observed at the highest inclusion level of 1.50 g fat 100 mL^{-1} medium (equivalent to 0.87 g C12:0 100 mL^{-1}). In feeding trials with weaned piglets, diets containing full-fat and defatted BSFL resulted in approximately 0.5 log reductions in *D-streptococci* counts in the stomach and proximal small intestine compared with the control diet, without negatively affecting average daily gain, feed intake or feed conversion ratio (Spranghers et al., 2018).

Another important aspect of BSFL meal is its amino acid profile. Essential amino acids such as leucine, lysine, valine and histidine were identified as the predominant amino acids in BSFL meal processed using different drying methods, supporting its suitability as a protein source for livestock diets (Zulkifli et al., 2022). The amino acid composition of BSFL meal is generally comparable with conventional protein ingredients, although differences in amino acid digestibility may require adjustments during feed formulation (Zulkifli et al., 2022).

Although BSFL meal contains all essential amino acids required for pig growth, some studies have reported slightly lower digestibility values compared with fish meal. Hosseindoust et al. (2023) observed higher apparent ileal digestibility of arginine, histidine, leucine, threonine, isoleucine and phenylalanine in fish meal diets than in BSFL meal diets. However, average amino acid digestibility did not differ significantly among treatments, indicating that BSFL meal can provide comparable overall amino acid availability for pigs. Furthermore, thermal processing and extrusion of BSFL meal tended to improve amino acid digestibility (Hosseindoust et al., 2023).

Table 1 presents the nutritional composition, selected amino acids and fatty acid profiles of BSFL-derived products with conventional feed ingredients used in pig diets. The data indicate that crude protein concentrations in full-fat BSFL meal (45–50%) are comparable to soybean meal (44–48%), while defatted BSFL meal may contain up to 56% crude protein, approaching values reported for fish meal (55–60%) (Zozo et al., 2022). In addition, BSFL meal provides considerable amounts of essential amino acids, particularly leucine, lysine, valine and histidine, supporting its suitability as a protein source for pig nutrition (Zulkifli et al., 2022). Compared with conventional protein sources, BSFL-derived products are characterized by a distinctive fatty acid profile rich in lauric acid, which accounts for approximately 36–42% of total fatty acids in BSFL oil and full-fat meal (van Heugten et al., 2022; Spranghers et al., 2018). This fatty acid composition may provide additional functional benefits related to gut health, antimicrobial activity and microbial regulation in pigs (Spranghers et al., 2018).

These nutritional characteristics have contributed to increasing in BSFL meal as a feed ingredient for pigs. The high productivity and adaptability of BSFL make them particularly suitable for large-scale insect farming. Research findings in pigs suggest that replacing conventional protein sources with BSFL meal does not negatively affect growth performance or feed efficiency (Chia et al., 2019; Crosbie et al., 2021). More recently, defatted BSFL meal containing 6.26% ether extract (fat), compared with 9.00% in fish meal and 11.44% in hydrolyzed BSFL meal, improved average daily gain, feed conversion ratio and feed cost per kilogram of gain compared with conventional fish meal diets in weaned pigs, further supporting its potential as a sustainable protein source for animal nutrition (Lee at al., 2024).

Table 1

Nutritional composition of black soldier fly larvae meal compared with conventional protein sources used in pig diets

Feed ingredient	Crude protein (%)	Fat (%)	Key amino acids (% DM)	Main fatty acids (% total FA)	Notable characteristics	Reference
Soybean meal	44–48	1–2	Lys 2.8–3.0; Leu 3.4–3.8	Linoleic acid 50–55; Oleic acid 20–25	widely used plant protein source in pig diets	Nørgaard et al., 2021
Fish meal	55–60	8–10	Lys 4.5–5.5; Met 1.5–2.0	EPA + DHA 15–30	high digestibility	Chia et al., 2021
BSFL meal (full-fat)	45–50	25–35	Leu 2.7–3.0; Lys 2.3–2.8; Val 2.0–2.4; His 1.0–1.4	Lauric acid 36–42; Palmitic acid 14–15; Oleic acid 13–14; Linoleic acid 17–18	antimicrobial properties, high energy	Spranghers et al., 2018; Zozo et al., 2022
BSFL meal (partially defatted)	50–56	10–15	Leu 2.7–3.1; Lys 2.4–2.9	Lauric acid 30–40; Linoleic acid 15–18	Better protein concentration and feed formulation flexibility	Lee et al., 2024
BSFL meal (defatted)	50–56	4–8	Leu 2.8–3.2; Lys 2.5–3.0	Residual lauric acid 15–25	suitable as concentrated protein ingredient	Zozo et al., 2022
BSFL oil	-	>95	-	Lauric acid ~37; Linoleic acid ~17; Palmitic acid ~14; Oleic acid ~13; Myristic acid ~10	antimicrobial activity, alternative lipid source	van Heugten et al., 2022
Soybean oil	-	99–100	-	Linoleic acid 50–55; Oleic acid 20–25; Palmitic acid 10–12	rich in unsaturated fatty acids	Buffoni et al., 2025; van Heugten et al., 2022

Notes: Lys – lysine, Leu – leucine, Met – methionine, Val – valine, His – histidine; EPA – eicosapentaenoic acid, DHA – docosahexaenoic acid.

Effects of black soldier fly larvae meal in pig diets

Several experimental studies have evaluated the effects of including BSFL meal in pig diets, and the majority of findings indicate that insect-derived ingredients can partially or completely replace conventional protein sources without compromising animal performance. The magnitude of the response, however, depends on inclusion level, processing method and the production stage of the animals.

Supplementation with BSFL oil resulted in a linear increase in growth performance. Nursery pigs receiving 6% BSFL oil achieved a final body weight of 30.0 kg compared with 28.4 kg in pigs fed corn oil, while average daily gain increased by approximately 7% and feed efficiency improved significantly during the first two feeding phases (van Heugten et al., 2022). In post-weaning pigs, replacing soybean oil with a BSFL oil blend for 39 days did not significantly affect growth performance. Final body weight was 27.58 kg in pigs receiving BSFL oil compared with 27.03 kg in pigs fed soybean oil, while overall average daily gain was 0.534 and 0.513 kg d^{-1}, respectively. Average daily feed intake remained similar between treatments (0.692 vs 0.672 kg d^{-1}), as did gain-to-feed ratio (0.763 vs 0.765 kg d^{-1}), indicating that BSFL oil can effectively replace conventional vegetable oil without impairing pig performance (Buffoni et al., 2025). These findings suggest that BSFL oil can be incorporated into pig diets without detrimental effects on growth performance or gut microbial development. In a 61-day feeding trial with weaned piglets, Biasato et al. (2019) evaluated the inclusion of partially defatted BSFL meal at 5% and 10% of the diet. In weaned piglets, inclusion of 5% and 10% partially defatted BSFL meal increased final body weight from 31.88 kg in the control group to 32.23 and 33.06 kg, respectively. Total weight gain increased from 25.78 kg in the control group to 26.14 kg and 26.96 kg in the BSF5 (5% inclusion) and BSF10 (10% inclusion) groups, while average daily gain increased from 0.42 to 0.43 and 0.44 kg d^{-1}, respectively; however, these differences were not statistically significant ($p>0.05$). Feed conversion ratio remained similar among treatments (1.71, 1.70 and 1.70, respectively). Apparent digestibility of crude protein ranged from 76.6 to 79.5%, and villus height-to-crypt depth ratio varied between 3.35 and 3.72, indicating that dietary BSFL meal did not adversely affect nutrient utilization or gut morphology (Biasato et al., 2019). Similarly, Crosbie et al. (2021) reported that replacing 25% or 50% of conventional animal protein sources with full-fat BSFL meal resulted in similar average daily gain (496 g d^{-1}), feed intake (743 g d^{-1}) and final body weight (27.6 kg) compared with antibiotic-containing

nursery diets, while gut morphology and immune response remained unaffected.

The effects of BSFL meal on gut health and metabolism have also been investigated. Feeding pigs, a diet in which BSFL served as the sole protein source altered intestinal microbial composition and resulted in the appearance of plasma metabolites such as sarcosine, methionine sulfoxide, α-aminobutyric acid and taurine, suggesting metabolic adaptations associated with improved intestinal functionality and host health (Kar et al., 2021). In addition, dietary BSFL reduced the relative abundance of *Mycoplasma* in the ileal digesta of nursery pigs compared with conventional protein diets, indicating a potential beneficial effect on intestinal microbial balance (Song et al., 2024).

Another important aspect of pig production is meat quality. Zhu et al. (2022) reported that replacing part of the fish meal and soybean meal with 4% or 8% full-fat BSFL meal significantly increased intramuscular fat content compared with the control diet. Growing pigs receiving 8% BSFL meal achieved the highest average daily gain (0.56 kg d^{-1}) compared with pigs fed the control diet (0.47 kg d^{-1}) or 4% BSFL meal (0.46 kg d^{-1}; p=0.029). In addition, first intercostal backfat thickness increased from 16.13 mm in the control group to 24.04 mm in pigs fed 8% BSFL meal, p=0.024. Intramuscular fat content also increased significantly from 1.49% in control pigs to 1.65–1.74% in pigs receiving BSFL meal (p=0.013), while drip loss decreased from 0.17% to 0.12–0.13% (p=0.026), indicating improvements in several meat quality traits (Zhu et al., 2022). Metabolomic analyses further revealed increased concentrations of several free amino acids and lipid-related metabolites in muscle tissue, suggesting positive modifications of meat quality characteristics (Zhu et al., 2022).

Positive responses have also been reported when fish meal was replaced with BSFL meal (Chia et al., 2021). In finishing pigs, replacing fish meal with BSFL meal increased carcass weight from 75.8 kg in the control group to 90.6, 88.3 and 94.4 kg in pigs receiving 50%, 75% and 100% fish meal replacement, respectively (p<0.001). Fasted body weight increased from 98.0 kg in the control group to 115.6–120.9 kg in BSFL-fed pigs, while dressing percentage remained similar among treatments (77.3–79.1%). These results indicate that BSFL meal can successfully replace fish meal without compromising carcass quality (Chia et al., 2021). Likewise, in growing pigs, replacing fish meal with BSFL meal at levels from 25% to 100% did not significantly affect final body weight, which ranged from 50.4 to 55.1 kg compared with 55.0 kg in the control group (p=0.474). Average daily gain ranged between 0.53 and 0.62 kg d^{-1} across all treatments, while average daily feed intake and feed conversion ratio remained comparable among groups. Return on investment varied from 132.4 to 162.4%, with no significant differences among dietary treatments (p=0.318), demonstrating that BSFL meal can replace fish meal without negatively affecting production or economic performance (Chia et al., 2019).

More recent studies have further confirmed the nutritional value of BSFL meal (Lee et al., 2024). In weaned pigs, complete replacement of fish meal defatted BSFL meal increased final body weight at week 6 from 21.80 kg in the fish meal group to 23.68 kg (p=0.017). Overall average daily gain increased from 324.1 to 369.4 g d^{-1} (p=0.001), while feed conversion ratio improved from 2.06 to 1.85 kg feed kg^{-1} gain (p=0.031). Feed cost per kilogram of gain decreased from USD 1.38 to USD 1.21 (p=0.009), indicating improved biological and economic efficiency of the defatted BSFL meal diet (Lee et al., 2024). Similarly, Noh et al. (2025) demonstrated that inclusion of BSFL larvae at levels replacing 25%, 50% or 100% of fish meal did not significantly affect body weight, average daily gain, feed intake or gain-to-feed ratio during the four-week nursery period (p>0.05). Final body weight ranged from 16.05 to 16.91 kg compared with 16.76 kg in the control group, while overall average daily gain ranged from 306 to 337 g d^{-1} compared with 332 g d^{-1} in the control treatment. Feed efficiency remained similar among groups, with gain-to-feed ratios ranging from 0.63 to 0.73. Differences in feed efficiency outcomes among studies may be related to variations in the type of BSFL product used (defatted versus partially defatted meal), inclusion level, replacement strategy (fish meal versus soybean meal), experimental duration, and animal age. Furthermore, feed efficiency was expressed as gain-to-feed ratio (G) by Noh et al. (2025), whereas Biasato et al. (2019) reported feed conversion ratio (FCR), making direct comparisons between studies more difficult. These findings indicate that BSFL meal can replace fish meal in weaning pig diets without compromising growth performance (Noh et al., 2025).

A summary of selected studies evaluating the inclusion of BSFL meal in pig diets is presented in Table 2. Collectively, the reviewed studies demonstrate that BSFL meal can replace between 25% and 100% of conventional protein ingredients depending on the production stage and dietary formulation. Across most experiments, average daily gain, feed intake, feed conversion ratio, nutrient digestibility, blood parameters and gut morphology remained comparable to conventional diets, while several studies reported additional benefits such as improved carcass traits, increased intramuscular fat content, favourable microbiota modulation and improved feed efficiency (Biasato et al., 2019; Chia et al., 2019, 2021; Lee et al., 2024; Zhu et al., 2022). Despite these promising results, several factors must still be considered before large scale adoption of insect meal in pig diets. These include production costs, regulatory frameworks and consumer acceptance. Although insect farming has significant environmental advantages, the current cost of insect meal is still relatively high compared with conventional feed ingredients. Continued technological development and scaling up of production systems may help reduce costs in the future.

Table 2
Summary of studies evaluating the inclusion of black soldier fly larvae meal in pig diets

Reference	Animal stage		Main findings
Biasato et al., 2019	weaned piglets	Partially defatted 5–10%	no negative effects on growth performance, nutrient digestibility or blood parameters
Zhu et al., 2022	growing pigs	Full-fat 4–8%	improved growth performance and increased intramuscular fat content
Chia et al., 2021	finishing pigs	Non-defatted 25–100% replacement of fish meal	higher carcass weight and acceptable meat quality
Spranghers et al., 2018	weaned piglets	Full-fat 4–8% and defatted 5.4%	antimicrobial effects in the gut due to lauric acid; no negative impact on performance

Overall, BSFL meal can partially replace conventional protein sources in pig diets without negatively affecting growth performance, although responses may vary depending on processing methods, inclusion levels and experimental conditions.

Despite the growing number of studies investigating BSFL meal in pig nutrition, several limitations and inconsistencies can be identified across the available literature. A key issue is the substantial variation in experimental design, including differences in animal age, BSFL inclusion levels, processing techniques, and trial duration. This heterogeneity complicates direct comparison between studies and likely contributes to the inconsistent results reported in the literature. Moreover, the nutritional composition of BSFL meal is not uniform, as it is strongly influenced by the rearing substrate and processing conditions. Fluctuations in protein and lipid content, as well as in the amino acid profile, can affect digestibility and animal performance. Consequently, studies using BSFL meal from different sources or processing methods may produce divergent outcomes. Another limitation is the predominance of short-term trials, particularly those conducted with weaned piglets. While these studies generally indicate no negative effects on growth performance in the short term, there is a lack of data on long-term impacts, including animal health, reproductive performance, and carcass quality. Moreover, although some studies suggest positive effects on gut microbiota and metabolic activity, the mechanisms underlying these effects remain insufficiently understood. In particular, the role of bioactive compounds such as lauric acid, warrants further investigation, especially under practical farming conditions.

Future research should focus on standardising BSFL production and processing methods, conducting long-term feeding trials and evaluating economic feasibility under practical farming conditions.

Conclusions

1. Black soldier fly larvae (*Hermetia illucens*) represent a promising alternative protein source for pig nutrition due to their high crude protein content, favourable amino acid profile and presence of biologically active compounds such as lauric acid.
2. The production of BSFL is compatible with circular economy principles because the larvae can efficiently convert organic waste streams and agricultural by-products into valuable biomass suitable for animal feed.
3. The nutritional composition of BSFL meal may vary depending on the rearing substrate, processing methods and level of defatting, but generally the meal contains 40–60% crude protein and a lipid fraction rich in medium-chain fatty acids.
4. Experimental feeding trials have demonstrated that partial inclusion of BSFL meal in pig diets can maintain normal growth performance, nutrient digestibility and animal health, confirming its potential as a substitute for conventional protein sources such as soybean meal or fish meal.
5. Despite the promising potential of BSFL meal, further research is required to standardize production methods and evaluate long-term effects under practical farming conditions. Economic feasibility and consumer acceptance also remain important factors influencing the wider adoption of insect-based feed ingredients.

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EGG PRODUCTION ANALYSIS IN AUSTRALORP BREED HENS

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Abstract
This study evaluated the effects of origin, farm, and observation period on laying intensity and average egg mass in free-range Australorp hens. A total of 1,032 daily records were analysed, with observations grouped into three production periods (Day 1–25, Day 26–45, and Day 46–129). The results demonstrated that laying intensity was significantly affected by origin ($p < 0.05$) and farm ($p < 0.05$), with the highest values observed during the peak production phase (Day 26–45). Hens of rooster David origin consistently showed higher laying intensity compared to Adisor across all periods. In contrast, average egg mass was significantly influenced by origin ($p < 0.05$) and period ($p < 0.05$), but not by farm, with Adisor hens producing slightly heavier eggs. Egg mass increased progressively with time, reaching the highest values in the late production period (Day 46–129). Regression analysis revealed a significant positive relationship between average egg mass and laying intensity ($p < 0.05$), indicating that higher egg mass was associated with increased productivity. Overall, the observation period was the dominant factor affecting both traits, while origin contributed consistently to performance differences. These findings highlight the importance of genetic background and production stage in optimizing laying performance in free-range poultry systems.
Keywords: laying intensity, egg mass, origin, production period, Australorp hens.

Introduction

Poultry production plays a crucial role in ensuring food security and providing high-quality animal protein worldwide. In many developing regions, poultry production contributes significantly to nutrition, economic development, and rural livelihoods (Shahid et al., 2025). Egg production traits, including egg number, egg weight, and egg quality, are key indicators of productivity and are influenced by both genetic and environmental factors (Shahid et al., 2025).

Genetic background is one of the most important determinants of performance in laying hens. Intensive selection in commercial layer breeding has focused on increasing egg production, egg mass, and feed efficiency, resulting in substantial improvements over time (Thiruvenkadan et al., 2010). However, such selection has also reduced genetic variability in certain traits and emphasized the need to consider multiple characteristics simultaneously, including egg quality and adaptability (Thiruvenkadan et al., 2010). In addition, genetic factors influence not only production traits but also welfare-related characteristics such as behaviour, bone strength, and resistance to environmental factors (Fernyhough et al., 2020).

The Black Australorp breed is widely recognized for its high egg production potential and adaptability. It has been reported that Australorp chickens demonstrate strong productive and reproductive performance, including high egg production rates and favourable egg quality traits (Shahid et al., 2025). Moreover, studies have shown significant relationships between production traits, such as body weight, egg weight, and reproductive performance, indicating that these traits are biologically interconnected (Shahid et al., 2025).

Environmental factors, particularly housing systems and management conditions, also play a critical role in determining productivity. Alternative production systems, including free-range housing, allow birds to express natural behaviours but may introduce additional variability in performance outcomes (Usman et al., 2020). The interaction between genotype and production system is therefore essential for understanding differences in egg production, egg quality, and overall performance (Usman et al., 2020).

Egg production is a complex trait composed of interrelated components. For example, egg mass is directly dependent on both egg number and individual egg weight (North & Bell, 1990; Bell & Weaver, 2002). Previous studies have demonstrated correlations between production traits, including strong positive relationships between body weight and egg weight, as well as between egg weight and reproductive parameters (Shahid et al., 2025). These relationships highlight the importance of applying appropriate statistical methods to distinguish biological effects from structural dependencies.

These methods enable a comprehensive assessment of the influence of genetic and environmental factors on poultry productivity.

The aim of the present study was to evaluate the effects of genetic origin and farm on egg production traits of Australorp laying hens under free-range conditions, and to analyse the relationship between laying intensity and average egg mass.

Materials and Methods

Data

The study was conducted on Black Australorp laying hens maintained under free-range housing conditions on two farms (KL and SM). In total, 47 hens were included in the study and distributed across farm and origin (rooster lines) and groups. The groups were established for practical breeding management purposes, as each group size corresponded to the number of hens that could be effectively mated by one rooster for subsequent research purposes. Therefore, the hen's group was not included as a separate factor in the further data analysis. (Table 1).

The study was conducted on hens hatched within a three-day window in January 2025, which commenced laying in late July 2025. Body weight was not assessed; however, no apparent differences in body

size were observed among the birds. All birds were reared under free-range housing conditions and monitored from the onset of lay until day 129 of production. The hens were maintained under relatively uniform feeding and management conditions, to the extent permitted by the free-range production system. While some environmental variability is unavoidable under free-range conditions, comparable husbandry practices were maintained across farms during the experimental period. Throughout the entire study period, the hens were fed a commercially manufactured complete feed mixture.

Table 1
Distribution of laying hens by farm and origin

Farm	Rooster	Hens	n
SM	David	D1	6
	David	D2	4
	Adisor	A1	6
	Adisor	A2	6
	David	D3	5
KL	David	D1	6
	Adisor	A1	7
	Adisor	A2	7

The dataset contained 1032 daily observations, including information on day of observation, farm, group, number of birds in the group, origin, total egg mass in the group, egg count in the group, average egg mass, and laying intensity. Data contained 44 missing values, resulting in 988 complete observations used in the data analysis.

The main response variable in the present analysis was laying intensity, expressed as the percentage of eggs produced relative to the number of hens in the group. In addition, average egg mass (g) was calculated from the total egg mass in each group and was analysed as a production trait.

The day of observation (day of laying) was used to create three biologically relevant observation periods: days 1–25, days 26–45, and days 46–129. These periods were defined to evaluate changes in laying performance over time and to compare production dynamics during the early, intermediate, and later phases of the laying cycle.

Data processing

Data processing and statistical analyses were performed in the R statistical environment (R Core Team, 2020), using the packages ggplot2 (Wickham, 2016), lmtest (Zeileis & Hothorn, 2002), dplyr (Wickham et al., 2023), and sandwich (Zeileis, 2004).

Initial data exploration was conducted using graphical methods. Barplot were used to visualize the distribution of laying intensity and average egg mass according to origin, farm, and observation period. Scatterplots with fitted linear regression lines were used to assess the relationship between laying intensity and average egg mass.

For descriptive presentation, mean values and standard errors were calculated for laying intensity and average egg mass within each farm, origin and period.

To evaluate the effects of genetic origin and farm in 3 observation periods on laying intensity and average egg mass two-way analysis of variance (ANOVA) was performed.

The relationship between laying intensity and average egg mass in 3 observation periods was evaluated using ANCOVA (Analysis of covariance). The model included farm as a factor, as well as the interaction between average egg mass and origin. The model follows:

$$laying\ intensity \sim average\ egg\ mass \times origin + farm$$

The assumptions of the fitted models were systematically evaluated.

For ANOVA and ANCOVA models, the normality of residuals was tested using the Shapiro–Wilk test, and the homogeneity of variances was assessed using Levene's test.

Because some models showed significant heteroscedasticity, heteroscedasticity-consistent robust standard errors (HC3) were additionally calculated for the main linear model of laying intensity using the sandwich and lmtest packages. This approach was used to confirm whether the main effects remained statistically significant after correcting for non-constant error variance.

The level of statistical significance was set at $\alpha = 0.05$. Differences and effects were considered statistically significant when $p < 0.05$.

Results and Discussion

Analysis of laying intensity and average egg mass

Research showed that overall laying intensity of the hens averaged 63.82% (SD 21.80) and egg mass averaged 55.99g (SD 6.24). Period-level means indicated a strong temporal pattern: laying intensity increased markedly from early to mid-period and then decreased slightly thereafter, whereas average egg mass increased monotonically across the three periods (Figure 1, Figure 2).

Figure 1 shows that laying intensity was lowest during days 1-25 across all groups (means ranging from 31.82% to 43.17%), increased sharply during days 26–45 (60.00% to 85.33%), and remained high during days 46–129 (62.76% to 73.21%). Average egg mass showed a consistent increase with time across all groups (Figure 2), rising from approximately 45.91–46.81 g during days 1–25 to 53.55–55.58 g during days 26–45 and to 58.06–59.91 g during days 46–129. Across periods and farms, David-origin hens tended to show higher laying intensity, while Adisor-origin hens tended to show higher average egg mass.

Within the early observation period (Day 1–25), laying intensity differed significantly between hens at different farms ($p<0.05$), with higher values observed in the SM farm, while no significant effect of origin was detected. In contrast, average egg mass did not differ significantly between either origin and farm in this period.

In the second observation period (Day 26–45), laying intensity was significantly affected by both origin and farm ($p<0.05$), indicating that both genetic and environmental factors contributed to differences among groups. For average egg mass, a significant effect of origin was observed ($p<0.05$), whereas farm had no significant influence.

In the final observation period (Day 46–129), laying intensity remained significantly influenced by origin ($p<0.05$), while no significant differences between farms were detected. A similar pattern was observed for average egg mass, where origin had a significant effect ($p<0.05$), but farm did not.

Overall, the results demonstrate that the significance of factors varied across observation periods. Farm-related differences were only evident in earlier stages, particularly for laying intensity, whereas origin consistently influenced both traits in later stages.

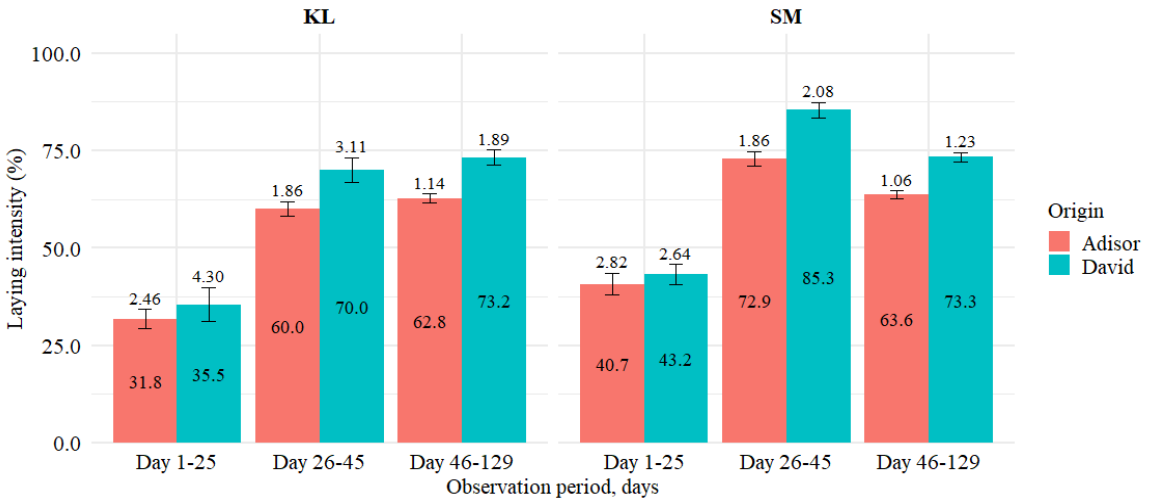
The observed increase in laying intensity from the initial period to later stages reflects the typical pattern of onset of lay, where egg production increases rapidly as hens approach peak production (Bain et al., 2016).

The increase in average egg mass with time is consistent with previous findings showing that egg weight increases with hen age due to physiological development and increased nutrient deposition (Johnston & Gous, 2007; Silversides & Scott, 2001).

The observed inverse tendency between laying intensity and egg mass suggests a trade-off between egg number and egg size, which has been widely reported in laying hens (Anang et al., 2000; Wolc et al., 2012).

Figure 1

The average egg-laying intensity of the hens (±SE) by period, farm, and origin



As we see (Figure 1), laying intensity peaked during days 26–45 for SM–David (85.33 ± 2.08; n = 60) and was lowest during days 1–25 for KL–Adisor (31.82 ± 2.62; n = 44), consistent with the strong period effect and higher David-origin values across periods. The dominant temporal structure is evident as a sharp increase from days 1–25 to days 26–45 followed by sustained high levels during days 46–129. This pattern reflects the typical egg production curve of laying hens, where production increases rapidly after the onset of lay and reaches peak levels before entering a phase of relatively stable production (Bain et al., 2016; Johnston & Gous, 2007).

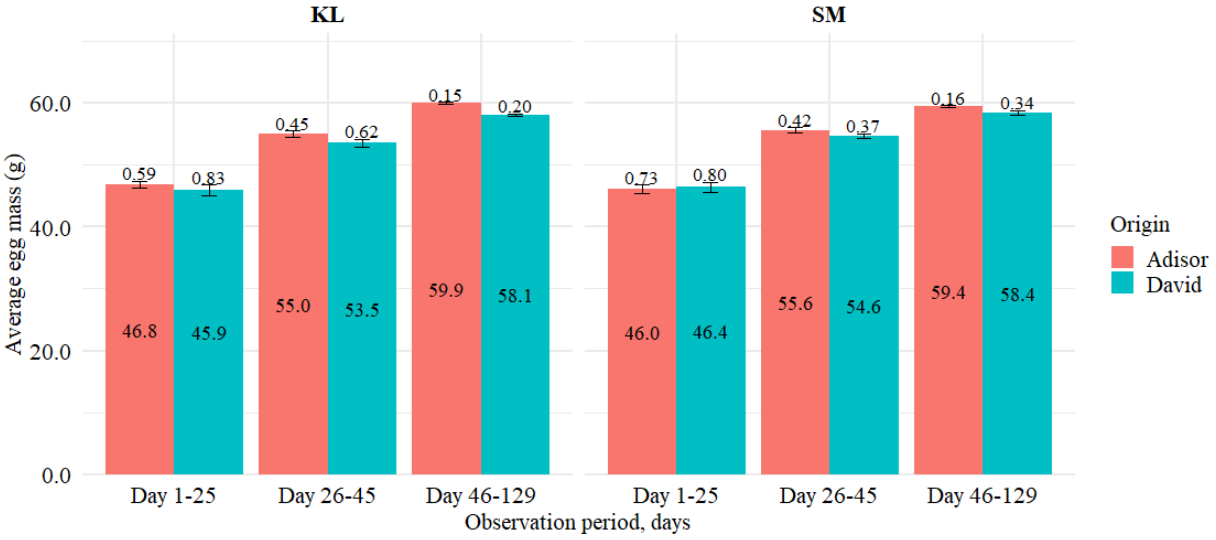
Within each farm and period, David generally exceeds Adisor ($p<0.05$), aligning with the significant origin main effect and the positive David–Adisor contrast. Such consistent differences between genetic lines are well documented, as egg production traits are strongly influenced by genotype, with substantial variation in laying intensity observed among different lines (Anang et al., 2000; Wolc et al., 2012). The higher performance of the David-origin birds, therefore, likely reflects genetic differences in production potential and resource allocation toward egg number.

Average egg mass for KL–Adisor increased from 46.81 ± 0.63 g (n = 44) from days 1–25 to 59.91 ± 0.15 g (n = 168) during days 46–129, illustrating a strong monotonic increase across periods (Figure 2). Across periods, Adisor tends to have higher egg mass than David (e.g., Day 46–129 in KL: 59.91 vs 58.06 g), consistent with the significant negative David − Adisor difference ($p<0.05$). The progressive increase in egg mass across periods is visually consistent across farms and origins. The modest but consistent separation between origins is also evident, with Adisor generally producing slightly heavier eggs ($p<0.05$).

The observed increase in egg mass with advancing production period agrees with previous studies demonstrating that egg weight increases as hens age due to continued development of the reproductive tract and increased deposition of egg components (Rizzi & Chiericato, 2005; Ledvinka et al., 2012). This age-related increase is primarily associated with enhanced albumen secretion and yolk deposition, resulting in progressively larger eggs over time (Molnár et al., 2016).

Figure 2

The average egg mass of the hens(±SE) by period, farm, and origin



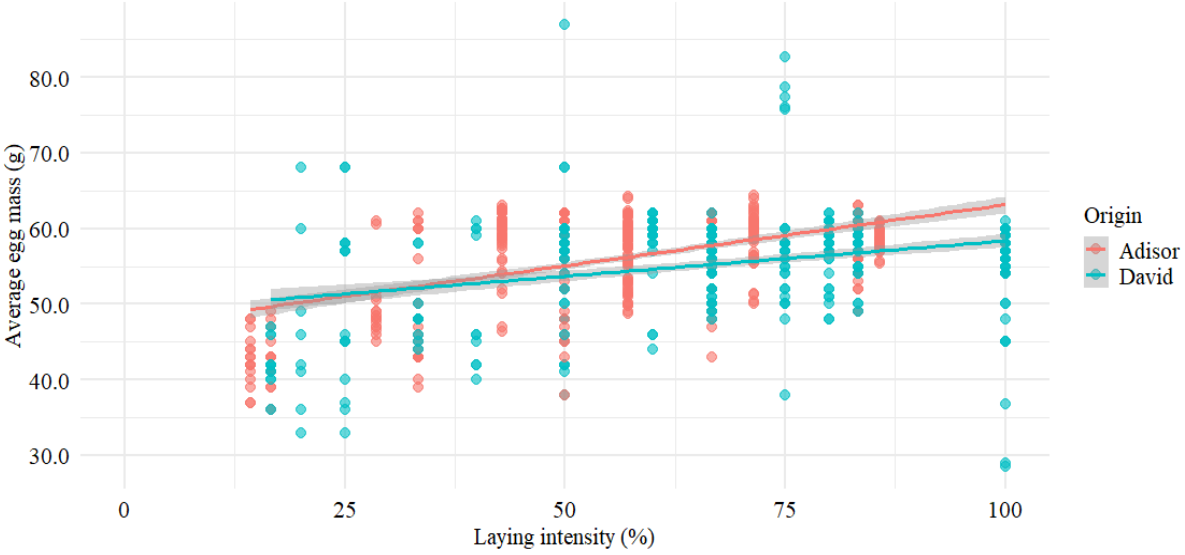
The consistent differences between origins further support the role of genetic background in determining egg size. Genetic variation in egg weight among lines has been widely reported, with egg mass being a moderately to highly heritable trait influenced by selection history and breeding objectives (Zita et al., 2009; Wolc et al., 2012). The slightly higher egg mass observed in Adisor-origin birds therefore likely reflects genetic differences in allocation of resources toward egg size rather than egg number.

Relationship between laying intensity and average egg mass

The plotted trend (Figure 3) corresponds to a positive association between egg mass and laying intensity ($p<0.05$).

Figure 3

Relationship between hens laying intensity and average egg mass by origin



Although egg number and egg weight are often considered competing traits, previous studies have shown that their relationship may vary depending on genetic background and analytical approach. When environmental and temporal factors are accounted for, positive associations between egg mass and production traits can be observed, reflecting overall productivity of the hen (Lwelamira et al., 2009).

The positive slope reflects the statistically significant relationship between laying intensity and average egg mass after adjustment for farm and period. Similar relationships have been reported in genetic and phenotypic studies of laying hens, where production traits are influenced by both direct and correlated responses to selection, resulting in complex interactions between egg number, egg weight, and overall productivity (Mrode, 2005; Wolc et al., 2012).

Figure 4

Relationship between laying intensity and average egg mass stratified by observation period and origin

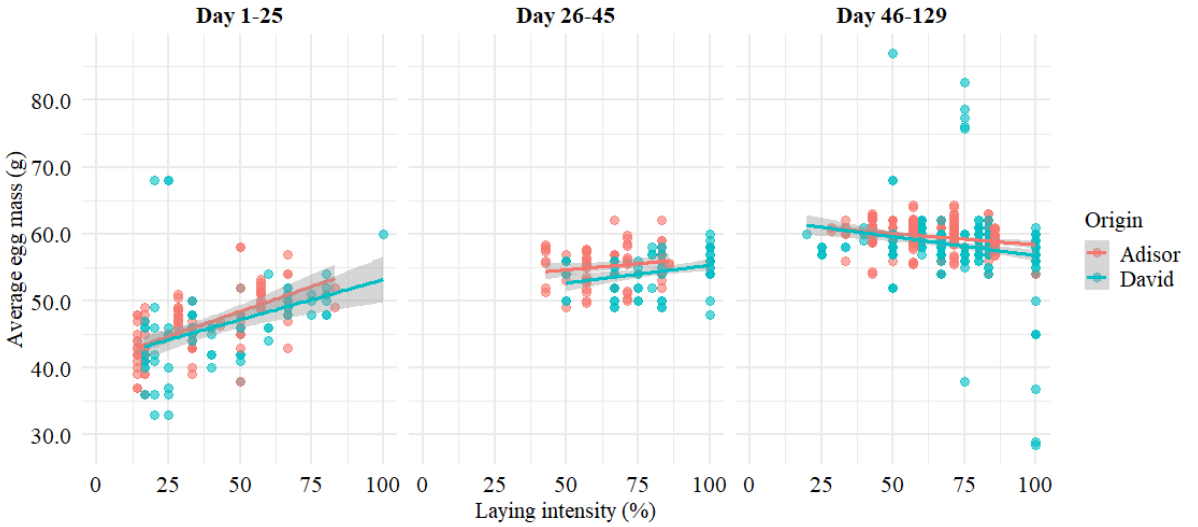


Figure 4 shows that the average egg mass–laying intensity relationship separately for days 1–25, days 26–45, and days 46–129, with regression lines and 95% confidence interval. This figure visualizes how the association pattern is embedded within the broader period structure highlighted in Figure 1 and Figure 2. The clear stratification by period reflects distinct physiological production states and supports the inferential finding that period is the dominant factor influencing both traits.

Australorp hens laying intensity was significantly influenced by origin, farm, and production period, with the observation period being the strongest determining factor ($p < 0.05$).

When the analysis was performed separately across observation periods, distinct patterns in the influence of origin and farm on laying intensity and average egg mass were observed. In the early period (Day 1–25), average egg mass was not significantly affected by either origin and farm, whereas laying intensity was significantly influenced by farm ($p<0.05$), indicating a stronger role of environmental conditions during the onset of lay. This is consistent with previous findings that early production is characterized by high variability and sensitivity to environmental and management conditions, as hens are still undergoing physiological adaptation to egg production (Bain et al., 2016; Roberts, 2004).

In the subsequent period (Day 26–45), both origin and farm significantly affected laying intensity ($p<0.05$), while average egg mass was influenced by origin only. This stage corresponds to the phase approaching peak production, where both genetic potential and environmental conditions contribute to performance variability (Anang et al., 2000; Wolc et al., 2012).

In the later period (Days 46–129), both traits were significantly affected by origin ($p<0.05$), whereas farm had no significant effect. This suggests that as production stabilizes, the influence of environmental variation decreases, and genetic differences become more consistently expressed. Similar patterns have been reported in laying hens, where the relative contribution of genetic factors increases as birds reach a stable production phase and environmental effects become less limiting (Bain et al., 2016; Zita et al., 2009).

These results can be explained by the progression of physiological adaptation from the onset of lay to a stabilized production state. During the early phase, incomplete physiological maturity and adaptation of the reproductive system result in greater variability and reduced expression of genetic differences (Roberts, 2004). As hens progress into a stable laying phase, biological systems become more regulated, allowing genetic potential to be more fully expressed and reducing the relative impact of environmental variation. Overall, the findings indicate that the relative importance of environmental and genetic factors shifts over time, with environmental effects being more pronounced during the initial phase and genetic effects becoming dominant as laying performance stabilizes. This temporal shift highlights the importance of considering the production stage when interpreting factors influencing laying performance.

Conclusions

1. The effects of farm and origin varied across production periods: farm significantly influenced laying intensity during the early and mid-production periods, whereas origin had a more pronounced effect during the mid- and late-production periods, particularly for laying intensity and egg.
2. Hens of David origin exhibited higher laying intensity, whereas Adisor hens produced slightly heavier eggs, indicating origin-related differences in productive performance under free-range conditions.
3. Both laying intensity and average egg mass increased throughout the observation period, with the highest laying intensity observed during the mid-production period (Day 26–45) and the greatest egg

mass during the late-production period (Day 46–129).
4. The effect of origin became more pronounced over time, significantly influencing both laying intensity and average egg mass in the mid- and late-production periods ($p<0.05$), indicating stronger expression of genetic differences as production stabilized.
5. A significant positive relationship between laying intensity and average egg mass was identified, indicating that higher productivity was associated with increased egg mass.

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ASSESSMENT OF VEGETATION INDICES DERIVED FROM UNMANNED AERIAL VEHICLE IMAGERY FOR EARLY-GENERATION SELECTION IN SPRING WHEAT

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Abstract
Early-generation selection in spring wheat is constrained by limited seed availability, making rapid, high-throughput, and non-destructive phenotyping essential. The objective of this study was to determine the most informative vegetation indices (VIs) for predicting key agronomic traits, including plant number, spike number, productive tillering, and grain yield, to support early-generation selection in spring wheat breeding (F_4–F_5 generations) using UAV- based remote sensing. Seventeen breeding lines from three crossing combinations and six parental varieties were sown in three randomized replications at the AREI Stende Research Centre in 2025 using a cassette-type plot seeder. Two sowing variants were tested: 500 seeds m^{-2} and a fixed row-based seeding of 40 seeds per row. Plots consisted of three 1 m rows with 33 cm spacing, and the standard variety 'Arabella' was included as a reference control. Seven UAV flights were conducted from the seedling to late-milk growth stages using a DJI Matrice 300 RTK with a Sentera AGX710 multispectral camera. Orthomosaics were radiometrically calibrated, and bare soil pixels were excluded using index thresholds and supervised classification. Sixteen vegetation indices (7 RGB, 9 multispectral) and vegetation fraction were extracted per plot along with ground-truth measurements. Multicollinearity analysis identified a subset of non-redundant indices for further evaluation. Vegetation index–trait relationships were growth-stage dependent, with the strongest correlations from stem elongation to milk development. Spike number demonstrated the most consistent associations with vegetation indices. NDRE showed the most stable relationships across UAV flights, indicating the potential of multispectral UAV indices for indirect assessment of yield-related traits in early-generation wheat breeding.
Keywords: *Triticum aestivum* L., spring wheat breeding, early-generation selection, grain yield prediction, multispectral imaging.

Introduction

Wheat (*Triticum aestivum* L.) is one of the most important and widely cultivated crops worldwide. To meet the continuously increasing global demand for food, it is essential to improve cereal yield per unit area. Therefore, a key objective of wheat breeding programs is to develop high-yielding genotypes that outperform existing cultivars under specific environmental conditions while also exhibiting improved disease resistance, resilience to climate change, and high processing and nutritional quality (Stella et al., 2023).

Phenotyping of agronomic traits remains one of the major bottlenecks in modern crop breeding programs due to the large number of genotypes that must be evaluated under field conditions (Song et al., 2021). This challenge is particularly pronounced during early-generation selection, when seed availability is limited and field trials are often conducted in small plots or single rows with thousands of breeding lines under evaluation (Crain et al., 2022; Krause et al., 2020). Traditionally, breeders rely heavily on visual scoring to assess breeding lines, which is labor-intensive, time-consuming, and prone to subjective bias (Ninomiya, 2022). Improving the efficiency of early selection stages is therefore critical, as these stages aim to reduce the number of genotypes advanced to more resource-intensive yield trials and thereby increase genetic gain per unit cost (Fischer & Rebetzke, 2018; Hu et al., 2020).

Recent advances in remote sensing technologies have enabled high-throughput field phenotyping of crop traits, allowing rapid and non-destructive evaluation of large numbers of breeding lines (Feng et al., 2021; Gill et al., 2022). In particular, unmanned aerial vehicle (UAV) platforms equipped with imaging sensors provide high spatial and temporal resolution data that support efficient phenotyping in breeding trials.

RGB cameras are among the most widely used sensors in UAV-based crop phenotyping because of their high spatial resolution and relatively low cost. However, they capture reflectance only in three broad spectral bands (red, green, and blue), which limits the spectral information available for crop analysis. In contrast, multispectral sensors measure reflectance in several discrete wavelength bands, enabling more detailed assessment of crop physiological status. UAV-based multispectral remote sensing has shown considerable potential for crop monitoring, phenotyping, and yield estimation due to its high throughput, non-destructive nature, and ability to collect multi-temporal data over experimental fields (Liu et al., 2025a). Vegetation indices (VIs) derived from RGB and multispectral imagery are widely used as proxies for canopy greenness, biomass accumulation, and crop physiological status, including chlorophyll-related traits (Liu et al., 2025b; Wang et al., 2024; Zhang et al., 2024). Despite the increasing application of UAV-based remote sensing in crop monitoring and yield prediction studies, its use for early-generation selection in breeding programs remains relatively limited and insufficiently documented in the literature (Liu et al., 2025a). In early breeding generations, direct evaluation of yield-related traits is often constrained by small plot size and limited seed availability, which complicates the identification of promising genotypes. UAV-derived vegetation indices therefore represent a potentially valuable tool for

indirect assessment of agronomic traits during early selection stages. The objective of this study was to determine the most informative VIs for predicting key agronomic traits, including plant number, spike number, productive tillering, and grain yield, to support early-generation selection in spring wheat breeding (F_4–F_5 generations) using UAV- based remote sensing.

Materials and Methods

Plant materials

The plant material used in this study consisted of seventeen breeding lines derived from three crossing combinations and six parental spring wheat varieties. Detailed information on the evaluated genotypes is provided in Table 1.

Table 1

Spring wheat parental varieties and breeding lines used in the study

Cross	Parents	Breeding lines
1	Jasna × Mooni	F-019-0170/8, /9, /12, /13, /18, /29
2	Sorbas × Uffo	F-019-0174/37, /40, /44, /59, /69, /92
3	Bombona × K-15033	F-019-0203/101, /103, /117, /119, /122

For brevity, only the suffixes of breeding line numbers are shown in the table. Each set of lines within a cross share the same prefix.

Experimental design

The experiment was established as a randomized block design with three replications. Each genotype was represented by plots consisting of three 1 m rows, which served as the experimental unit for both field measurements and UAV-based analysis. Two sowing approaches were evaluated: a target density of 500 seeds m^{-2} and a fixed row-based seeding of 40 seeds per row. UAV-derived vegetation indices were extracted at the plot level and subsequently linked with ground-based measurements of agronomic traits.

Field trials were conducted at the AREI Stende Research Centre experimental site in northwestern Latvia (57°18′ N, 22°56′ E; WGS84) in 2025. The trials were sown on 17 April using a cassette-type experimental plot seeder. Each plot consisted of three 1 m rows with 33 cm row spacing, and the standard variety 'Arabella' was included as a reference control. Standard crop protection practices were applied. Herbicides were used according to local agronomic recommendations. At maturity, each row was harvested separately by cutting stems with a sickle, and the harvested material was subsequently threshed using a small-plot combine.

Measurement of agronomic traits

The evaluated agronomic traits included plant number (PN), spike number (SN), and grain yield (GY). Plant number per row was recorded at early growth stages on 12 May, while spike number per row was determined at maturity on 4 August. Grain samples from each row were cleaned using a Pfeuffer Sample Cleaner equipped with a 2.0 mm screen and subsequently weighed to determine grain yield per row, which was expressed as grams per row (g row^{-1}) based on a harvested row length of 1 m.

UAV data acquisition and processing

Images were acquired using a DJI Matrice 300 RTK unmanned aerial vehicle (UAV) equipped with a Sentera AGX710 multispectral camera capturing RGB, red-edge, and near-infrared (NIR) bands. All flights were conducted with a nadir (90°) camera orientation.

UAV data were acquired seven times during the growing season (Table 2). UAV flights were scheduled to capture the main wheat developmental stages throughout the growing season. Because slight differences in phenological development may occur among breeding lines, the Zadoks growth stage assigned to each flight represents the dominant crop stage observed across the experimental plots at the time of image acquisition. In total, 251 images were collected at an average flight altitude of approximately 20 m above ground level (AGL), resulting in a ground sampling distance (GSD) of 5.7 mm per pixel. Flights were conducted between 11:00 a.m. and 1:00 p.m. under near-clear sky conditions. The flight speed was set to 0.4 m s^{-1}, and both forward and side image overlap ratios were set to 75%.

Table 2

UAV flight dates and corresponding wheat growth stages during the 2025 growing season

Flight	Date	GS	Growing stage description
F1	13 May	12	Seedling stage
F2	26 May	25	Tillering
F3	10 June	32	Stem Elongation
F4	23 June	43	Booting
F5	9 July	65	Anthesis
F6	22 July	70	Early milk
F7	28 July	77	Late milk

Note: GS indicates the approximate Zadoks growth stage at the time of UAV flight.

Multispectral images were processed using Pix4DMapper Pro (Pix4D SA, Switzerland) to generate radiometrically calibrated reflectance orthomosaics. The orthomosaics were further processed in QGIS version 3.16 using multispectral bands (Red, Green, Blue, NIR, and Red-edge).

Vegetation was separated from soil using empirically defined NDVI thresholds. Pixels with NDVI ≤ 0.15 (sparse vegetation) or ≤ 0.25 (dense canopy) were classified as soil and masked as NoData to minimize soil background influence.

Experimental plots were delineated according to the field layout, and each plot was treated as a single sampling unit for vegetation index extraction using zonal statistics.

Based on a review of relevant literature, sixteen VIs widely used for assessing crop growth, yield, and biochemical parameters were calculated, including seven RGB-based and nine multispectral indices. The vegetation indices and their calculation formulas used in this study are presented in Table 3.

Table 3
List of spectral vegetation indices used in this study and formulas for their calculation

Index	Full name	Equation
RGB		
VARI	Visible Atmospherically Resistant Index	(g−r)/(g+r−b)
ExG	Excess Green Index	2*g−r−b
ExR	Excess red vegetation index	1.4*r − g
ExGR	Excess green minus excess red index	ExG-ExR
RGBVI	RGB Vegetation Index	$(g^2-(b*r))/(g^2+(b*r))$
GLI	Green Leaf Index	(2*g−r−b)/(2*g+r+b)
NGRDI	Normalized green-red difference index	(g−r)/(g+r)
Multispectral		
NDVI	Normalized Difference Vegetation Index	(NIR−R)/(NIR+R)
NDRE	Normalized Difference Red Edge Index	(NIR−RE)/(NIR+RE)
GNDVI	Green NDVI	(NIR−G)/(NIR+G)
RVI	Ratio vegetation index	NIR/R
EVI2	Two-band Enhanced Vegetation Index	2.5*(NIR-R) / (NIR + 2.4*R + 1)
MSR	Modified simple ratio red-edge	((NIR/Red) − 1) / (SQRT(NIR/Red) + 1)
MSAVI	Modified Soil-Adjusted Vegetation Index	(2*NIR+1-SQRT((2*NIR+1) ^2-8*(NIR-RED)))/2
SIPI	Structure insensitive pigment index	(NIR-B)/(NIR-R)
RDVI	Renormalized Difference Vegetation Index	(NIR-R)/SQRT(NIR+R)

Notes: R, G, and B denote reflectance values in the red, green, and blue bands, respectively; NIR denotes near-infrared reflectance and RE denotes red-edge reflectance. r, g, and b represent normalized RGB components calculated as r = R/(R+G+B), g = G/(R+G+B), and b = B/(R+G+B).

Statistical analysis

All statistical analyses were performed in Python using the Google Colab environment. Data processing and statistical computations were conducted using the libraries pandas, NumPy, and SciPy. Multicollinearity among vegetation indices was assessed separately for each flight using Pearson correlation matrices and hierarchical clustering; from each cluster, the index with the lowest mean absolute correlation was retained to reduce redundancy. Relationships between agronomic traits and vegetation indices were evaluated using Pearson's correlation analysis. Regression analysis was performed using linear mixed-effects models implemented in the statsmodels package. Data visualization was carried out using matplotlib and seaborn, including correlation heatmaps and dendrograms.

Results and Discussion

Selection of non-redundant vegetation indices

Multicollinearity analysis identified a subset of VIs with non-redundant spectral information across UAV flights and sowing variants (Table 4). Five RGB-based indices (VARI, ExGR, ExR, RGBVI, and GLI) and four multispectral indices (NDRE, GNDVI, SIPI, and RDVI) were selected for further analysis. Multicollinearity analysis is commonly applied in UAV-based crop monitoring studies to identify non-redundant predictors and improve the stability of statistical models (Zhang et al., 2025).

The composition of the selected VI set varied across flight dates and between sowing variants, indicating changes in complementary spectral information during crop development. Overall, multispectral indices were retained more consistently than RGB-based indices.

Table 4
Vegetation indices retained after multicollinearity analysis for each UAV flight and sowing variant

Vegetation indices	F1	F2	F3	F4	F5	F6	F7
VARI					●		
ExGR	○						
ExR	○●						
RGBVI	○●	○	○			○	
GLI	●	●	●			●	
NDRE	○●	○●	○●	○●	○●	○●	○●
GNDVI	○		○●	○●	○●		○●
SIPI	○●		○●				
RDVI	○●	○			○●	○●	

Notes: ○ – sowing variant 1 (500 seeds m^{-2}); ● – sowing variant 2 (40 seeds per row); F1–F7 – consecutive UAV flights during the growing season; Symbols indicate vegetation indices retained after multicollinearity screening; Abbreviations of vegetation indices are given in Table 3.

NDRE was selected across all UAV flights and both sowing variants, suggesting that the red-edge spectral region provides stable information throughout the growing season. Because red-edge reflectance is closely associated with chlorophyll concentration and canopy nitrogen status, NDRE may represent a robust indicator of crop physiological status in wheat breeding trials (Cao et al., 2021; Šušlikova et al., 2023). The stability of NDRE across both sowing variants further suggests that this index is relatively insensitive to differences in plant density and canopy structure.

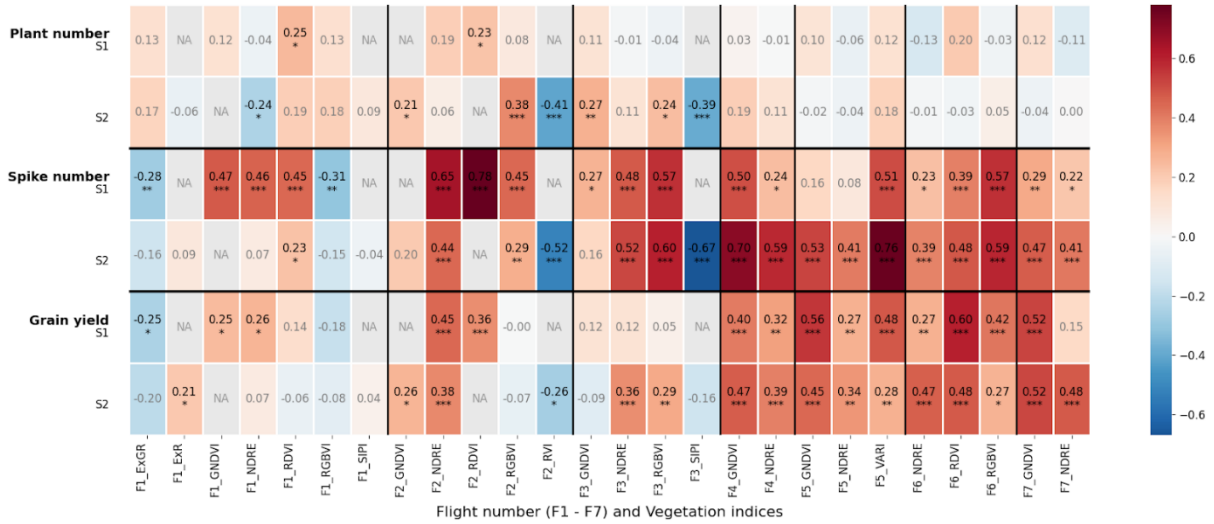
GNDVI and RDVI were also frequently retained, indicating their relevance for capturing variations in canopy vigor and chlorophyll-related traits during crop development. In contrast, RGB-based indices showed greater variability across flight dates and sowing variants. RGB indices were most often retained during the early flights (F1–F2), when canopy cover was sparse and soil background influence was stronger, whereas multispectral indices became more dominant at later growth stages. These results suggest that combining RGB and multispectral vegetation indices may provide complementary information for UAV-based phenotyping across crop growth stages.

Correlations of agronomic traits with selected VIs across UAV flights and sowing variants

Clear relationships between vegetation indices and agronomic traits were observed across UAV flights, with the strongest and most consistent correlations detected for multispectral indices. These patterns are illustrated in the Pearson correlation heatmap shown in Figure 1. Overall, the most stable VI–trait relationships were observed for indices incorporating NIR and/or red-edge bands. This observation is consistent with previous studies showing that multispectral indices generally provide more robust associations with crop traits than RGB-based indices, although RGB indices may perform well at specific growth stages (Heinemann et al., 2025; Cao et al., 2021). In the present study, RGB indices also showed relatively strong correlations with agronomic traits at the stem elongation, anthesis, and early milk stages.

Figure 1

Pearson correlation heatmap between agronomic traits and selected vegetation indices across UAV flights (F1–F7) and sowing variants (S1–S2)



F1 - two-leaf stage (GS12); F2 - tillering (GS25); F3 - stem elongation (GS32); F4 - booting (GS43); F5 - anthesis (GS65); F6 - early milk (GS70); F7 - late milk (GS77).

Across the season, VI–trait associations were strongest from stem elongation to late milk stages (F3–F7), whereas relationships were generally weaker during the early seedling and tillering stages (F1–F2). This pattern agrees with previous UAV studies demonstrating that VI–trait relationships are strongly growth-stage dependent (Camenzind & Yu, 2024), indicating that the reliability of VI-based trait assessment increases as canopy development progresses.

Among the evaluated traits, spike number showed the strongest and most consistent correlations with vegetation indices. Significant correlations were observed from F3 to F7, corresponding to stem elongation, booting, anthesis, and milk development stages. For grain yield, significant correlations were mainly detected from F4 to F7 in both sowing variants, corresponding to the period from booting to late milk. These results align with previous studies reporting that wheat yield prediction accuracy typically peaks around flowering and early milk stages, when vegetative development (biomass accumulation and plant height) is largely completed (Camenzind & Yu, 2024; Chu et al., 2025; Liu et al., 2023; Prey et al., 2022).

In contrast, plant number showed weak and inconsistent relationships with vegetation indices across the season (mostly $r < 0.3$), with only occasional moderate correlations at individual flights. This likely reflects the limited sensitivity of spectral indices to plant density after canopy closure, when spectral variation is primarily driven by canopy cover and

greenness rather than by the number of individual plants (Wilke et al., 2021). NDRE showed the most consistent correlations with spike number, particularly in sowing variant S2, where positive relationships were observed across multiple flights (F2–F7) with r values ranging from 0.39 to 0.59.

However, the highest single correlations in S2 were observed for VARI at F5 (r = 0.76) and GNDVI at F4 (r = 0.70). In sowing variant S1, spike number also showed strong positive associations, with the highest correlation observed for RDVI at F2 (r = 0.78). These results indicate that, although NDRE provided the most stable correlations across flights, individual RGB and multispectral indices occasionally showed stronger correlations at specific growth stages, consistent with previous studies showing that index performance depends on phenological stage (Camenzind &Yu, 2024; Heinemann et al., 2025).

VI–trait correlations also differed between the two sowing variants, indicating that sowing pattern influenced the spectral response of the crop canopy. In general, S2 showed stronger and more consistent correlations, especially for spike number, suggesting that canopy structure and plant density affected how effectively vegetation indices captured agronomic variation.

Taken together, these results indicate that multispectral VIs, particularly NDRE and GNDVI, were the most informative for assessing spike number and grain yield, especially from stem elongation to late milk stages.

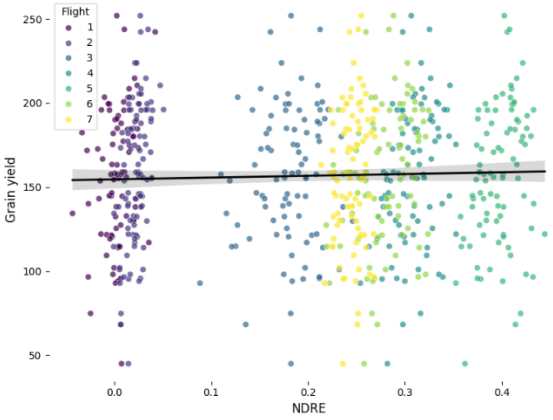
Relationship between NDRE and Grain Yield

Figures 2 and 3 show positive but weak mixed-effects relationships between NDRE and grain yield across seven UAV flights during the 2025 growing season for sowing variants 1 and 2. For both sowing variants, the fitted trend lines indicated a positive association between NDRE and grain yield, with higher NDRE values generally corresponding to higher final grain yield. This tendency was observed in both S1 and S2, although the wide dispersion of data points indicates substantial variability among plots. In both models, the NDRE effect was statistically significant ($p < 0.001$), indicating that higher NDRE values were associated with higher final grain yield.

These results support the correlation analysis presented in Figure 1, where NDRE showed stable associations with spike number and grain yield across multiple growth stages. The relationship is biologically plausible because NDRE reflects canopy chlorophyll status and green canopy vigor, both of which are closely related to crop productivity. Red-edge indices are particularly valuable in wheat because the red-edge spectral region is sensitive to chlorophyll concentration and generally less prone to saturation than red-based indices under dense canopy conditions (Cao et al., 2021; Liu et al., 2022). Similar findings have been reported in UAV-based wheat studies, where red-edge and multi-temporal vegetation indices demonstrated good potential for grain-yield estimation (Camenzind & Yu, 2024; Liu et al., 2023).

Figure 2

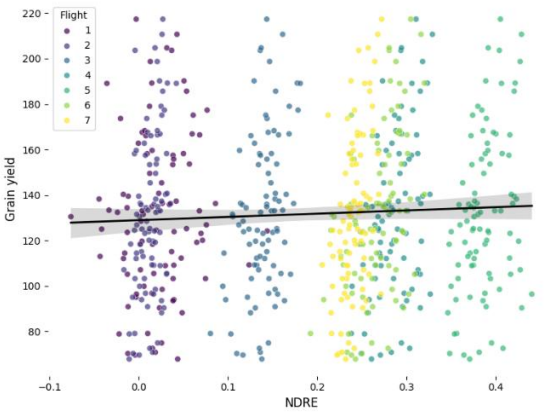
Mixed-effects regression between NDRE and grain yield (g row^{-1}) across all UAV flights for sowing variant 1



Despite the significant relationship, the relatively large scatter of observations around the fitted trend lines indicates that NDRE explains only part of the yield variability. This is expected because grain yield is a complex trait influenced by multiple interacting factors, including crop phenology, genotype differences, and environmental conditions (Liu et al., 2022; Mankin et al., 2024). The visible grouping of observations by UAV flight also suggests that temporal variation across growth stages contributed to the observed pattern. The visible grouping of observations by UAV flight also suggests that temporal variation across growth stages contributed to the observed pattern.

Figure 3

Mixed-effects regression between NDRE and grain yield (g row^{-1}) across all UAV flights for sowing variant 2



Previous studies similarly report that multi-temporal UAV observations generally improve wheat yield estimation compared with single- date imagery

(Camenzind & Yu, 2024; Liu et al., 2023). Overall, the consistent positive relationship observed in both sowing variants indicates that NDRE can serve as a useful indirect indicator of yield-related performance in early-generation wheat breeding trials.

Conclusions

1. Multicollinearity analysis identified a limited subset of non-redundant vegetation indices, among which NDRE, GNDVI, and RDVI were most consistently retained across UAV flights and sowing variants.
2. Vegetation index–trait relationships were strongly growth-stage dependent, with the strongest correlations observed from stem elongation to late milk stages, while relationships were weaker during early canopy development.
3. Among the evaluated agronomic traits, spike number showed the strongest and most consistent correlations with vegetation indices, whereas plant number exhibited weak relationships across the growing season.
4. NDRE showed the most stable associations with spike number and grain yield across UAV flights, and mixed-effects regression confirmed a significant positive relationship between NDRE and grain yield in both sowing variants, highlighting the potential of red-edge–based indices for UAV-assisted phenotyping in early-generation wheat breeding.

Acknowledgements

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PATHOGENICITY OF TWO *ALTERNARIA* SPECIES ON POTATO AND THEIR COMPATIBILITY WITH A *BACILLUS SUBTILIS*-BASED PRODUCT

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Abstract
Potato early blight is caused by several species of the genus *Alternaria*, but information about the spectrum of species involved remains limited. This study investigated the pathogenicity on potato leaves of two *Alternaria* species that cause early blight, as well as their antagonistic interactions with a *Bacillus subtilis*-based biological product under *in vitro* conditions. Fungal isolates – *A. solani* and *A. protenta* were obtained from the pathogen collection (collected from tomatoes) of the Institute of Soil and Plant Sciences and both are identified as *Alternaria* species that cause potato early blight. Antagonism assays showed that the inhibitory effect of *B. subtilis* depended on the application method: mycelial growth was strongly reduced when the medium was rinsed with the preparation, whereas only minor effects were observed when the bacterium was applied separately from the fungal inoculum. Pathogenicity assays demonstrated significant species-related differences in lesion development ($p < 0.05$), with *A. protenta* producing larger lesions than *A. solani*. Although the concentration and timing of *B. subtilis* application did not significantly affect lesion size, a tenfold higher concentration reduced lesion area by approximately 1.5 times. Comparing the species, *A. solani* showed a higher mycelial growth rate on PDA compared with *A. protenta*, with faster growth occurring during the first seven days post-inoculation. Overall, the results highlight species-specific differences in pathogenicity and a partial inhibitory effect of *B. subtilis*.
Keywords: antagonism, *A. solani*, *A. protenta*, biological control, early blight.

Introduction

In recent years, developed countries have tended to reduce their potato growing areas while substantially increasing processing activities. However, farmers continue to face daily challenges posed by potato diseases. Growing high-yield, high-quality potatoes without the use of plant protection products (PPP) against diseases and pests is practically impossible in both biological and integrated growing systems. Therefore, biologically based PPP containing various beneficial fungi and / or bacteria for plants, may offer a promising alternative to chemical PPP, potentially leading to improved yields.

The two most common and widespread foliar diseases affecting potatoes are early blight (caused by *Alternaria* spp.) and late blight (caused by *Phytophthora infestans*). Both of these diseases are observed together in potato fields every year. However, early blight has received limited study under the specific environmental conditions of Latvia.

Potato early blight is caused by fungi of the genus *Alternaria*. The pathogen belongs to the *Ascomycota* phylum, *Pleosporales* order. The genera of *Alternaria* are currently divided into 29 sections – *Porri*, *Alternaria*, *Ulocladioides*, and *Infectoriae* etc., encompassing numerous species with varying ecological roles, ranging from highly aggressive plant pathogens to weakly pathogenic or non-pathogenic. Taxonomic revisions are still in progress (Ahmadpour et al., 2025; Schmey et al., 2024; Vinogradova et al., 2026). *Alternaria* contains melanin in the cell walls of both hyphae and conidia. This melanin contributes to increased cell wall rigidity, enhancing resistance to antifungal agents. Moreover, this adaptive capacity enhances the pathogen's ability to survive overwintering conditions (Fernandes et al., 2021; Schmey et al., 2024).

Alternaria species can infect a wide range of host plants across multiple families, including but not limited to *Solanaceae* (Bessadat et al., 2014; Dučkena et al., 2024, 2019; Gou et al., 2023; Ivanović et al., 2022). Until recently, only two *Alternaria* species – *A. solani* and *A. alternata* were reported in potato crops. *A. protenta* (Woudenberg et al., 2014) and *A. grandis* (Rodrigues et al., 2010) were also identified as potentially harmful to potatoes (Landschoot et al., 2017). *A. protenta* was initially identified as a pathogen affecting *Helianthus annuus*, but more recently it has been recognized as an *Alternaria* species capable of causing early blight in potatoes (Cho & Yu, 2000; Ivanović et al., 2022).

The host range of *A. protenta* has significantly expanded and now includes plant species from the *Asteraceae*, *Gramineae*, and *Solanaceae* families. Due to their close morphological and molecular similarity, *A. protenta* and *A. solani* can be accurately differentiated only by locus sequencing (Woudenberg et al., 2014). Recent collections of isolates from the Mediterranean region have revealed that the species *A. protenta* can also be isolated from potato leaves (Bessadat et al., 2019). A study conducted in Russia also identified *A. protenta* as one of the most prevalent *Alternaria* species in potato fields. The isolates were collected from both the Far Eastern and European regions of the country (Kokaeva et al., 2022). In a long-term study carried out in Serbia, *Alternaria solani*, *A. protenta*, *A. grandis*, and *A. linariae* were isolated from potato foliage (Ivanović et al., 2022).

Potato plants are resistant to early blight at juvenile stages, but susceptibility increases with plant age (Yuldashova et al., 2023). Despite the lack of observed sexual reproduction, high species diversity indicates pathogen recombination (Schmey et al., 2024; Tsedaley, 2014).

Pathogens survive and overwinter in plant debris, soil, and potato tubers as mycelium or conidia, and their spores are disseminated by wind, water, and occasionally insects (Chaudhary et al., 2021; Tsedaley, 2014; Yuldashova et al., 2023). These pathogens reproduce asexually via conidia. In spring, conidia spread from infected plant debris to lower leaves and germinate, followed by mycelial growth on infected tissues. Conidiophores are formed at night under humid conditions, while conidia develop during the subsequent dry daylight conditions, and reach full maturity by the next humid night (Tsedaley, 2014). Warm, humid conditions promote pathogen development, with rapid conidial formation at 20–30 °C, especially under relative humidity below 70% (Escuredo et al., 2019; Tsedaley, 2014).

Alternaria spp. symptoms mainly involve leaf spotting appearing on mature lower leaves before or during flowering, around 37–40 days after emergence (Chaudhary et al., 2021; Meno et al., 2022; Tsedaley, 2014). Lesions appear as large brown necrotic areas with concentric yellow rings or as numerous small brown to black spots, and infected leaves may dry out and remain attached or fall off (Schmey et al., 2024). Lesions differ among species: *A. grandis* and *A. linariae* produce small dark concentric rings, *A. solani* forms large dark spots, and *A. protenta* causes light to dark brown spots (Ivanović et al., 2022). Pathogen also infects stems and tubers (Chaudhary et al., 2021; Tsedaley, 2014).

Beneficial bacteria and fungi can support biological and sustainable farming. Microbiological products containing bioagents like *Trichoderma* spp. and *Bacillus* spp. are most commonly mentioned in experiments and scientific literature.

Genus *Bacillus* belongs to the kingdom *Bacteria*, class *Bacilli*, family *Bacillaceae*. It is a gram-positive, rod-shaped, aerobic and motile bacteria. These bacterial species include both beneficial and pathogenic members, ranging from plant growth-promoting and disease-suppressing bacteria to highly pathogenic species with severe or lethal effects in humans (for example, *B. anthracis*, which causes anthrax) (Khan et al., 2022; Tam et al., 2006). *Bacillus* spp. is one of the most widespread rhizobacteria used in agriculture, with *B. subtilis* being the best-known species.

These rhizobacteria support plant health by: releasing volatile compounds that stimulate root exudation; producing antibiotic secondary metabolites, and; forming protective biofilms on roots that shield them from harmful organisms, and help them attach more easily to substrates and further increase their survival abilities; form endospores, which play a significant role in enhancing their survival capabilities (Choudhary & Johri, 2009; Khan et al., 2022).

Previous studies have demonstrated the potential of *Bacillus* species in potato disease management. Foliar application of *B. subtilis* spores has been shown to reduce the incidence of black scurf (caused by *Rhizoctonia solani*) and common scurf (caused by *Streptomyces* spp.). Several studies also report the effectiveness of *B. subtilis* against *Phytophthora infestans*, as well as improvements in plant physiological traits. In addition, treatment of potato mini-tubers with *Bacillus* strains has been shown to reduce disease incidence under laboratory conditions, while *B. velezensis* has demonstrated in vitro activity against *R. solani* and *Fusarium* spp. (Choudhary & Johri, 2009; Kumar et al., 2013; Kumbar et al., 2019; Lastochkina et al., 2022; Wei et al., 2024).

Therefore, there is a reason to believe that biological plant protection – using preparations containing non-pathogenic fungi and bacteria – cannot only enhance plant resistance to pathogens but also lead to an increase in yield. The aim of this study was to evaluate the pathogenicity of *Alternaria solani* and *A. protenta* on potato leaves and their antagonistic interactions with a *Bacillus subtilis*-based biological product (strain MSCL 1441).

Materials and Methods

Pathogen isolates

The study used two *Alternaria* spp. isolates – *A. solani* LD187 and *A. protenta* LD008. These isolates were obtained from the collection of the Institute of Soil and Plant Sciences. For pathogenicity and antagonism tests, the isolates used were from the second passage, 14 days after inoculation on PDA (potato dextrose agar) media.

Antagonism test

Preparation is based on a microbiological product containing the bacterial strain *Bacillus subtilis* MSCL 1441, which was isolated from Latvian soil and provided by the Latvian State Institute of Wood Chemistry. In this experiment, the antagonism between the *B. subtilis*-based preparation and two *Alternaria* isolates was examined under *in vitro* conditions on PDA plates. For this assay, the preparation was applied without dilution. Antagonistic activity was assessed under different setups: when both organisms were placed on the plate simultaneously; when *B. subtilis* was introduced first and the *Alternaria* isolates added later; and when plates were rinsed with the *Bacillus* preparation before placing the *Alternaria* mycelial discs.

Positive and negative controls were established using either sterile PDA discs or mycelial discs of the fungal isolates. Sterile PDA discs served as negative controls to verify the absence of contamination or external factors, while mycelial discs of the pathogens were used as positive controls to confirm their ability to colonize the medium.

All Petri dishes were sealed with cling film to maintain sterility.

Pathogenicity test

The pathogenicity of two Alternaria isolates was evaluated based on their ability to infect potato leaves under different in vitro conditions. *Bacillus subtilis* preparation was tested at two different concentrations (1.5×10^{12} CFU mL^{-1}; 1.5×10^{13} CFU mL^{-1}) and at

two different treatment times (treatment one day before inoculation and treatment one day after inoculation).

Initially, under laboratory conditions, Pre-basic Tissue Culture (PBTC) minituber category seed potatoes of the cultivar 'Madara' were grown in pots. Seed tubers were planted in pots containing a universal garden peat substrate. One month after planting, leaves of the same age (from the 3rd–4th leaf level) counted from the base of the plant, were selected for the experiment. Metal trays (450 × 300 × 50 mm) were surface-disinfected with 96% ethanol and air-dried. Two layers of filter paper were placed inside each tray, followed by the addition of 100 mL of sterile distilled water. Two disinfected glass rods (280 mm long) were placed in each tray, and the potato leaves were arranged on them, so that they did not come into contact with the moist filter paper.

Similar to the morphological description, 5 mm PDA or mycelial discs were obtained using a cork borer and transferred onto the leaves with a metal needle, ensuring direct contact between the mycelial disc and the potato leaf. The mycelial discs were positioned at the center of each leaf. As a positive control, *Alternaria* isolates were used to confirm the ability to cause infection, whereas sterile PDA discs were placed on the potato leaves and served as the negative control. In Variant A, *Alternaria* isolates were applied first to the potato leaves, and the following day, the leaves were sprayed with the *B. subtilis* preparation at two different concentrations. In Variant B, the leaves were first sprayed with the preparation (at the same two concentrations), and inoculation with the isolates was carried out 24 hours later. Each variant was performed in four replicates.

The metal trays were covered with cling film (plastic wrap) to maintain moisture and ensure optimal conditions for fungal development. The metal trays were maintained at +20 °C. After 144 hours (6 days) from the first inoculation, the diameter of the lesions formed by the mycelium was measured (two measurements – at the widest and narrowest points, expressed as the average value).

Data analysis

To determine the significance of the results obtained in the pathogenicity test, a one-way analysis of variance ANOVA was performed using the R software. Significance was assessed at the $p \leq 0.05$ level. In cases where differences were statistically significant, the LSD and Bonferroni post hoc tests were performed.

Results and Discussion

Colony morphology

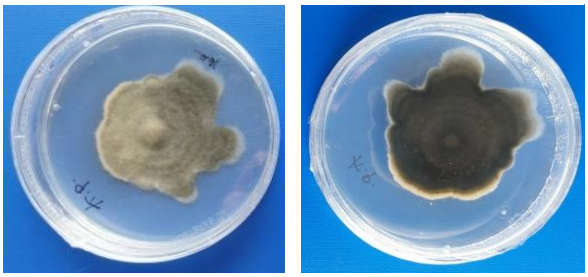
Visual photographs of the colonies were taken on day seven after inoculation (Figure 1). *Alternaria protenta* (LD008) formed olive-grey to dark-grey colonies with cottony mycelium. The colony expanded evenly and developed distinct concentric rings of lighter and darker shades around the initial mycelium. Colony elevation was generally flat, slightly raised in the center, with smooth, rounded margins and light grey to white edges. No visible pigmentation of the medium was observed. Similar colony colour and morphology of *A. protenta* have been reported in previous studies (Bessadat et al., 2019; Cho & Yu, 2000).

In contrast, *Alternaria solani* (LD187) formed slightly greenish-yellow colonies with cottony mycelium and similar concentric zonation. The colonies were also flat with smooth margins, but a light-yellow pigmentation of the medium was observed. Previous studies report that *A. solani* may exhibit yellowish pigmentation and morphological variability among isolates (Bessadat et al., 2019; Kumar et al., 2008).

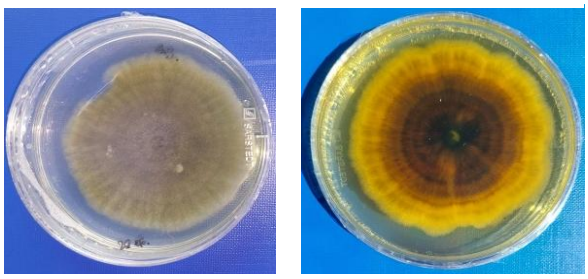
Figure 1

Colony morphology of Alternaria isolates A. protenta and A. solani (left: upper surface; right: lower surface)

A. protenta



A. solani



Comparison of the isolates showed that *A. solani* isolate demonstrated a higher growth rate compared to the *A. protenta* isolate. Both isolates grew faster up to seven days after inoculation, after which their growth rate declined. However, *A. solani* isolates from different locations may vary in mycelial growth rate and can also differ markedly in their morphological characteristics (Kumar et al., 2008; Marak et al., 2014; Nikam et al., 2015).

Antagonism test

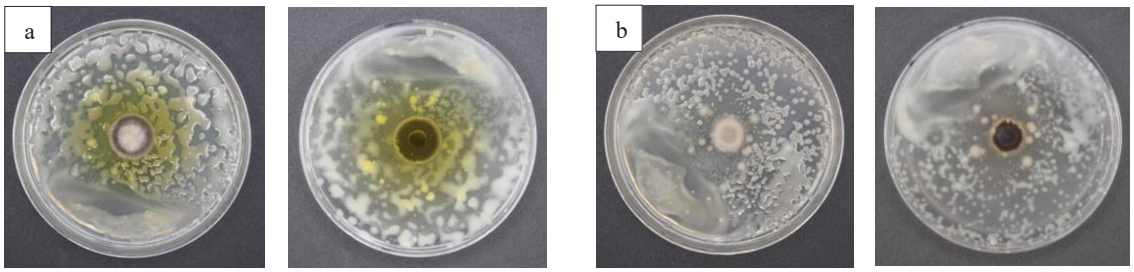
After 7 days, antagonism was observed in all variants, except where *Alternaria* isolates were applied after 10 days and antagonism was evaluated one week later.

Both self-pairings of *Alternaria* isolate and the interactions between the two isolates were compatible, with no visible demarcation line observed at the contact interface.

In the treatment where the Petri dish was rinsed with the *Bacillus* spp. preparation and subsequently inoculated with a mycelial disc placed at the center, mycelial growth was initiated but progressed very slowly (Figure 2). Compared with the negative control

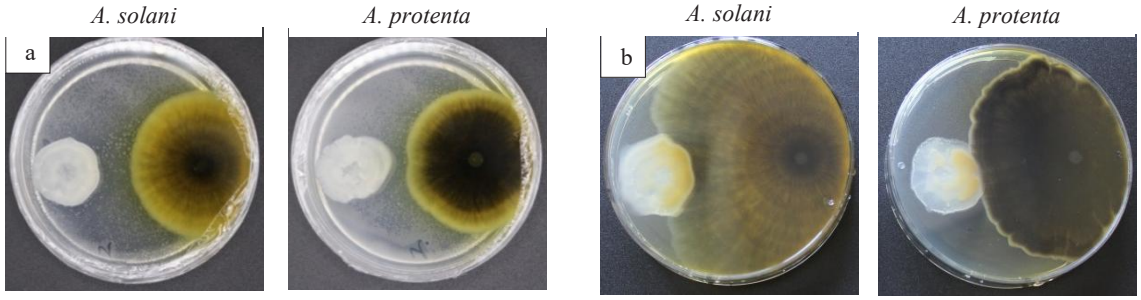
(pathogen inoculated on PDA medium only) colony expansion was markedly suppressed, and further radial growth was almost completely arrested. The colonies appeared compact, and the mycelium did not spread beyond the initial inoculation site, creating the appearance of an inhibition zone in which the mycelium seemed encapsulated around the inoculated disc.

Figure 2
Evaluation of antagonistic activity on PDA medium rinsed with a Bacillus subtilis preparation.
Left – top view of Petri plate, right – bottom view: a – mycelial disc of A. solani; b – mycelial disc of A. protenta



A different experimental variant was performed, in which a drop of the *B. subtilis* preparation was applied to the medium, and the plate was sealed to promote bacterial growth. After seven days, an *Alternaria* isolate was inoculated on the opposite side (Figure 3). Both organisms showed visible growth. Although visible *B. subtilis* growth was observed, the pathogenic isolates also grew relatively rapidly once transferred onto the Petri plate. Images taken five days later showed that the fungal colonies appeared substantially larger than the *B. subtilis* colony, whereas the bacterial inoculum remained relatively small (Figure 3a). A subsequent set of photographs taken one week later (after 19 days from start) revealed that the fungal mycelium eventually suppressed *B. subtilis* growth, with no demarcation line observed at the contact zone (Figure 3b).

Figure 3
Antagonistic interactions between B. subtilis and Alternaria isolates on PDA medium:
a – five days after inoculation with fungal isolates; b – one week later



It becomes evident that when a drop of *B. subtilis* is applied one week prior to the pathogen mycelium, it grows more extensively, forming a larger colony and experiencing less restriction compared to the situation where both antagonists are introduced simultaneously. The growth patterns of both organisms on PDA medium illustrate their interaction dynamics. In similar studies, *Bacillus* spp. have exhibited antagonistic activity both *in vitro* and *in vivo* against *Alternaria* species associated with tomato early blight (Matar et al., 2009; Pane & Zaccardelli, 2015).
B. subtilis demonstrated strong inhibitory properties in the treatment where the Petri dish surface was rinsed with the preparation. It can be assumed that when the surface is saturated with *B. subtilis*, there is insufficient space or resources for the competing organism to grow. In contrast, in the treatment where a drop of *B. subtilis* was placed opposite the pathogen isolates, a slight reduction in the radial growth of the mycelium was observed, but the pathogen was not completely suppressed. Furthermore, *B. subtilis* did not develop as rapidly as the *Alternaria*, which allowed the latter to continue spreading.

Pathogenicity test

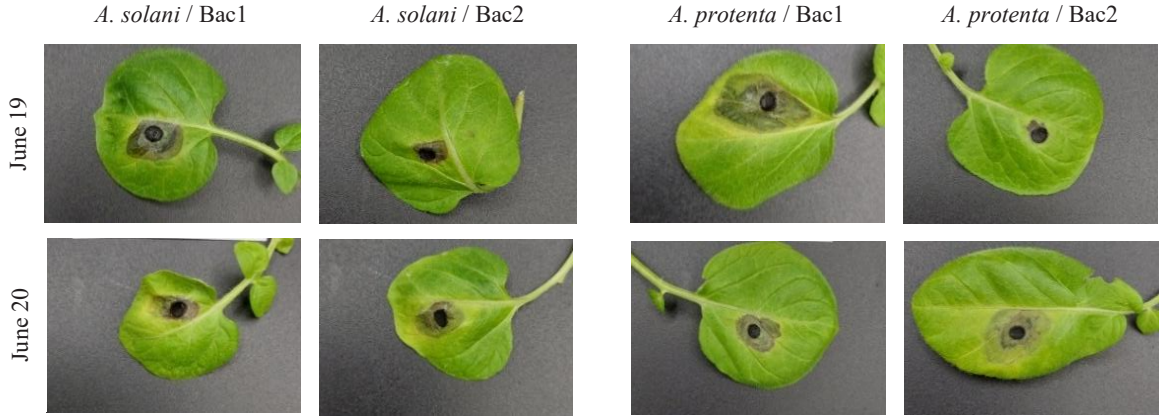
The experiment involved two *Alternaria* isolates – *A. protenta* and *A. solani* and potato cultivar 'Madara'. Three days after inoculation (DAI), mycelial growth was observed in both isolates originating from the inoculated discs, indicating the onset of infection.
Six DAI, lesion diameter of the *A. solani* isolate ranged from 6 to 12 mm, whereas the lesions formed by the *A. protenta* isolate on potato leaves ranged from 6 to 31 mm, depending on the treatment variant (Figure 4). Symptoms observed on the leaves at six DAI in both cases were typical of potato early blight. Necrotic, dark brown lesions developed at the inoculation sites,

followed by the formation of yellow concentric rings around the necrotic tissue. In some treatment variants for both isolates, further infection was also observed, appearing as scattered small spots on the leaf surfaces.

Figure 4

Impact of application timing and concentration of Bacillus subtilis on the severity of Alternaria infection in potato foliage.

Potato leaves inoculated with Alternaria solani (right) and A. protenta (left). The top row shows leaves treated with a Bacillus subtilis preparation one day prior to inoculation, while the bottom row shows leaves inoculated first and treated the following day. Bac1: 1.5 × 10¹² CFU mL⁻¹; Bac2: 10-fold higher concentration



Statistical analysis showed that species had a significant effect ($p < 0.05$) on the growing rate of infection.

On average, *A. protenta* formed larger lesions in diameter than *A. solani*. In contrast, the concentration of the *B. subtilis* preparation and the timing of its application had no statistically significant effect on lesion development. Although the concentration of the preparation did not show a statistically significant effect on lesion diameter, the obtained p-value ($p = 0.054$) corresponds to a confidence level of 94.6%. The diameter of the infected lesions was 1.5 times smaller when using the 10-fold higher concentration of the *B. subtilis* preparation compared to the lower concentration. In a similar study by Baltzakis et al. (2025) on detached potato leaves, different *Alternaria* species were compared for their pathogenicity. *A. solani* and *A. protenta* both caused significant lesion development. In our study, *A. protenta* produced larger lesions, whereas in the study referenced above, *A. solani* was reported as the more aggressive species in terms of lesion size. It should be noted that Baltzakis et al. (2025) used isolates originating from potato fields and inoculation was performed using a spore suspension.

Conclusions

1. *B. subtilis* exhibited strong inhibitory effects when the Petri plate surface was thoroughly rinsed with the preparation, likely limiting space and resources for the competing pathogen. In contrast, when a drop of *B. subtilis* was applied opposite the pathogen isolates, only a slight reduction in mycelial radial growth was observed, and the pathogen was not completely suppressed.
2. Statistical analysis indicated that the isolate species significantly influenced growing rate ($p < 0.05$). On average, *A. protenta* produced larger lesions than *A. solani.*
3. In contrast, neither the concentration nor the timing of application of the *B. subtilis* preparation had a statistically significant effect on lesion development.

Acknowledgements

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A REVIEW: THE INFLUENCE OF VARIOUS FACTORS ON THE COMPOSITION OF STARCH IN POTATO TUBERS

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Abstract
Potato (*Solanum tuberosum* L.) starch is one of the main components of potato tubers, accounting for approximately 75% of tuber dry weight, and plays an important role in determining tuber quality, nutritional value, and processing properties. Potato starch primarily consists of amylose (AM) and amylopectin (AP), and the ratio between these polymers influences starch functionality, digestibility, gelatinisation behaviour, and glycaemic response. Higher amylose content (AMC) is associated with increased resistant starch formation, slower digestion, and reduced starch hydrolysis. However, most commercially cultivated potato varieties produce starch rich in amylopectin. This review summarises current knowledge on factors influencing potato starch composition and quality, with particular emphasis on AMC variation. The analysed studies demonstrated that genetic background is one of the main factors affecting starch-related traits, including starch composition, AMC, and granule structure. Environmental factors such as temperature, altitude, location, and seasonal variability may also influence starch synthesis and accumulation, often through genotype × environment interactions. In addition, tuber developmental stage, agronomic practices, and post-harvest storage conditions can modify starch composition and physicochemical properties. Recent studies have increasingly focused on relationships between starch molecular structure, AMC, and functional properties important for food and industrial applications. Nevertheless, the effects of environmental and agronomic factors reported across studies are not always consistent, indicating the need for further research on the combined influence of genotype, growing conditions, and crop management on potato starch quality.
Keywords: potato, starch, starch composition, amylose content, factors affecting starch composition.

Introduction

The potato is one of the most widely cultivated crops in the world and represents an important component of human nutrition. Compared with many other staple crops, potatoes provide a favourable nutritional profile, including a higher protein-to-carbohydrate ratio than most cereals and other root and tuber crops. Potato proteins contain a well-balanced composition of essential amino acids important for human nutrition. Potatoes are also an important source of dietary energy and provide valuable micronutrients. Due to their nutritional value and versatility in food preparation, potatoes can be considered an important component of a balanced and healthy diet alongside vegetables and whole-grain foods (Niederhauser, 1993; Bamberg & del Rio, 2005; Camire et al., 2009; McGill et al., 2013; Visvanathan et al., 2015; Devaux et al., 2021).

Potatoes have a wide range of applications and are consumed in various forms worldwide. They are used both as fresh produce and as processed products, including semi-finished products and snack foods such as chips. Beyond their role in human nutrition, potatoes and potato starch also have broad applications in several industries, including food processing, cosmetics, pharmaceuticals, and other industrial sectors (Dupuis, & Liu, 2019).

Carbohydrates are the main nutritional component of potato tubers, with starch representing the predominant carbohydrate and serving as the primary energy reserve for the plant (Camire et al., 2009; Pfister & Zeeman, 2016; Li et al., 2021).

Potato starch is important from a technological perspective due to its functional properties, including thickening, gelling, coating, and encapsulation, which are largely determined by the structure and organisation of the two main polymers, amylose (AM) and amylopectin (AP). Differences in physicochemical, thermal, and pasting properties among potato starches also determine their suitability for various food and industrial applications (Li et al., 2006; Pfister & Zeeman, 2016; Sanchez-González et al., 2019). Breeding efforts have therefore focused on developing cultivars with improved processing characteristics, although clear differences between modern and heirloom cultivars in terms of AMC or starch granule morphology are not always observed. As industrial and food applications of potato starch continue to diversify, the characterization of starch parameters in breeding lines remains important for identifying valuable germplasm with properties suitable for specialised and emerging applications (Fajardo et al., 2013).

Current research has identified several factors influencing starch composition and quality in potato tubers, including genetic background, environmental conditions, tuber developmental stage, and agronomic practices. AMC is considered one of the most important parameters affecting the nutritional and technological properties of potato starch. Therefore, the aim of this review is to analyse the factors influencing starch composition and quality in potato tubers, with particular emphasis on changes in amylose content and the role of genetic, environmental, and agronomic factors in regulating these variations.

Materials and Methods

This review was conducted using a semi-systematic monographic approach to analyse scientific information on factors influencing starch composition and quality in potato tubers. The aim was to summarise research findings on the effects of genetic, environmental, and agronomic factors on potato starch

formation and properties. The literature search was performed using the EBSCO and CAB Abstracts databases, complemented by Google Scholar searches. The analysed literature included articles published in journals from major academic publishers, including Elsevier, Springer Nature, Wiley, Taylor & Francis, MDPI, and others.

This study used ChatGPT (GPT-5.3), a large language model developed by OpenAI, as a supportive tool for language editing and structuring ideas. The AI-generated suggestions were reviewed and critically evaluated by the author, and all final interpretations, analyses, and conclusions remain the responsibility of the author.

Results and Discussion

Structure and Composition of Potato Starch

Starch is the main component of potato tuber dry matter and the primary reserve carbohydrate of the plant. In potato tubers, starch generally accounts for approximately 66–80% of dry weight, although the exact amount may vary depending on cultivar and plant developmental stage (Li et al., 2006; van Eck, 2007; Pfister & Zeeman, 2016; Dupuis & Liu, 2019).

Chemically, starch is a polysaccharide composed of glucose units and occurs in two main forms: AM and AP. AM is mainly a linear polymer linked by α-1,4-glycosidic bonds, whereas AP has a highly branched structure containing both α-1,4- and α-1,6-glycosidic linkages (Hoover, 2001; Yusuph et al., 2003; Storey, 2007; Pfister & Zeeman, 2016; Dupuis & Liu, 2019; Wang et al., 2025). The relative proportion and molecular organisation of these polymers largely determine the physicochemical and functional properties of potato starch.

Starch granules contain crystalline and amorphous regions that influence their susceptibility to hydrolysis and other physicochemical changes. Limited hydrolysis mainly affects amorphous regions and may correlate with AMC, whereas more intensive hydrolysis also affects crystalline structures formed by AP (Yusuph et al., 2003).

The composition and structure of potato starch are also associated with its nutritional properties and digestibility. Lal et al. (2024) reported that the addition of potato peels to potato flesh may help moderate postprandial blood glucose responses by affecting starch digestibility parameters, including the glycaemic index and starch hydrolysis index. The incorporation of potato peels also increased total starch and AMC, likely due to the naturally occurring starch and carbohydrate fractions present in potato peel tissues.

Overall, the structure and composition of potato starch are primarily determined by the proportion and organisation of AM and AP, which influence nutritional, functional, and technological properties. These characteristics are further shaped by interactions among genetic, environmental, and agronomic factors.

Genetic Factors Influencing Potato Starch Composition

As summarised in Table 1, studies analysing the genetic diversity of potato starch have consistently demonstrated significant differences in starch composition, particularly in AM content, among potato genotypes.

Genetic background plays a key role in determining starch composition and physicochemical properties in potato tubers. AMC in potato starch typically ranges from approximately 17% to 25%, though considerable variation occurs among cultivars and genetic lines (Li et al., 2006).

Differences in starch composition are also associated with structural characteristics of starch granules. A negative correlation between AMC and starch granule diameter has been identified, indicating that smaller granules generally contain higher levels of AM. This relationship has been observed in both cultivated and wild potato species. Most commercial cultivars contain up to approximately 28% AM, whereas some wild potato clones may reach 30–33% AM (Jansen et al., 2001).

Increased AM levels may improve the nutritional properties of potato starch, as higher AMC is associated with greater resistance to enzymatic digestion and the formation of resistant starch (Camire et al., 2009). However, despite the importance of cultivar-related differences, studies conducted under uniform growing conditions suggest that physicochemical properties among potato cultivars may vary less than expected, indicating that starch functionality and digestibility are also influenced by additional interacting factors (Alvani et al., 2011).

Studies of coloured potato cultivars have demonstrated significant differences in AM content, phosphorus content, molecular structure, and pasting behaviour among genotypes, including yellow, purple, and red potatoes, which in turn affect rheological and functional properties relevant for food and industrial applications (Yang et al., 2018). Similarly, starch from light-coloured potato varieties has been reported to contain slightly higher AM levels than starch from coloured varieties (Krystyjan et al., 2022). Differences in starch molecular architecture have also been observed between mealy and waxy pigmented potatoes, where mealy starches show higher AMC, lower branching degree, a reduced proportion of short-chain AP fractions, and lower molecular weight (Wang et al., 2025). Higher AM concentrations may also be associated with structural differences in starch granules, including increased surface irregularities (Rivas et al., 2023).

Studies from different regions further support the strong influence of genetic factors. Research in Brazil reported relatively small variation in AMC among six potato varieties, although differences in AM and AP proportions affected starch granule structure and pasting properties (dos Santos et al., 2016).

Table 1
Factors affecting potato amylose content

Trial location	AMC, %	Number of genotypes	Factors, significance	Reference
Poland, Bydgoszcz	20.1 - 22.2	1	St*	Pobereżny et al., 2021
Poland	24.6 - 32.4	8 (4)[1]	G and Grs*	Krystyjan et al., 2022
Poland, Tomaszkowo	23.0 - 28.9	3	G, Grs, St and T*	Brążkiewicz et al., 2025
Czech Republic	18.8 - 23.0	16[2]	G and A*, Grs n/s	Šimková et al., 2013
Denmark, Northern Jutland	28.0 - 29.0	4[2]	H n/s	Christensen & Madsen, 1996
Denmark	1.9 - 36.5	6	G*	Kozlov et al., 2007
UK, Dundee	25.2 - 29.1	11	G*	Alvani et al., 2011
UK, Perthshire	25.8 - 31.2	12	G*	Yusuph et al., 2003
Germany	21.9 - 42.7[3]	1220/1103[3]	G*	Jansen et al., 2001
	23.0 - 37.0	466/344		
Sweden	<0.5, 14.5 -98.1	17	G*	Zhao et al., 2023
USA, Hancock, Wisconsin	23.1 - 32.7	20	G, Grs and St*	Fajardo et al., 2013
USA, Hancock and Antigo, Wisconsin	28.1 - 32.1	9[4]	G, A, St and Grs***	Jansky & Fajardo, 2014
USA, Hancock, Wisconsin	22.2 - 34.8	11	G, H, Grs*	Jansky & Fajardo, 2016
USA, Washington	23.7 - 60.9	60	G*	Rivas et al., 2023
Brazil, São Paulo	28.8 - 31.9	1	F_N n/s	Ebúrneo et al., 2018
Brazil, Minas Gerais state	16.1 - 23.4	6	G n/s	dos Santos et al., 2016
China, Anhui	20.3 - 25.2	3 (2)[1]	G*	Yang et al., 2018
China, Anhui	27.6 - 30.0	1	H*	Yang et al., 2021
China, Hangzhou	18.9 - 29.4	29	G*	Ahmed et al., 2018
China, Yunnan	24.7 – 33.0	6 (5)[1]	G*	Wang et al., 2025
China, Hubei	26.3 - 30.2	2	F_K*	Zhang et al., 2018
China, Sichuan	25.4 - 31.0	2	G, A and G×A**	Hu et al., 2023
China, Zhejiang	23.6 - 31.1	7	G and G×L**, L*	Ahmed et al., 2019
Colombia, Nariño	29.0 - 40.0	6	G*	Pineda-Gomez et al., 2021
India, Gwalior	15.0 - 23.1	21	G and A*	Kaur et al., 2007
India, Shimla	6.5 - 32.2	42	G*	Singh et al., 2018
India	25.5 - 32.5	2	G*	Lal et al., 2024
Indonesia, West Java	23.1 - 26.6	1	A*	Rohima et al., 2024
Japan, Hokkaido	11.4 - 24.2	105	G*	Zaidul et al., 2007
Japan, Hokkaido	17.1 - 22.4	7[2] and 9	G*	Noda et al., 2004
Peru, Otuzco	15.5 - 32.1	4	G*	Sanchez-González et al., 2019
New Zealand	24.5 - 28.0	5	G and St*	Singh et al., 2008

[1]Coloured flesh varieties, [2]starch varieties, [3]wild potatoes, [4]tetraploid varieties, G-genotype, Grs-growing seasons, L – locations, A- altitude, F- fertilizations, F_N-nitrogen fertilization, F_K- potassium fertilization, St- storage, H- harvesting time, T- treatment application, *P<0.05, **P<0.01, ***P<0.001, n/s – not significant.

In the United States, significant varietal effects on AMC were observed, with higher levels detected in certain cold-induced sweetening (CIS)-resistant cultivars (Jansky & Fajardo, 2014). Studies in India reported AM values ranging from approximately 15% to 23% among cultivars (Kaur et al., 2007), while research in Peru also confirmed significant varietal differences (Sanchez-González et al., 2019).

Overall, genetic factors strongly influence starch composition and properties in potato tubers; however, variation in the amylose–amylopectin ratio may also be influenced by environmental conditions and agronomic practices (Noda et al., 2004; Sanchez-González et al., 2019; Singh et al., 2018).

Environmental Factors Affecting Starch Composition

Environmental conditions during plant growth can significantly influence starch synthesis and accumulation in potato tubers. Studies summarised in Table 1 indicate that factors including location, altitude, temperature, and seasonal variability affect

starch composition, particularly AMC. Significant effects of genotype, environment, and genotype × environment interaction on AMC have been reported in potatoes grown under different environmental conditions (Ahmed et al., 2019; Hu et al., 2023; Jansky & Fajardo, 2014). In addition, temperature conditions during the growing season may influence starch composition, as higher average temperatures were associated with increased AMC in potato starch (Brążkiewicz et al., 2025).

Several studies demonstrated that potatoes cultivated at higher altitudes tend to exhibit increased AM levels and altered amylose–amylopectin ratios compared with potatoes grown at lower elevations (Hu et al., 2023; Šimková et al., 2013). Environmental variation related to altitude has also been shown to affect physicochemical and functional starch properties, including swelling power, solubility, absorption capacity, and pasting behaviour (Rohima et al., 2024, 2025).

Seasonal and climatic conditions may further contribute to variation in starch composition. Research conducted in the United States revealed that location and year significantly affect AMC, suggesting that climatic variability influences starch biosynthesis in potato tubers (Jansky & Fajardo, 2014). However, not all studies observed a consistent environmental effect, as research in the Czech Republic reported no statistically significant influence of year on AMC (Šimková et al., 2013).

Overall, available studies indicate that environmental conditions can influence potato starch composition and functionality, although the magnitude of these effects depends on genotype and growing conditions.

Changes in Amylose Content During Maturation

The developmental stage of potato tubers influences starch accumulation and composition. Cultivar maturity type and growing season length significantly affect tuber yield and starch production. Early-maturing cultivars generally have a shorter vegetation period and therefore tend to accumulate lower starch content and produce smaller tuber yields than late-maturing cultivars, which usually achieve greater starch accumulation during extended growth periods (van Eck, 2007; Camire et al., 2009).

Studies investigating the relationship between tuber maturity and AMC have produced variable results. Research conducted in the Czech Republic on sixteen potato cultivars identified the lowest AMC in a very late cultivar and the highest in a semi-early cultivar, although the effect of growing season length was not consistently expressed across all genotypes (Šimková et al., 2013).

Additional insight into changes in AMC during tuber development was provided by field experiments in the United States. A three-year study involving eleven cultivars demonstrated that AMC was highest during early tuber formation and gradually decreased as tubers matured, declining from approximately 30.0% in late June to 26.8% in late August (Jansky & Fajardo, 2016). However, not all studies have identified a clear relationship between maturity and AMC. Research conducted in Denmark reported that AMC in four potato cultivars was independent of harvest date and tuber size (Christensen & Madsen, 1996).

Changes in starch molecular structure during tuber development may additionally influence starch functionality. Variations in AP chain-length distribution during starch granule development have been associated with changes in pasting behaviour, gelatinisation, retrogradation, and digestibility (Yang et al., 2021).

Overall, available studies indicate that tuber maturation and growing season duration may influence starch accumulation and AMC, although the extent and direction of these changes depend on cultivar characteristics and environmental conditions.

Agronomic Practices Influencing Potato Starch Composition

As summarised in Table 1, agronomic management practices may influence starch composition and functional properties in potato tubers. Among agronomic factors, nitrogen fertilisation is considered one of the most important practices in potato production. However, studies conducted in Brazil showed that nitrogen fertilisation did not significantly affect AMC in potato starch (Ebúrneo et al., 2018). In contrast, research on sweet potato demonstrated that increasing nitrogen levels reduced AMC and increased the proportion of AP (Duan et al., 2019), suggesting that nitrogen effects on starch composition may vary among crop species.

Agronomic treatments may also affect starch characteristics. Research conducted in Poland demonstrated that combined agronomic treatments increased AMC in potato starch (Brążkiewicz et al., 2025).

Overall, agronomic practices can influence starch composition and quality in potato tubers, although their effects are often smaller than genetic influences.

Postharvest Storage Effects on Potato Starch Quality

Whereas long-term storage reduced AM levels by approximately 0.9 percentage points, starch quality was only slightly affected when constant storage conditions and appropriate potato seed treatment products were applied, suggesting that suitable storage management may help maintain starch quality during prolonged storage (Brążkiewicz et al., 2025). Similarly, studies evaluating potato cultivars under different production environments indicated that storage and production conditions generally had a smaller influence on AM levels than cultivar-related differences (Fajardo et al., 2013).

Storage-related changes may also affect starch retrogradation behaviour. Studies have shown that AM retrogradation occurs mainly during the early stages of storage, whereas AP retrogradation becomes more pronounced during long-term storage. Changes in viscoelastic properties, hardness, resistant starch content, and gel stability during refrigerated storage

have also been associated with AMC and AM chain length (Dobosz et al., 2019).

Post-harvest storage conditions can further modify starch composition and physicochemical properties. Storage treatments may influence AMC depending on cultivar and storage regime (Jansky & Fajardo, 2014), while prolonged storage can reduce AM levels (Poberežny et al., 2021). Low-temperature storage has been associated with smaller starch granules, reduced solubility, and changes in thermal, pasting, and textural properties, whereas AMC and swelling power are generally less affected (Singh et al., 2008; Kaur et al., 2009).

Overall, storage conditions can influence starch composition and quality in potato tubers, although their effects are generally smaller than those associated with genetic factors.

Conclusions

1. Potato starch composition is mainly determined by the proportion and structure of amylose and amylopectin, which influence its functional, nutritional, and technological properties.
2. Genetic factors are the primary source of variability in starch composition, with significant differences in amylose content and physicochemical properties observed among potato cultivars, particularly in wild and coloured genotypes.
3. Environmental conditions (e.g., temperature, altitude, and location) influence starch synthesis and composition, but their effects are strongly dependent on genotype and show inconsistent patterns across studies.
4. Tuber developmental stage and post-harvest storage can modify amylose content and starch functionality; however, the magnitude and direction of these changes vary, indicating incomplete understanding of underlying mechanisms.
5. Recent research increasingly focuses on starch fine structure, genotype × environment interactions, and post-harvest modifications, while remaining gaps exist in explaining variability across studies and standardising methodological approaches.

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THE OCCURRENCE OF TOMATO DISEASES CAUSED BY *ALTERNARIA* SPP. AND *STEMPHYLIUM* SPP. IN THE BALTIC REGION

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Abstract
Fungi from the genera *Alternaria* and *Stemphylium* belong to the family *Pleosporaceae* and are responsible for severe agricultural yield losses in temperate zones affecting various hosts, including tomatoes *Solanum lycopersicum* L. Both *Alternaria* spp. and *Stemphylium* spp. are characterized by similar disease symptoms, thus challenging the management of tomato diseases caused by these fungi. In our study, a total of 17 greenhouses and high tunnels were surveyed in the Baltic region from 2022 to 2024 for the collection of tomato samples with typical disease symptoms. Fungi were recovered from symptomatic tomato leaves and fruits on potato dextrose agar (PDA) media and characterized based on colony morphology. Further identification of fungal strains at the genus and subgeneric section levels was based on the analysis of the ITS region. A total of 845 leaves and fruits representing brown to black necrotic lesions were collected and 1181 fungal strains were obtained, predominantly small-spored *Alternaria* spp. (n=575) representing three subgeneric sections (*Alternaria*, *Ulocladiodes,* and *Infectoriae*). Large-spored *Alternaria* species comprised within *Alternaria* section *Porri* (n=125), *Stemphylium* spp. (n=60) and other fungi (n=421) were also isolated from tomatoes. Brown spot disease of tomatoes associated with small-spored *Alternaria* spp. dominated in 2023 and 2024 with the occurrence of 71-80% in the Baltic region. The occurrence of tomato diseases caused by large-spored *Alternaria* spp. was 20-60% whereas those caused by *Stemphylium* spp. had the occurrence of 29-60%, depending on the sampling location and year.
Keywords: *Solanum lycopersicum* L., fungal diseases.

Introduction

Tomatoes *Solanum lycopersicum* L. are characterized by various health benefits due to high levels of biologically active compounds, predominantly carotenoids and phenols (Bertin et al., 2025; Gómez-Romero et al., 2010; Perveen et al., 2015). Fungal diseases are associated with reduced yield and quality of tomatoes in temperate regions (Ally et al., 2023; Schmey et al., 2024; Wang et al., 2025).

Considerable yield losses in tomato production are caused by two related genera within phylum Ascomycota, class Dothideomycetes, family Pleosporaceae, order Pleosporales, viz., *Alternaria* (Bessadat et al., 2017; Kokaeva et al., 2022; Schmey et al., 2024; Thomma, 2003) and *Stemphylium* (Bessadat et al., 2022; Franco et al., 2017; González-Ghiena et al., 2025; Torres et al., 2024).

Both *Alternaria* spp. and *Stemphylium* spp. are characterized by production of various secondary metabolites, including mycotoxins and phytotoxins (Bhunjun et al., 2024; Kim & Dettman 2025; Stricker et al., 2021). Therefore, these fungi are also associated with human health threats (Grignano et al., 2025; Zhao et al., 2025) and food safety (Manno et al., 2025; Tournas et al., 2005).

To date, over 400 fungal species are comprised in the genus *Alternaria* that is divided into 30 subgeneric sections (Ahmadpour et al., 2025; Li et al., 2023). Furthermore, a total of 37 species are described in the genus *Stemphylium* (Ahmadpour et al., 2024; Brahmanage et al., 2019, 2020; Crous et al., 2020; Marin-Felix et al., 2019; Phukhamsakda et al., 2020; Qian et al., 2023; Woudenberg et al., 2017). Fungi from both genera are characterized by similar colony morphology and micro-morphological characteristics, for instance, production of multiseptated and pigmented conidia that are indistinguishable at early stages of development (Simmons, 2007; Woudenberg et al., 2013, 2014, 2017).

Previous studies have confirmed that morphological characteristics do not allow reliable identification of *Alternaria* spp. and *Stemphylium* spp.; therefore, molecular phylogenetic analysis is required for their delimitation (Bessadat et al., 2022; Dettman & Eggertson, 2022; Lawrence et al., 2016; Li et al., 2022; Woudenberg et al., 2013, 2017).

The precise identification of tomato diseases caused by *Alternaria* spp. and *Stemphylium* spp. is necessary for the development of effective control strategies. There are limited reports available on fungi from the genera *Alternaria* and *Stemphylium* affecting the production of greenhouse tomatoes in the Baltic region (Dučkena & Bimšteine, 2023; Dučkena et al., 2024, 2026; Shidlauskiene & Surviliene, 2002) and also globally (Ally et al., 2023; Sanoubar & Barbanti, 2017).

The aim of the present study was to characterize morphological characteristics of *Alternaria* spp. and *Stemphylium* spp. and analyze the occurrence of tomato diseases caused by these fungi in the Baltic region.

Materials and Methods

The research was conducted from 2022 to 2024 and comprised a total of 17 greenhouses and high tunnels, including 13 integrated and 4 organic farming systems of tomato cultivation in the Baltic region. These

included the following locations: i) Bērze, Daugmale, Līvbērze, Iecava, Jaunsvirlauka, and Vircava from Latvia; ii) Jõgeva, Vedu, Koimula, and Lemmatsi from Estonia; and iii) Babtai, Ringaudai, Virbaliskiai, and Karkiskes from Lithuania.

Tomato diseases caused by *Alternaria* spp. and *Stemphylium* spp. were identified based on visual evaluation of symptoms and confirmed via light microscopy. Symptomatic samples were collected at the beginning and end of intensive tomato production and brought to the Plant Pathology Scientific Laboratory (LBTU, Latvia). Tomatoes were examined for conidia of *Alternaria* spp. and *Stemphylium* spp. using an Olympus BX43 microscope (Olympus Cooperation, Japan). The obtained data were compared with criteria from Simmons (2001, 2007).

Plant tissue samples (0.5 cm^2) were excised from symptomatic tomatoes and 1% solution of sodium hypochlorite (NaOCl) was used for their sterilization for 1 min, followed by rinsing three times in distilled water. Thereafter, plant samples were transferred to Petri dishes containing potato dextrose agar media (PDA) amended with penicillin (0.1 mg L^{-1}) and streptomycin (0.1 mg L^{-1}). After seven days of incubation in darkness at 23 °C, a single representative colony from each PDA plate was selected for purification according to Leyronas et al. (2012).

Further analyses of *Alternaria* spp. and *Stemphylium* spp. strains were conducted at the Institute of Research on Horticulture and Seeds, France. The microwave mini-prep method (Goodwin & Lee, 1993) was used for the extraction of the genomic DNA. The polymerase chain reaction (PCR) analyses of the internal transcribed spacer regions 1 and 2 (ITS1, ITS2) and intervening 5.8S nuclear ribosomal DNA (nrDNA) were conducted according to White et al. (1990). Sanger sequencing of the obtained amplicons was conducted by Eurofins Genomics (Ebersberg, Germany). Further identification of fungal strains at the genus and the subgeneric section levels was conducted according to Woudenberg et al. (2013, 2014, 2015, 2017).

The occurrence of tomato diseases caused by fungi from the genera *Alternaria* and *Stemphylium* was calculated using the number of greenhouses where the disease was observed compared to the total number of greenhouses surveyed in each country, expressed as a percentage.

Results and Discussion

Fungal isolation and identification

A total of 845 tomato leaves and fruits with disease symptoms caused by *Alternaria* spp. and *Stemphylium* spp. were obtained and 1181 fungal strains were isolated from symptomatic samples. A total of 4 groups were identified using the analysis of colony morphology, the size and catenation of conidia. First, small-spored *Alternaria* spp. formed small conidia (length <60 µm) in chains (n=575). Second, large-spored *Alternaria* spp. (n=125) were characterized by the formation of large conidia (length >60 µm). Third, *Stemphylium* spp. (n=60) formed conidia ≤55 µm in length. Fourth, other fungi isolated from tomatoes were excluded from further analysis (n=421).

A total of 300 representative strains of *Alternaria* spp. and *Stemphylium* spp. were selected for further identification using the ITS region. The National Center for Biotechnology Information (NCBI, USA) BLAST analysis of the ITS region confirmed the occurrence of *Stemphylium* spp. along with *Alternaria* spp. from four sections. These included the sections *Porri* (32%), *Infectoriae* (24%), and *Alternaria* (22%) identified in Latvia, Lithuania, and Estonia. Members of the section *Ulocladioides* (1%) were identified in Jõgeva (Estonia) and Ringaudai (Lithuania). Our results align with reports by Schmey et al. (2024) confirming sections *Alternaria*, *Porri*, *Infectoriae*, and *Ulocladioides* as disease causal agents in tomatoes.

However, other studies have reported on greater diversity of *Alternaria* spp. associated with tomatoes, for instance, members of the sections *Japonicae* (Bessadat et al., 2020), *Brassicicola*, *Dianthicola* (Woudenberg et al., 2013), *Embellisia* (Sadeghi & Mirzaei, 2018) along with *Embellisioides* and *Eureka* (Bessadat et al., 2021).

Characterization of tomato diseases associated with small-spored Alternaria species

In the present study, small-spored *Alternaria* spp. represented three sections (*Alternaria*, *Ulocladiodes*, and *Infectoriae*) were obtained from symptomatic leaves and fruits of tomatoes (Figure 1) in line with previous studies (Bessadat et al., 2017; Gherbawy et al., 2018; Kokaeva et al., 2018). In the Baltic region, these fungi were associated with small, brown to black lesions without concentric rings on symptomatic leaves as reported by Schmey et al. (2024).

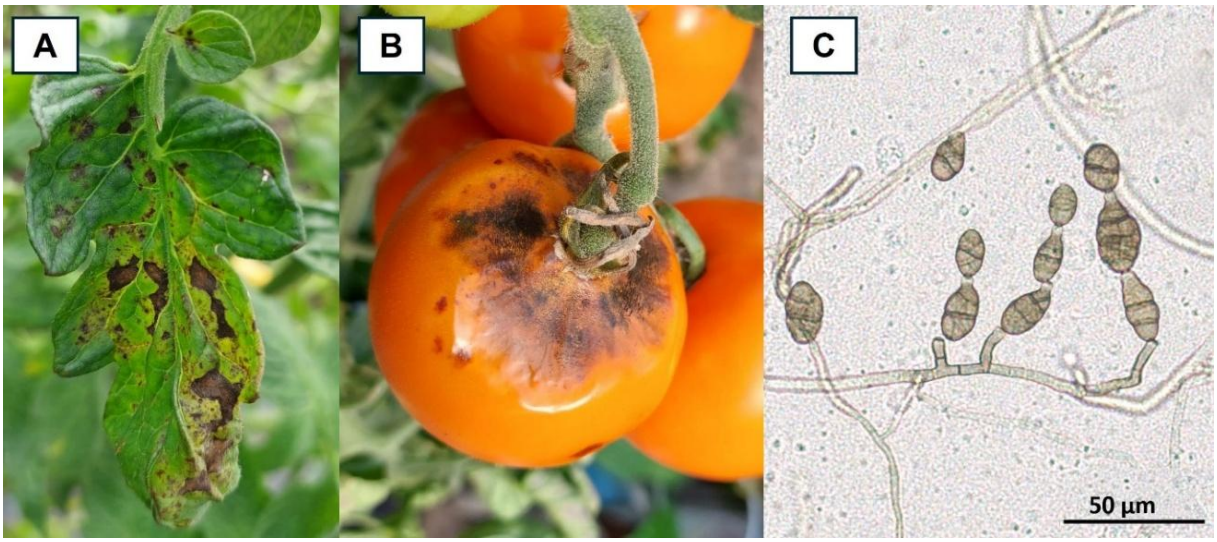
Brown spot disease of tomatoes caused by small-spored *Alternaria* spp. dominated in the Baltic region in 2023 and 2024. In Estonia, this fungal disease was noted in 4 of the 5 surveyed greenhouses located in Jõgeva, Vedu, and Koimula (occurrence 80%). In Latvia, brown spot disease of tomatoes was identified in 5 of the 7 surveyed greenhouses located in Bērze, Daugmale, Līvbērze, and Iecava (occurrence 71%). In Lithuania, this fungal disease was recorded in 4 of the 5 surveyed greenhouses located in Babtai, Ringaudai, Virbaliskiai, and Karkiskes (occurrence 80%).

Early blight (EB) disease caused by large-spored *Alternaria* species (section *Porri*) was detected every year during intensive tomato production (from August to September).

Characterization of tomato diseases caused by large-spored Alternaria species

Early blight (EB) was identified on tomato leaves characterized by brown, necrotic lesions with yellow halos. Compared with small-spored *Alternaria* spp., those of large-spored *Alternaria* spp. were distinguished by larger lesions with typical concentric rings (Figure 2) in line with reports from other studies (Bessadat et al., 2017; El Gobashy et al., 2018; Ding et al., 2019; Zhao et al., 2022).

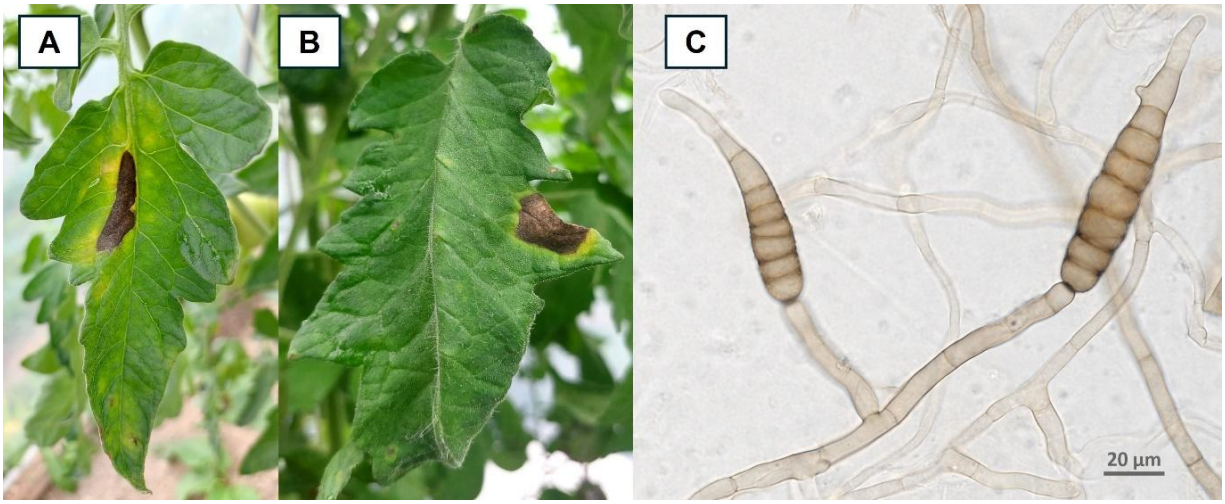
Figure 1
Symptoms of brown spot disease of tomatoes in the Baltic region caused by small-spored Alternaria spp.: dark brown lesions on leaves (A), black, sunken lesions on fruits (B), and chains of conidia of small-spored Alternaria spp. at 200× magnification (C). Scale bar = 50 µm. Photos A and B by L. Dučkena



The occurrence of early blight in Estonia during the survey was 60%, and it was identified in Vedu and Jõgeva in 2023 and 2024. In contrast, the occurrence of early blight in Latvia was 29%, and it was recorded in Bērze and Iecava (2023), followed by Bērze and Daugmale (2024). Moreover, the occurrence of early blight in Lithuania was 20%, and it was recorded in Ringaudai during 2023 and 2024.

Moreover, a complex infection caused by both large-spored and small-spored *Alternaria* species was observed on symptomatic leaves at the end of intensive tomato production in Latvia, Lithuania, and Estonia.

Figure 2
Symptoms of early blight of tomatoes in the Baltic region caused by large-spored Alternaria species comprised within the section Porri: elongated (A) or circular (B) dark brown lesions with typical concentric rings that are surrounded by yellow halos, and conidia of large-spored Alternaria spp. at 400× magnification (C). Scale bar = 20 µm. Photos A and B by L. Dučkena



Previous studies have also confirmed the co-occurrence of large-spored *Alternaria* species (section *Porri*) with small-spored *Alternaria* spp. (sections *Infectoriae* and *Alternaria*) on symptomatic tomatoes and potatoes in different regions of Russia (Kokaeva et al., 2018). Therefore, it is also named as early blight/brown spot disease complex affecting various solanaceous hosts (Vandecasteele et al., 2018).

Tomato diseases caused by fungi from the genus Stemphylium

In the present study, *Stemphylium* spp. were associated with symptomatic leaves of tomatoes in line with previous reports confirming these fungi as important foliar pathogens of tomatoes (Bessadat et al., 2022; González-Ghiena et al., 2025; Torres et al., 2024). *Stemphylium* spp. are also associated with leaf spots on

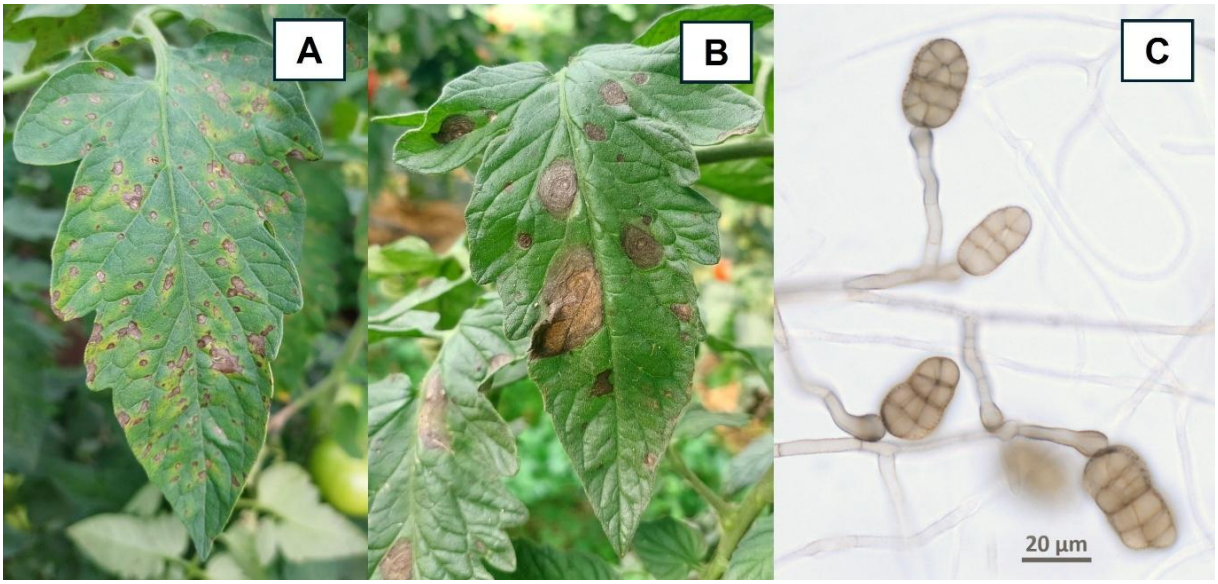
other related hosts from the *Solanaceae* family, for example, potatoes (Yang et al., 2018), pepinos *Solanum muricatum* Aiton (Nasehi et al., 2016), peppers *Capsicum annuum* L. (Sun & Huang, 2022), and wild eggplants *Solanum torvum* Sw. (Xie et al., 2016). Moreover, *Stemphylium* spp. are also infecting tomato fruits causing brown specks but are not affecting tomato stems or petioles (Bessadat et al., 2022). Tomato diseases caused by fungi from the genus *Stemphylium* are most frequently referred to as a grey leaf spot of tomatoes (Franco et al., 2017; Nasehi et al., 2012; Sun et al., 2016).

In the Baltic region, *Stemphylium* spp. were isolated mainly from brown lesions on tomato leaves (Figure 3A). Similar observations have been reported in Algeria by Bessadat et al. (2022), confirming that *Stemphylium* spp. are associated with small, dark brown spots leading to leaf chlorosis, necrosis, and defoliation of tomatoes. Reports from Germany also suggested that small, brown to dark necrotic lesions are associated with *Stemphylium* spp., referring to this disease as brown spot of tomato (Karbowy-Thongbai et al., 2023). Moreover, reports from Taiwan have suggested that tomato diseases caused by these fungal pathogens should be referred to as Stemphylium leaf spot of tomato (Huang & Tsai, 2017).

Disease symptoms caused by *Stemphylium* spp. were observed every year during intensive tomato production (from August to September). In Lithuania, fungal diseases caused by *Stemphylium* spp. were observed in Karkiskes and Babtai, with the occurrence of 40% in 2023 and 60% in 2024. In Latvia, tomato diseases caused by fungi from the genus *Stemphylium* were noted in Bērze and Iecava and their occurrence during 2023 and 2024 was 29%. In Estonia, the occurrence of fungal diseases caused by *Stemphylium* spp. was 40% in 2023, and it was observed in Koimula and Jõgeva, whereas in 2024 the occurrence was 60%, and it was recorded in Vedu, Jõgeva, and Lemmatsi.

Figure 3

Symptoms of brown leaf spot of tomatoes caused by fungi from the genus Stemphylium in the Baltic region: small brown spots with or without yellow halos (A); necrotic lesions with concentric rings representing co-occurrence of Alternaria spp./ Stemphylium spp. (B); and conidia of Stemphylium spp. at 400× magnification (C). Scale bar = 20 µm. Photos A and B by L. Dučkena



Co-occurrence of fungi from the genera Alternaria and Stemphylium

In the current study, both large-spored and small-spored *Alternaria* spp. were characterized by co-occurrence with *Stemphylium* spp. on tomatoes (Figure 3B). Moreover, the complex infection caused by fungi from the genera *Alternaria* and *Stemphylium* was mainly observed at the end of intensive tomato production, i.e., from mid-September to the end of September. The co-occurrence of these fungi was characterized by a mixture of symptoms that are indistinguishable using visual observations alone in line with reports from Bessadat et al. (2022).

Previous studies have confirmed that *Alternaria* spp./*Stemphylium* spp. complex is associated with necrosis and defoliation of tomato plants (Bessadat et al., 2022) along with black, sunken lesions on fruits (Feng et al., 2025). The co-occurrence of *Alternaria* spp. and *Stemphylium* spp. has been recorded in various tomato growing areas, including Australia (Feng et al., 2025), Algeria (Bessadat et al., 2017, 2022), and China (Zhao et al., 2022).

Interestingly, complex infections involving both *Alternaria* spp. and *Stemphylium* spp. have also been reported on other hosts, such as onion *Allium cepa* L. (Abdel-Rahim et al., 2017; Reyes-Tena et al., 2024),

leek *A. ampeloprasum* L. (Suheri & Price, 2001), lettuce *Lactuca sativa* L. (Bessadat et al., 2025), and faba bean *Vicia faba* L. (Bankina et al., 2021).

Conclusions

1. The current study confirms a wide range of fungal pathogens comprised within four subgeneric sections of the genus *Alternaria* and *Stemphylium* spp. as disease causal agents of tomatoes that may vary in their interaction with the host plant, sensitivity to fungicides, and aggressiveness.
2. The co-occurrence of both large-spored and small-spored *Alternaria* spp. with *Stemphylium* spp. on symptomatic tomatoes in the Baltic region highlights the complexity of management of tomato diseases.
3. In further studies, multi-locus phylogenetic analyses are necessary for species identification and subsequent development of tomato disease control strategies.

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THE IMPACT OF THERMOREFLECTIVE SURFACES ON THE OVERWINTERING OF *APIS MELLIFERA CARNICA:* PRELIMINARY STUDY

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Abstract
The Western honeybee (*Apis mellifera*) is an important agricultural pollinator. The ability of honeybee colonies to survive the winter is significantly affected by rapid temperature fluctuations. These sharp changes prevent honeybees from maintaining the essential hive temperature, resulting in high mortality. The thermal conductivity and durability of hive materials are among the factors influencing overwintering success. To assess how hive thermal conductivity affects overwintering, this study evaluated whether shielding hive walls with a thermoreflective surface could maintain stable internal conditions and improve overwintering survival rates. Four control and four shielded hives were continuously monitored (weight, ambient and internal hives temperatures, internal hives CO_2 and RH levels) between 24 September 2024 and 5 March 2025, covering cluster formation and overwintering periods. In autumn, anomalously warm weather triggered wasp attacks on all hives, but sustained attacks only destroyed one control hive. Despite losing one shielded hive to nosemosis in early winter, three shielded colonies successfully overwintered. Conversely, two additional control hives collapsed over winter, leaving only a single weak surviving colony. Data from the sensors confirmed that shielding helped maintain a higher internal temperature during autumn and winter, enabling honeybees to actively defend against wasp attacks and achieve greater overwintering success. These results suggest that shielding hives with a thermoreflective surface can be an effective method for reducing honeybee winter mortality.
Keywords: Carniolan honeybee, aluminium foil, beekeeping, microclimate.

Introduction

The Western honeybee (*Apis mellifera*) is considered an important pollinator due to its efficiency and widespread availability. Bee-assisted pollination influences the productivity and profitability of many crop varieties (Khalifa et al., 2021). In a study of 87 of the world's most utilised food crops, which together account for 35% of total crop production, it was concluded that their ability to produce fruit and seeds depends directly on pollination (Klein et al., 2007). Consequently, a decline in pollinator numbers may negatively impact global agriculture and food trade (Gallai et al., 2009).

Assessing honeybee colony mortality across 5,798 apiaries in 17 European countries revealed that winter colony losses range from 2% to 32% (Jacques et al., 2017). In another study spanning 37 countries worldwide, winter colony losses varied from 7.4% to 36.5%, with average rates reaching 18.1% (Gray et al., 2023).

Individual mortality and colony losses are influenced by various factors and can be categorised into manageable, semi-manageable, and unmanageable. Key manageable factors include beekeeping practices and the use of agricultural pesticides. Among semi-manageable biotic factors are pests and pathogens, such as the varroa mite *Varroa destructor* and the fungus *Nosema ceranae*, whose negative impact on honeybee population density is gradual. Conversely, unmanageable factors include variable climate conditions, which have a starkly negative impact on honeybee colonies (Gregorc, 2020; Hristov et al., 2020; Van Esch et al., 2020). The ability of honeybee colonies to survive the winter is significantly affected by rapid temperature changes (Insolia et al., 2022; Switanek et al., 2017).

Honeybee colonies regulate the air temperature within the hive, cooling it in summer and maintaining warmth inside the honeybee cluster in winter. When the outside temperature falls below 10 °C, honeybees start to form a winter cluster (Meikle et al., 2022; Stabentheiner et al., 2021). However, during sharp ambient temperature fluctuations in winter, honeybees may not be able to adapt quickly and maintain the temperature required for colony survival, thus leading to a rapid loss of a large number of honeybees (Jarimi et al., 2020).

Thermoreflective surfaces are widely used in industrial refrigeration equipment, frozen food transport packaging and construction, where maintaining stable internal temperatures is required regardless of ambient conditions. Given the ability of thermoreflective surfaces to slow down temperature changes or maintain a constant internal temperature, the idea arose to apply thermoreflective surface technology to the inner walls of the hives. It was hypothesised that utilising passive heat reflection could help honeybees better maintain hive temperature despite ambient temperature fluctuations. Thus, by reducing the impact of ambient air temperature fluctuations on honeybee colonies, this strategy would decrease winter honeybee mortality.

Beyond thermoregulation, relative humidity (RH) and internal carbon dioxide (CO_2) levels are important indicators of a honeybee colony's overall health. The optimal RH range for a colony is 50-70% (Amdam & Omholt, 2002; Hou et al., 2016). During the cluster formation period and throughout the winter, honeybees regulate moisture exclusively within the cluster itself. Both extremes in humidity represent risks. Thus, excessively low humidity causes desiccation of the cluster's inner layers, increasing honeybee mortality. Conversely, insufficient ventilation leads to condensation

on the hive walls and within the cluster, creating a cold and damp environment. This increases honeybees' energy demands and facilitates the proliferation of mould and bacteria in unoccupied hive spaces. Consequently, colony health may be compromised, leading to diminished colony size at the onset of spring (Kutby et al., 2024).

Similarly, CO_2 concentrations reflect metabolic activity and the efficacy of ventilation. Maintaining appropriate CO_2 levels is essential for preserving colony health. While CO_2 in well-ventilated areas approximates the ambient atmospheric concentration of 0.04-0.05% (400-500 ppm), intra-hive levels exhibit both diurnal and seasonal variations driven by air exchange rates, population size, and ambient temperatures (Newton et al., 2022). In more enclosed areas of the hive, CO_2 typically exceeds 5,000 ppm (Newton et al., 2024). However, prolonged exposure to substantially high CO_2 levels subjects bees to hypercapnia and hypoxia, which may impair immunity, cause spatial disorientation, and potentially increase mortality rates (Human et al., 2013). Under chronically unfavourable microclimatic conditions, the combined stress and energetic costs of intensified ventilation divert resources away from immune maintenance, leaving the colony highly susceptible to disease (Kovac et al., 2007; Stabentheiner et al., 2010). Because intense ventilation can cool the hive, colonies must carefully balance air exchange with heat conservation (Bujok et al., 2002), intentionally tolerating higher CO_2 levels in the centre of the winter cluster.

Using the above-mentioned sensor-transmitted temperature, RH, and CO_2 level recordings, the aim of this study was to investigate the impact of hive wall shielding with a thermoreflective material on the behaviour of honeybee colonies during cluster formation and overwintering.

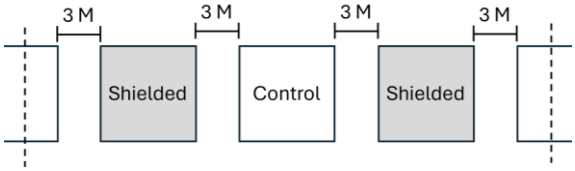
Materials and Methods

Eight Carniolan honeybee colonies *(Apis mellifera carnica)*, each comprising a queen and approximately 3,000 workers, were sourced from Ogre district, Latvia (56°54'21.6''N 24°25'56.3''E). Experiments were conducted in Dreilini, Ropazi municipality, Latvia (56°55'54.2''N 24°15'00.0''E) from 24 September 2024 to 5 March 2025, with weekly visits to assess hive condition and colony behaviour. Eight ten-frame Farrar-style expanded polystyrene (EPS) hives (BeeBox Dadant, Paradise Honey; 170 x 450 x 500 mm, 1.5 kg) were arranged in a single row at 3 m intervals, alternating between control and shielded groups (Figure 1).

To protect hives against environmental factors, the control group was coated with white Bostik Super Colour Epoxy (Bostik, USA), while the shielded group was coated with silver Bostik Super Colour Metallic (Bostik, USA) containing aluminium powder. The hives were left in the open air for seven days to allow the paint to dry. Internal surfaces of the shielded hives (excluding the bottom mesh) were lined with 0.03 mm self-adhesive aluminium tape (Alnor TAPE AL, Poland).

Figure 1

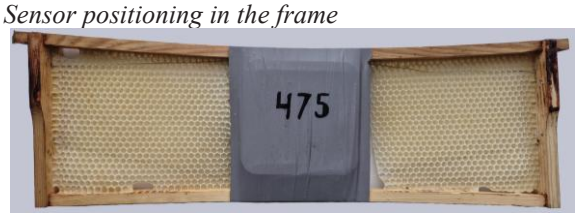
Arrangement of hives during the experiment



Hives were continuously monitored by recording weight, ambient and internal temperatures, internal CO_2 and RH levels. Mass and ambient temperature were recorded hourly via BeeSage (Latvia) smart scales, while an internal sensor (Connected AirWits, Connected Inventions, Finland) monitored CO_2, temperature, and humidity every 30 minutes. All data were transmitted to a cloud server. The sensors were taped to the centre of the comb frame and placed in the centre of the hive (Figure 2).

Figure 2

Sensor positioning in the frame



At the onset of winter, honeybees typically position themselves in the lower or middle part of the hive on empty wax combs, located directly below the line of capped honey. During the winter, as they consume food, the cluster slowly moves vertically upwards and sometimes towards the back. In cold weather, bees rarely move horizontally (from one frame to the next), as crossing the space outside the warming cluster carries the risk of freezing (Mitchell, 2023). To determine the statistically average temperature of the colonies within a single group, the median (central tendency) temperature of each group was measured on an hourly basis. If one of the colonies moved too far from the sensor, its results would minimally affect the group's average temperature.

All recorded data were compiled in LibreOffice 25.2.2 and analysed using RStudio 1.4. Hive internal parameters were expressed as medians, while ambient temperature was characterised by the daily highest (T_{max}) and lowest (T_{min}) temperatures. Group means were compared using one-way ANOVA with standard deviations (SD) only for the cluster formation period. Statistical analysis was not performed for the overwintering period, as only one colony in the control group survived. To evaluate relationships between colony and environmental conditions, Pearson correlation coefficients (r) were calculated for mean

temperature, RH, and CO_2 against ambient T_{max} and T_{min}. This approach was justified by the linear relationship between variables and the normal distribution (Caldwell & Cheuvront, 2019).

Results and Discussion

Observations were categorised into two distinct periods: cluster formation period and overwintering.

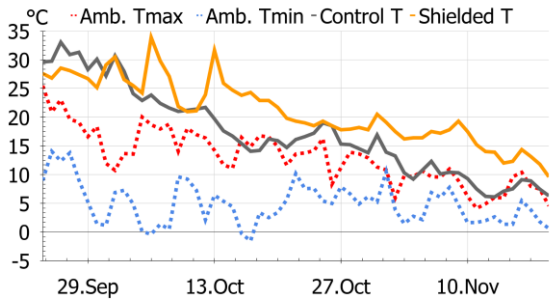
The cluster formation period began on 24 September 2024, following the removal of the honey store and the restriction of the hive. Triggered by T_{max} below 10 °C, honeybees initiated winter cluster formation. The process concluded on 19 November once the hives mean internal temperature reached approximately 10 °C.

In autumn 2024 in Latvia, the seasonal average temperature of 9.6 °C was the third warmest on record, exceeding the climatic norm by 2.5 °C. September was the warmest on record at 16.1 °C (3.8 °C above the norm), with temperatures above the daily average for nearly the entire month. This warming trend persisted through October and November, with temperatures remaining 1.6 °C and 2.0 °C above their respective monthly norms (LVGMC, 2024). The duration of the cluster formation period was extended due to inconsistent daytime temperatures, as periodic warming inhibited the formation of a stable winter cluster. If ambient temperature in the cluster formation period exceeds 10 °C, the cluster becomes diffuse, and honeybee activity increases (Rajagopalan et al., 2024; Stabentheiner et al., 2003).

The mean T_{max} in the apiary was 13.78 ± 4.68 °C, while the T_{min} in this period reached 4.96 ± 3.82 °C (Figure 3). The mean temperatures differed significantly between experimental groups (p = 0.00045). The shielded group maintained a higher temperature (20.93 ± 5.58 °C) compared to the control group (16.61 ± 7.48 °C; p = 0.00045).

Figure 3

T_{max} and T_{min} of the apiary, and T_{mean} of the control and shielded groups (°C) in the cluster formation period



The SD of mean hive temperatures reveals higher fluctuations in the control group than in the shielded group. The ability of honeybees to actively regulate the temperature within the cluster means that temperature fluctuations in the hive, particularly near the cluster, should be smaller than ambient temperature fluctuations. Therefore, a smaller SD in the shielded group suggests better thermoregulation.

Internal and ambient temperatures were strongly, positively correlated in both groups ($p < 0.0001$). For the control group, this correlation held against both T_{max} (r = 0.917, $p < 0.0001$) and T_{min} (r = 0.753, $p < 0.0001$), indicating high susceptibility to ambient temperature fluctuations. This exposure placed a greater load on the honeybee cluster during cold nights, possibly causing oxidative stress, which may impair their immunocompetence and accelerate physiological ageing (Frunze et al., 2024; Kunat-Budzyńska et al., 2025).

Conversely, the shielded group better retained cluster-generated heat and resisted cooling during the coldest periods. This difference is likely due to the foil reflecting thermal radiation generated by the cluster, thus reducing energy loss. However, the strong correlation with T_{min} suggests that the foil's high thermal conductivity did not prevent heat loss on the coldest nights. This implies that foil shielding may be a useful addition but not a replacement for traditional hive insulation aimed at reducing thermal conductivity.

Higher average daily temperatures induced phenological shifts, leading to intensive wasp attacks observed on 13 November 2024. Certain wasp species, most notably *Vespula vulgaris* and *Vespula germanica*, are aggressive predators of honeybee colonies. In autumn, as natural forage becomes scarce, wasps may intensify their search for additional food sources, including honey and bees. While they rarely cause large-scale colony losses, weakened colonies or hives with reduced populations are particularly vulnerable during this period of heightened foraging activity (Beggs et al., 2011).

On average, wasps visited each hive 10 times per minute, primarily attacking honeybees to harvest thoracic muscle tissue for protein. Control hives experienced significantly higher wasp attacks. It is hypothesised that the higher mean internal temperatures in the shielded group maintained the bees in a more active state, enhancing their defensive capabilities against wasp attacks. In contrast, control colonies transitioned into a more compact cluster, potentially reducing their ability to defend themselves against intruders. Notably, one control colony was destroyed within a single day. Consequently, for the overwintering period, the study cohort was reduced to three control and four shielded colonies.

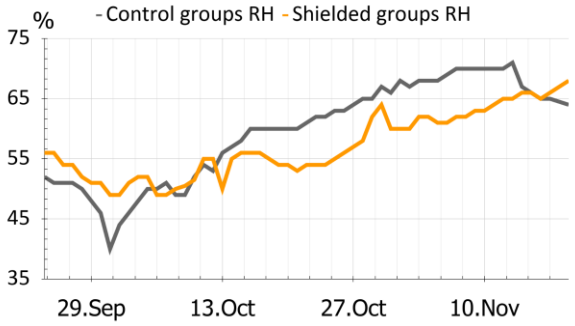
During the cluster formation period, the mean RH of the control group was 72.3 ± 8.5%, which differed significantly (p = 0.004) from that of the shielded group (68.1 ± 10.2%) (Figure 4).

The higher RH variability in shielded hives may stem from the foil's rapid thermal response or altered honeybee ventilation behaviour. In the control group, RH exhibited a significant negative correlation with ambient temperature, particularly T_{min} (r = –0.58). Conversely, this correlation was statistically

insignificant in the shielded group, suggesting that the shielding acts as a moisture buffer against external temperature fluctuations.

Figure 4

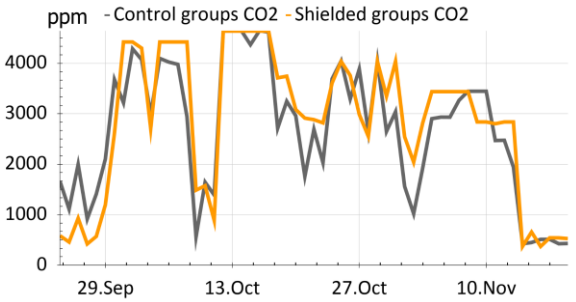
RH fluctuations in the control and shielded groups (%)



No statistically significant differences in CO_2 levels were observed between the control (2853.17 ± 1410.49 ppm) and shielded (2811.38 ± 1448.71 ppm) groups ($p = 0.9108$) (Figure 5).

Figure 5

CO_2 fluctuations in the control and shielded groups (ppm)



In the control group, CO_2 showed a significant negative correlation with T_{max} (r = –0.4136) and T_{min} (r = –0.3180), aligning with expectations that metabolic heat production increases as temperatures drop (Kovac et al., 2007; Meikle et al., 2022). This negative correlation was stronger in the shielded group (T_{max} r = –0.4862; T_{min} r = –0.4280), suggesting that shielding may influence CO_2 retention or metabolic intensity.

The overwintering period began on 20 November 2024 and ended on 5 March 2025, when the ambient temperature reached 10 °C. During this period, mortality occurred in two control colonies and one shielded colony. The only surviving control colony was in a weakened state.

Mortality within the shielded group occurred on 3 January (T_{max} = 0.9 °C and T_{min} = –3.1 °C). Although honeybees remained in a cluster, the presence of dysentery symptoms on the combs suggests a pathological cause, likely *Nosema* infection. Consequently, this loss was likely stochastic rather than a direct consequence of the shielding treatment.

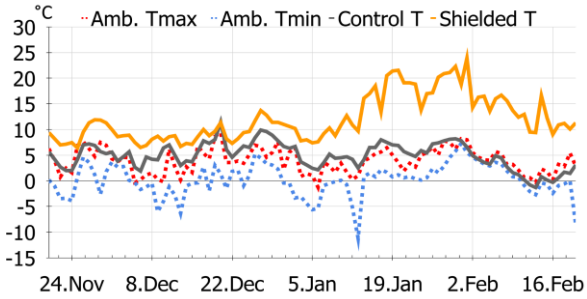
Conversely, the control colony losses occurred during periods of relatively mild ambient temperatures. One colony died on 3 December (T_{max} = 4.6 °C and T_{min} = 2.8 °C). The other colony died on 30 January (T_{max} = 6.2 °C and T_{min} = 5.8 °C). In both cases, the absence of a cohesive cluster and the scattering of dead honeybees across the grid suggest a failure of cluster thermoregulation, leading to colony collapse.

While the survival of only one control colony precluded statistical analysis, continuous monitoring of this colony provided observable trends for a detailed qualitative assessment.

Since interruptions in data transmission occurred from January 21 to March 5 2025, it is not possible to precisely determine temperature differences between the control hive and the shielded group. However, when calculating T_{max} and T_{min} without the missing data, the difference between the control hive and the shielded group was statistically significant ($p < 0.001$). The surviving control hive maintained an average daily temperature of 5.2 ± 2.3 °C, while in the shielded group it averaged 11.9 ± 4.2 °C (Figure 6).

Figure 6

Fluctuations of apiary T_{max} and T_{min}, and T_{mean} of the control hive and shielded group (°C)



The observed mean temperature difference between the groups was 6.7 °C, which was both statistically significant ($p < 0.001$) and biologically significant. Shielding effectively reduced heat losses, which is consistent with the operating principles of aluminium foil as a radiation barrier.

The elevated temperatures (20–25 °C) observed in the shielded hive between 19 January and 2 February (Figure 6) directly demonstrate the effect of the thermoreflective shielding. The shielding enabled the internal ambient temperature to stabilise above 10 °C, a critical threshold that triggered the queen to resume egg-laying. In contrast, the unshielded hive failed to reach this temperature during the same period. Once early brood rearing started, the winter cluster had to maintain a central core temperature of approximately 34.5 °C. The cluster then became stationary to prevent the chilling the brood, even at the risk of starvation (Döke et al., 2015; Minaud et al., 2024; Tautz et al., 2003). Thus, the sustained 20–25 °C readings did not indicate a cluster randomly moving over the sensor, but rather reflected the stable peripheral heat generated by a stationary, brood-rearing cluster that was facilitated by

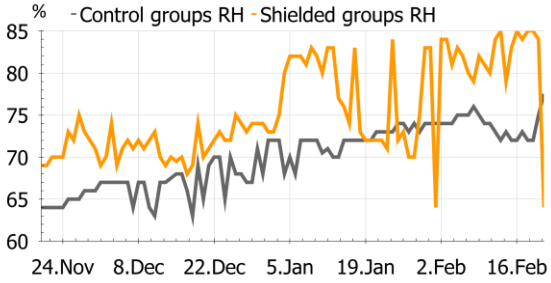
the shielding.

As shown in Figure 6, the control hive's inner temperature closely followed that of the ambient T_{max} and T_{min}, indicating that the control hive was subjected to the influence of external environmental conditions. In contrast, in the shielded group, the correlations with ambient T_{max} ($r = 0.57$) and T_{min} ($r = 0.47$) were moderate, indicating that shielding's insulating effect reduced heat losses and mitigated the external environment's impact on the hive microclimate.

The mean RH in the control hive was 68.60 ± 3.87%, whereas in the shielded group, it was significantly higher ($p < 0.001$), reaching 74.52 ± 4.87% (Figure 7).

Figure 7

RH fluctuations of the control and shielded groups (%) during overwintering



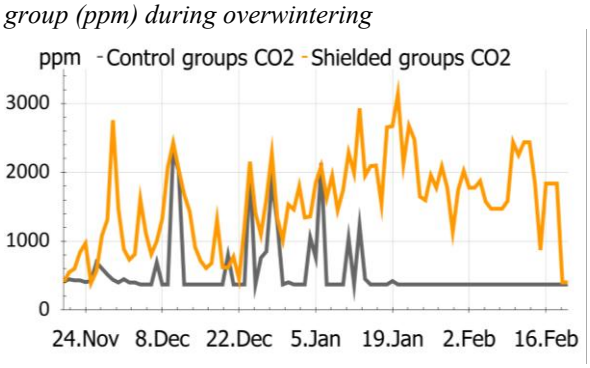
The higher RH in the shielded group may result from the aluminium foil's water-impermeability, which traps metabolic moisture. The correlation between RH and apiary temperatures was negligible (T_{max} $r = 0.034$; T_{min} $r = –0.088$). This independence from external temperature fluctuations suggests that honeybees can actively regulate the microclimate of their hive.

The shielded group exhibited significantly higher CO_2 concentration compared to the control hive ($p < 0.000001$) (Figure 8). Mean levels reached 1517.6 ± 691.2 ppm in the shielded group, whereas the control hive remained at 551.9 ± 512.1 ppm, indicating that shielding substantially elevated internal CO_2 concentrations during overwintering.

In the shielded group, CO_2 levels exhibited significant weak negative correlations with both T_{max} ($r = –0.221$, $p = 0.032414$) and T_{min} ($r = –0.370$, $p = 0.000288$). This inverse relationship suggests that the foil barrier not only passively increased CO_2 levels but also modulated the colony's dynamic respiratory response to external thermal fluctuations. As the ambient temperature decreased, the widening temperature gradient accelerated heat loss. To compensate, honeybees increased honey consumption, accelerated metabolism, and formed a tighter cluster, inherently elevating CO_2 production.

Figure 8

CO_2 fluctuations of the control hive and shielded group (ppm) during overwintering



The foil barrier likely suppressed convection and retained the metabolic heat and CO_2 more efficiently than in the control hive. Consequently, the shielded group showed a more pronounced increase in CO_2 as the external temperature decreased, indicating that shielding enhanced thermal stability and significantly improved overwintering survival rates.

Conclusions

1. Thermoreflective shielding is an effective method for enhanced colony viability amid changing climatic conditions. By mitigating overwintering stress, shielding resulted in a markedly lower mortality rate.
2. During the cluster formation period, shielding ensured more uniform cooling within the hive. This gradual transition to the overwintering regimen extended the period for late-season brood development and food storage, while also enabling the colonies to defend more effectively against autumn wasp attacks.
3. During the overwintering, shielding substantially reduced heat loss, maintaining cluster temperatures an average of 6.7 °C higher than the control hive. This thermal stability lowered the metabolic demands of thermogenesis, thereby reducing food consumption and mitigating the risk of late-winter starvation.
4. In addition to heat retention, the shielding protected winter clusters from premature activation during brief thaws, which could lead to higher mortality when frosts return. Shielding also improved moisture control by minimising internal condensation.
5. Because the high mortality rate within the control group precluded comprehensive statistical analysis, the current findings primarily represent strong observational trends. To robustly validate observed outcomes and definitively attribute them to the thermoreflective surfaces, future studies must incorporate larger sample sizes, requiring at least six hives per experimental group.

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COMPARISON OF CALCULATED AND ON-FARM MEASURED METHANE EMISSIONS IN A DAIRY HERD FOR SUSTAINABLE MANAGEMENT

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Abstract
Methane (CH_4) is a significant greenhouse gas emitted by livestock. The study aimed to investigate compliance or differences between calculated and measured CH_4 emissions on a high-productivity 900-head Holstein Friesian (HF) cow farm. Data from two feeding programs (NorFor and AMTS Pro) and on-farm CH_4 measurements using the Methane Detector-Transmitter E2608-CH_4 (Evikon, Estonia) were used. The feed program NorFor predicted a CH_4 output of 652 g per cow^{-day}. However, with AMTS Pro, the amount was determined to be 828 g per cow^{-day} ($p < 0.05$). The measured on-farm CH_4 values were 810.5±229.81 g^{-day}, and they ranged from 648 to 973 g^{-day} per cow ($p<0.05$). Feeding programs and generally accepted calculation methods assume that an HF cow weighs around 600 kg, but on our farm, there was a wider range of live weights of cows (up to 1100 kg). On-farm measurements could also depend on parameters, such as the cow's lung volume and respiratory rate, which can vary with ambient temperature and humidity. In conclusion, because the calculated values span a wide range based on theoretical parameters, measuring CH_4 concentration at specific times using sensors provides greater accuracy. Furthermore, this method enables the real-time monitoring and reduction of CH_4 emissions through targeted management and feeding adjustments. Consequently, sharing these empirically verified results demonstrates a commitment to transparency, which is a key element of credible sustainability communication with stakeholders and the public.
Keywords: enteric methane, GHG, dairy cattle, precision livestock farming, sustainability communication.

Introduction

Livestock agriculture is one of the major sources of greenhouse gas (GHG) emissions, with enteric fermentation accounting for nearly 90% of CH_4 emissions. Given its high global warming potential, accurate quantification of CH4 is essential for effective climate change mitigation strategies (Ghassemi Nejad et al., 2024). Methane is a significant contributor to the greenhouse effect and global warming and has been a hot topic in recent decades, especially in the livestock sector (Our World in Data, 2026). The Greenhouse Gas Protocol was developed by the World Business Council for Sustainable Development, in collaboration with the World Resources Institute (The Greenhouse Gas Protocol, 2004). It includes two important related standards: The Emissions Protocol Corporate Accounting and Reporting Standard, which provides companies with guidance on measuring greenhouse gas (GHG), and the Emissions Protocol Project Quantification Standard. Based on these frameworks, GHG calculation methods are widely accepted in many agricultural sectors, including livestock (Greenhouse Gas Protocol, 2026).

In general, CH_4 estimation approaches fall into three main categories: direct measurement techniques at the facility level, indirect inventory-based models using emission factors, and remote sensing methods for large-scale detection (Ghassemi Nejad et al., 2024). The Intergovernmental Panel on Climate Change (IPCC) defines three methodological tiers for national GHG reporting, with the highest tier relying on direct measurements to develop country-specific emission factors and requiring robust verification systems (IPCC, 2019). This also highlights the need for locally measurement-supported emission factors to improve national CH_4 inventories and support effective emission-reduction measures that are essential for meeting UNFCCC (United Nations Framework Convention on Climate Change), Kyoto Protocol, and EU climate and air quality targets (Amon et al., 2021). The desire to maintain a positive reputation and navigate social pressures can inadvertently lead to biased sustainability reporting (Steiner et al., 2018). Understanding and accurately communicating the true environmental impact of dairy production is an essential prerequisite for sustainable livestock management and transparent sustainability reporting.

Until now, in practical livestock farming, direct emission measurements have not been widely carried out. Emissions have typically been measured using specialized equipment in scientific studies (Tedeschi et al., 2022). However, invasive measurement techniques are often not feasible in practical farming due to welfare standards. Since GHG emissions depend on well-known individual factors, there is a lack of precise data on how closely the calculated values reflect each farm's specific situation. Moreover, there are currently no tools for herd owners to monitor or influence their animals' emissions. Consequently, farmers lack practical, data-driven ways to reduce emissions and transparently report their progress. Without direct monitoring, there is no way to track emissions dynamics or understand the correlations with specific management factors that the owner can influence. Bridging this data gap provides a robust evidence base for effective stakeholder management and authentic sustainability communication. By aligning theoretical calculations with real-time measurements, farmers can provide transparent, credible data for reporting, thereby mitigating the risks of social desirability bias and fostering long-term trust with stakeholders. This data gap is particularly critical in the context of the UN Sustainable Development Goals and has become a key benchmark for practical

action by governments, NGOs (Non-governmental organisations), and entrepreneurship (including farmers). Sustainability is normatively defined not only by environmental protection and responsibility toward future generations, but also through active participation, characterized by specific, measurable actions and transparent communication (Weder et al., 2019).

Future work should focus on strengthening country-specific data collection and refining emission models through comparative studies that integrate measured data (Besson et al., 2026). Because mitigation effectiveness varies by region and production system, accurate, locally calibrated emission factors and a deeper understanding of how inventories influence policy decisions are essential for reliable climate planning and achieving meaningful agricultural GHG reductions (Nugrahaeningtyas et al., 2024). Effective livestock CH_4 mitigation relies on accurate measurement technologies, robust data systems, and system-wide changes across the agri-food chain (Bretscher et al., 2025). Therefore, this study aimed to compare the measured and predicted CH_4 amounts from feeding programs on a high-producing dairy farm. To achieve the goal, two feeding programs and practical measurements were carried out to process statistical data for comparison and to assess their correspondence. This is necessary to obtain data for future research that would allow us to understand how the amount of CH4 emitted on a dairy farm can be monitored and influenced. Demonstrating a proactive commitment to continuous environmental improvement is a foundational element of credible sustainability communication with stakeholders (Bittner-Fasseler & Weicht, 2020). The methodology and format used to present emission data are as vital as the content itself, directly influencing how stakeholders perceive the value of emission-reduction efforts, which ultimately fosters sustainable progress (Liu et al., 2025).

Materials and Methods

The study was conducted in a high-producing HF dairy herd of more than 900 animals during the summer of 2025. The annual milk yield in the previous year was more than 14,000 kg per cow. A freshly prepared, total mixed ration (Table 1) was distributed once a day and replenished to the cows three times a day. To ensure maximum even feed intake and cows' interest in feed, feed is pushed closer to the cows once an hour. The animals included in this study received identical feed composition.

The farm manager records the amount of feed distributed and the surplus remaining in each cow group (about 500 kg^{-day}). Drinking water was provided *ad libitum* in collective automatic drinkers. Due to high productivity, cows are milked three times a day in a rotary milking carousel (PR3100HD DeLaval, DelPro system, Sweden).

Feces and urine were removed from cow groups three times a day while the cows were being moved to the milking waiting area before the milking carousel (PR3100HD, DeLaval, Sweden). The farm uses sand bedding, which is changed once a week. To ensure better air quality and an optimal indoor temperature, the forced ventilation system is automatically set to 14 °C during the summer. An automatic water-spraying system is set to activate at 22 °C. Cows are given hoof care twice a year.

Table 1

Feed composition in the study period

No	Parameter	Amount in May
1.	Dry Matter Intake predicted per cow (kg^{-day})	27.22
2.	Dry Matter (%)	44.92
3.	Forage (%DM)	52.01
4.	Crude Protein (%)	17.33
5.	Starch (%DM)	25.07
6.	Sugar (%DM)	5.29
7.	Neutral detergent Fibre (%DM)	27.32
8.	Acid Detergent Fibre (%DM)	17.49
9.	Nonfibrous carbohydrates (%DM)	43.09
10.	Energy-corrected milk (kg^{-day})	51.81
11.	Predicted Milk Production (kg^{-day})	47.55
12.	Rumen pH predicted	27.22

This research was conducted on cows before the dry period and 120 days after calving. Measurements were taken on 21 multi-lactations and 45 first-lactation cows. The cows varied in their days in milk. CH_4 and CO_2 measurements were taken during the hoof trimming process, which lasted 6-10 minutes depending on the particular cow's hoof length and health status.

Calibrated Detector-Transmitters E2608-CO2-10K and E2608-CH4 were used to measure CO_2 and CH_4 concentration in cows' breath/burp. CO_2 was measured for CH4 calculation reasons. Sensors were set up and calibrated in accordance with ISO 9001:2015 quality management system requirements. Data were collected every 5 seconds. The CH_4 (and parallel CO_2) measurements were taken once a month in June, July and August. An average CH_4 data value was used because feeding programs predicted the same value each month. This was done one week to 10 days after the feed recipe was changed due to farm conditions. Feed changes were insignificant given the same dry matter intake and energy capacity.

Two feeding programs (NorFor and AMTS Pro) were used to calculate potential CH_4 production from one cow^{-day}.

The CH4 output from cows was calculated using data on CO2 and CH4 obtained (Madsen et al., 2010). The formula (1) was:

$$\text{CH4 output}\left(\frac{\text{L}}{\text{day}}\right) = a \times \frac{b-d}{c-e} \qquad (1)$$

In which: a means the CO2 exhaled by the cow (L^{-day}); b is the concentration of CH4 in the gas mix exhaled (ppm); c is the concentration of CO2 in the ambient air mix (ppm); d is the concentration of CH4 in the barn air (ppm); e is the concentration of CO2 in the barn air (ppm).

To calculate CH_4 L to grams, CH_4 volume was converted to mass using the fact about a density of 0.68 g L^{-1} at standard conditions (15 °C, 101.325 kPa) and the molar mass of CH_4 (16.04 g/mol). For example, 500 $L^{-day} \rightarrow 500 \times 0.68 = 340 g/day$. A similar approach was done by Bell et al. (2014). A data logger was used to collect and store the data obtained. Data was transferred from a flash drive to a computer. The software *FieldLoggerConfig* was used to take data from the flash drive. CH_4 concentrations in the exhaled breath/burp were recorded in LEL% (Lower Explosive Limit) and transformed to ppm (particles per million). The LEL is considered the minimum concentration of flammable gas or vapour in air that can cause a sudden appearance of flame. On a 0–100% scale, 100% LEL is the threshold at which a gas mixture becomes flammable, and for CH_4, the LEL in air is 5% by volume. It is a crucial safety measure to prevent or avoid explosions. Subsequently: - 100% LEL = 5% vol CH_4 = 50,000 ppm; - 10% LEL = 0.5% vol = 5,000 ppm; - 1% LEL = 0.05% vol = 500 ppm. And because of this, the formula (2) is:

$$ppm = \%\ LEL\ x\ 500, \qquad (2)$$

where *ppm* – particles per million; *LEL* - Lower Explosive Limit.

To estimate CH_4 emissions (L day^{-1} cow^{-1}), the previously used formula (Madsen et al., 2010) has been adopted by other researchers (Negussie et al., 2017). Microsoft Excel and IBM SPSS Statistics 21 were used for statistical analysis (Arhipova et al., 2006). Because the main CH4 is produced in the rumen and expelled by burping, it is acceptable to compare calculated values from programs with measured CH4 values (Bačėninaitė et al., 2022).

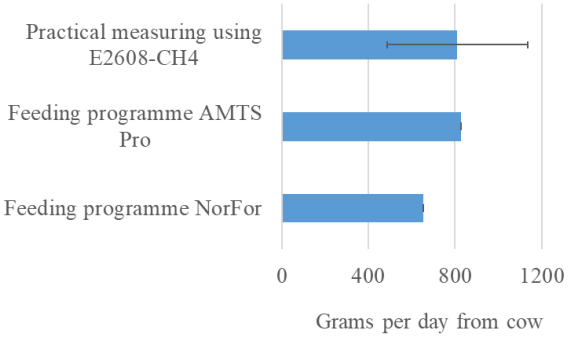
An average, standard deviation, bivariate correlation (body weight and CH_4 amount) and the One-sample t-test were used to compare feeding program results with practical measurement data. A statistically significant difference was recognized if the *p*-value was less than *0.05*.

Results and Discussion

The measured on-farm CH_4 values were 810.5±229.81 g^{-day} and ranged from 648 to 973 g^{-day} per cow ($p<0.05$), indicating considerable individual variation. An individual cow's CH4 emission was also noticed by other scientists (Bell et al., 2014). Based on the current feed recipe, the feed program NorFor predicted a CH_4 output of 652 g per cow per day, which was statistically significantly lower than the CH_4 output measured in practical measurements using sensors ($p<0.05$). In contrast, with AMTS Pro, the amount was determined to be 828 g per cow per day, which was statistically higher than the results obtained with the NorFor feeding program and practical measurements ($p<0.05$; Figure 1). Calculated values were similar in all three months for the AMTS Pro feeding programme. So, the NorFor calculation was conducted just in May. It would be advisable to monitor CH4 levels on farms to gauge a specific company's sustainability performance.

Generally, feeding programs and accepted calculation methods assume that an HF cow weighs around 600 kg, but on our farm, there was a wider range of live weights (640 kg, up to 1100 kg). Cow bodyweight did not correlate with CH_4 output nor rumination time ($p>0.05$). The same result was obtained by other scientists (Bell et al., 2014). On-farm measurements also could depend on parameters, such as the cow's lung volume and respiratory rate, which can vary with ambient temperature and humidity (Gallivan et al., 1989).

Figure 1
Methane emissions per cow



These criteria regarding pulmonary capacity were investigated quite some time ago; in contrast, CH4 production was reported not to correlate with cow body weight (Oikawa et al., 2025). The amount of GHG emitted by cows depends on the composition and amount of feed consumed; relying solely on standard calculations based on the same feed highlights the wide generalisation of these models and does not allow for the timely identification and breeding of animals that emit less GHG.

The data suggests a need to re-evaluate internal corporate actions and processes for implementing and communicating sustainability. This shift is essential to overcome specific barriers hindering local-level sustainability. Furthermore, despite a generally positive disposition towards sustainability, enterprises frequently fail to allocate sufficient time and energy to translate internal intent into measurable actions (Serttas et al., 2022). This highlights two primary challenges. First, for farmers and SMEs (small and medium-sized enterprises), it is a struggle to translate gathered data into actionable insights, indicating a need for effective sustainability communication tools and perhaps an external 'translator'; secondly, farmers' (and SMEs') sustainability strategies are

strongly linked to implicit attitudes (Steiner et al., 2018; Aliyev, 2025).

Conclusions

1. The incomparability is proven if data are obtained using different feeding programs to calculate CH_4 emitted by cows, as well as by in vivo measurement.
2. Since different amounts of CH_4 emissions were found in cows with the same diet, further research is needed on the influence of individual factors.
3. Different live weights of cows are not a significant factor in the amount of CH_4 emitted from cows. Perhaps the answer should be sought within the physiological limits of CH4 release, such as genetic factors.
4. On-farm monitoring would allow tracking individual emission dynamics and accounting for specific herd circumstances, whereas standard calculation methods offer only generalised predictions. The precision of this data is vital for stakeholder transparency, as the accuracy of environmental reporting is just as important as the content for fostering sustainable progress and maintaining robust sustainability communication.
5. The findings indicate a deficiency in understanding how to apply emission data to the decision-making and communication processes, reinforcing the need for small enterprises to bridge the gap between internal sustainability intent and measurable action.

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MANAGING BIOMASS YIELD AND ENERGY POTENTIAL OF SWITCHGRASS UNDER DIFFERENT SOWING CONDITIONS

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Abstract
The formation of biomass in perennial energy crops requires optimization of agronomic practices to ensure high productivity and efficient use of agricultural land for bioenergy purposes. Switchgrass (*Panicum virgatum* L.) is considered a promising lignocellulosic energy crop; however, its biomass yield and energy potential largely depend on cultivation conditions, particularly during the establishment phase. The aim of this study was to assess the effect of sowing date and seed burial depth on biomass yield and energy potential of switchgrass in the Forest-Steppe zone. Field experiments were conducted using different sowing dates and seed burial depth variants. Biomass yield and energy output per unit area were evaluated based on the obtained experimental data. The results showed that early sowing combined with a seed burial depth of 1.0–1.5 cm ensured the highest biomass yield. The maximum average biomass yield reached 11.9 t ha^{-1}, which corresponded to the highest solid biofuel yield and energy output of 386.83 GJ ha^{-1}. A gradual increase in biomass productivity was observed from the first to the third year of vegetation, confirming the biological characteristics of switchgrass as a perennial crop. The findings demonstrate that optimization of agronomic parameters is an effective tool for managing the biomass yield potential of switchgrass and increasing the energy potential of agricultural land used for bioenergy production.
Keywords: agronomic management, bioenergy crops, biomass productivity, planting depth, bioenergy.

Introduction

The growing demand for renewable energy sources stimulates the search for sustainable biomass resources capable of providing stable energy supply. The implementation of energy-efficient technologies and renewable energy systems is also consistent with the principles of the European Green Deal aimed at sustainable industrial and agricultural development (Hutsol, 2023). Lignocellulosic energy crops are considered one of the most promising feedstocks for solid biofuel production due to their high productivity, environmental benefits, and ability to grow on marginal lands (McLaughlin & Kszos, 2005; Wright & Turhollow, 2010).

Among such crops, switchgrass (*Panicum virgatum* L.) occupies a leading position as a perennial C4 grass with high biomass productivity, broad ecological adaptability, and relatively low cultivation costs (Moser & Vogel, 1995; McLaughlin & Kszos, 2005; Mitchell et al., 2008; Parrish & Fike, 2009). Switchgrass has been widely studied as a bioenergy crop due to its ability to produce large amounts of lignocellulosic biomass suitable for biofuel production systems (Vogel et al., 2011). Long-term field studies demonstrate the stability of switchgrass biomass yield and its suitability for large-scale bioenergy production (Fike et al., 2006).

The productivity of switchgrass largely depends on agronomic management practices, including fertilization, planting density, harvesting regimes, and stand age (Monti et al., 2008; Muir et al., 2001; Wolf & Fiske, 2009). Proper management of these factors makes it possible not only to increase biomass yield but also to improve the structural characteristics of plant material important for subsequent conversion processes (Frank et al., 2004; Sharma et al., 2022).

From an engineering perspective, the quality and energy potential of biomass are determined not only during post-harvest processing but also at the stage of crop cultivation. Agronomic parameters influencing plant development can significantly affect biomass accumulation and its technological characteristics during further processing (Flint et al., 2021; Mosier et al., 2024).

In addition, the development of sustainable bioenergy systems requires the integration of agronomic management with broader bioeconomy strategies and renewable energy development frameworks (Kucher et al., 2024). In this context, energy crops such as switchgrass, miscanthus, and energy willow are considered important components of future biomass supply chains (Nedilska et al., 2023; Yermakov et al., 2023a, 2023b).

Despite the considerable number of studies devoted to the productivity of energy crops, the issue of effective management of biomass yield potential under different agronomic conditions remains relevant. Therefore, the aim of this study was to evaluate the influence of selected agronomic practices on the biomass yield potential of switchgrass (*Panicum virgatum* L.) as an energy crop.

Materials and Methods

Experimental site and conditions

Field experiments were conducted during 2022–2024 at the experimental fields of Higher educational institution 'Podillia State University' located in the Western Forest-Steppe of Ukraine. The region is characterized by a moderately continental climate with warm summers and relatively mild winters.

The soil of the experimental site was typical chernozem with medium loamy texture. Before establishing the experiment, soil samples were analyzed to determine the main agrochemical properties, including humus content, available nitrogen, phosphorus, and potassium. The soil

of the experimental field was deep low-humus heavy loam chernozem formed on loess-like loams. The main agrochemical properties of the soil layer (0–30 cm) were as follows: humus content 4.34 %, soil pH 6.8, easily hydrolyzed nitrogen 124 mg kg^{-1}, available phosphorus 86 mg kg^{-1}, and exchangeable potassium 167 mg kg^{-1}. Such soil characteristics are generally considered suitable for the cultivation of perennial energy crops, including switchgrass (*Panicum virgatum* L.).

Figure 1
Switchgrass for the growing season



The vegetation period of the crop was determined as the interval between the dates when the average daily air temperature exceeded 5 °C in spring and dropped below this threshold in autumn. The thermal regime during the study years was characterized by the sum of active temperatures, which reflects the total heat available for plant growth.

During the research period, weather conditions differed between years. In April 2022, the average air temperature was 8.6 °C, which was relatively low for rapid seed germination. In contrast, April 2023 was significantly warmer, with an average temperature of 14.5 °C, which created more favorable conditions for crop establishment. In April 2024, the average temperature was 10.2 °C.

The temperature conditions in May also differed between years. In 2022, the average temperature was 14.0 °C, which contributed to satisfactory seed germination. In 2023, the temperature reached 17.9 °C, which was the highest during the study period, whereas in 2024, it was 15.2 °C. The long-term average sum of active temperatures above 5 °C in the region is about 2990 °C and above 10 °C about 2660 °C.

Precipitation during the study years also varied considerably. In 2022, the amount of precipitation in April was 35.5 mm and decreased to 26.7 mm in May. The lowest precipitation was observed in April 2023 (16 mm), while in May of the same year, it exceeded 31 mm. The total annual precipitation that year reached 564 mm. In 2024, the amount of precipitation in April was 52 mm, while in May it reached 100 mm, which had a significant effect on the formation of switchgrass biomass productivity.

Experimental design

The field experiment was designed to evaluate the influence of selected agronomic practices on the biomass productivity of switchgrass.

The following experimental factors were studied:

Factor A – sowing time:

1. early sowing - third decade of April;
2. optimal sowing - first decade of May;
3. late sowing - second decade of May.

Factor B – seed burial depth:

1. 0.5–1.0 cm;
2. 1.0–1.5 cm;
3. 1.5–2.0 cm.

The experiment was established using a sequential arrangement of treatments with three replications. The total experimental area consisted of multiple plots where each treatment combination was represented in each replication.

The experimental design allowed assessment of both the individual and combined effects of sowing time and seed placement depth on the growth and productivity of switchgrass.

Agronomic management practices during the experiment corresponded to the generally accepted cultivation technologies for perennial energy crops. Before sowing, the experimental plots were prepared using conventional soil preparation practices to create a suitable seedbed for small seeds.

Sowing was carried out according to the experimental design during the first, second, and third ten-day periods of April depending on the treatment. Seeds of switchgrass were sown manually within the research plots. The seeding rate was 6 kg ha^{-1} of viable seeds. During the establishment period, crop management included manual weed control and maintenance of optimal soil moisture conditions through periodic irrigation when necessary.

Biomass harvesting was carried out at the end of the growing season (Nadykto et al., 2023). Plants were cut manually close to the soil surface within the accounting area of each experimental plot. The accounting area was 6 m^2. The harvested biomass from each plot was weighed to determine yield per unit area.

Measurements and observations

Observations and measurements during the growing seasons included plant development stages, stand density, and biomass accumulation.

Biomass yield was determined at the end of the vegetation period by harvesting plants from the accounting plots followed by weighing and recalculation per hectare. Dry matter content was determined using standard drying procedures.

Field experiments and biometric measurements were conducted according to the generally accepted methodologies for agronomic and biological studies (Hrytsaienko et al., 2003; Volkodav, 2000).

Calculation of biomass and energy yield

The potential yield of solid biofuel from switchgrass biomass was determined using a calculation approach based on biomass productivity and fuel characteristics.

The yield of solid biofuel was determined using the following Equation 1:

$$T = U \cdot c \cdot (1 - w) \quad (1)$$

where:
T – yield of solid biofuel, t ha⁻¹;
U – biomass yield, t ha⁻¹;
c – dry matter content coefficient;
w – fuel moisture content.

Such approaches are commonly used for evaluating the energy potential of biomass crops and estimating their suitability for bioenergy production systems (Vogel et al., 2011).

Statistical analysis

Experimental data were processed using standard statistical methods applied in agronomic research. The significance of treatment effects was evaluated using analysis of variance (ANOVA).

Statistical processing of experimental results was carried out following the methodological recommendations for agricultural experiments (Hrytsaienko et al., 2003; Volkodav, 2000).

Results and Discussion

Weather conditions during the experimental years differed in temperature and precipitation, which influenced biomass formation in different years.

During the three-year experimental period, switchgrass biomass yield was evaluated depending on sowing date and seed burial depth.

Overall, the highest average biomass yield among the studied variants was obtained for the first sowing date with a seed burial depth of 1.0–1.5 cm, reaching 11.9 t ha⁻¹. Slightly lower yields were recorded when the seed burial depth was 1.5–2.0 cm (11.6 t ha⁻¹). When the seed burial depth was reduced to 0.5–1.0 cm, biomass yield reached 11.3 t ha⁻¹. According to the LSD05 values, the influence of sowing date and seed burial depth on biomass yield was statistically significant.

Table 1

*Biomass yield of switchgrass depending on sowing date and seed burial depth**

Sowing time	Burial depth, cm	1st year	2nd year	3rd year	Average yield, t ha⁻¹
I	0.5-1.0	6.4	12.1	15.4	11.3
	1.0-1.5	6.9	12.6	16.1	11.9
	1.5-2.0	6.6	12.4	15.8	11.6
II	0.5-1.0	6.1	11.2	14.8	10.7
	1.0-1.5	6.5	11.8	15.3	11.2
	1.5-2.0	6.3	11.5	15.1	10.9
III	0.5-1.0	5.8	10.2	14.4	10.1
	1.0-1.5	6.3	10.6	15.0	10.6
	1.5-2.0	6.0	10.4	14.7	10.3
	LSD05 A 0.1 B 0.13 AB 0.12				

*Differences exceeding LSD05 values were considered statistically significant.

The biomass yield obtained during the second sowing period was generally lower than that of the first sowing period. The highest yield in this group was observed at a burial depth of 1.0–1.5 cm, where biomass production reached 11.2 t ha⁻¹. Other variants of seed burial depth produced slightly lower yields: 10.9 t ha⁻¹ at 1.5–2.0 cm and 10.7 t ha⁻¹ at 0.5–1.0 cm.

The third sowing date produced the lowest biomass yield among the analyzed variants. In this case, the yield reached 10.6 t ha⁻¹ at a seed burial depth of 1.0–1.5 cm, 10.3 t ha⁻¹ at 1.5–2.0 cm, and 10.1 t ha⁻¹ at a depth of 0.5–1.0 cm.

The obtained differences between the studied variants exceeded the LSD05 values, confirming their statistical significance.

The total biomass yield for the entire experimental period was highest for the first sowing date and ranged from 33.9 to 35.6 t ha⁻¹ depending on seed burial depth. The highest value was obtained at a depth of 1.0–1.5 cm. The second sowing date produced slightly lower yields, with a maximum value of 33.6 t ha⁻¹. The lowest yields were observed for the third sowing date, where the maximum value reached 31.9 t ha⁻¹.

Because switchgrass is a perennial crop, vegetation resumed in subsequent years, and biomass yield increased annually as the plants became better established. The highest yield values were observed in 2024, which corresponded to the third year of crop growth.

The highest yield in 2024 (16.1 t ha⁻¹) was obtained for the first sowing date at a seed burial depth of 1.0–1.5 cm. Slightly lower yields were observed at depths of 1.5–2.0 cm (15.8 t ha⁻¹) and 0.5–1.0 cm (15.4 t ha⁻¹).

The second sowing date produced somewhat lower yields. The highest value was 15.3 t ha⁻¹ at a burial depth of 1.0–1.5 cm. At depths of 1.5–2.0 cm and 0.5–1.0 cm, biomass yield reached 15.1 and 14.8 t ha⁻¹, respectively.

The third sowing date in 2024 showed the lowest yield values among the studied sowing periods. The highest yield was 15.0 t ha⁻¹ at a burial depth of 1.0–1.5 cm, while the other variants produced 14.7 and 14.4 t ha⁻¹, respectively.

The final indicator characterizing the efficiency of switchgrass cultivation is the yield of solid biofuel and the corresponding energy output. Based on biomass productivity data, the yield of solid biofuel and energy was calculated (Table 2). The dry matter content of switchgrass biomass was determined experimentally using the gravimetric method and averaged 52%.

The highest solid biofuel yield (20.91 t ha⁻¹) and energy output (386.83 GJ ha⁻¹) were obtained for the first sowing date at a seed burial depth of 1.0–1.5 cm.

The results of the study demonstrated that sowing date and seed burial depth significantly influence the formation of switchgrass biomass and its suitability for further energy use. Early sowing created more favorable conditions for plant establishment, which contributed to higher biomass productivity and more uniform plant structure.

The optimal seed burial depth was 1.0–1.5 cm, which ensured favorable conditions for seed germination and early plant development. Both deeper and shallower seed placement resulted in lower plant density and reduced biomass yield and energy potential per unit area.

Table 2

*Switchgrass biomass yield and calculated solid biofuel and energy output depending on sowing date and seed burial depth (total for 2022–2024)**

Sowing time	Burial depth, cm	Total biomass yield, t ha^{-1}	Solid biofuel yield, t ha^{-1}	Energy yield, GJ ha^{-1}
I	0.5-1.0	33.9	19.91	368.33
	1.0-1.5	35.6	20.91	386.83
	1.5-2.0	34.8	20.44	378.14
II	0.5-1.0	32.1	18.86	348.91
	1.0-1.5	33.6	19.74	365.19
	1.5-2.0	32.9	19.33	357.60
III	0.5-1.0	30.4	17.86	330.41
	1.0-1.5	31.9	18.74	346.69
	1.5-2.0	31.1	18.27	337.99

*LSD05 values are presented to indicate statistically significant differences between treatments at $p \leq 0.05$.

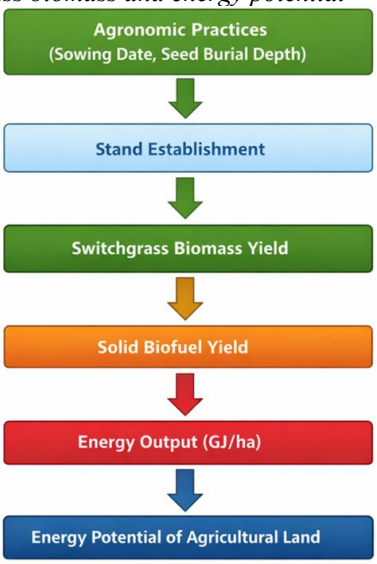
The obtained results demonstrate that agronomic practices play a key role in the formation of switchgrass biomass productivity and, consequently, in the energy potential of cultivated areas. Similar observations were reported by Parrish & Fike (2005), who emphasized that successful establishment during the early stages of switchgrass development is one of the key factors determining long-term biomass productivity. Mitchell et al. (2008) also noted that agronomic management practices significantly influence the stability and productivity of switchgrass biomass production systems. The relationship between agronomic management practices, biomass formation, and energy yield is conceptually presented in Figure 2. The conceptual scheme presented in Figure 2 illustrates the sequence of processes linking agronomic management practices with the formation of biomass yield and the resulting energy potential of switchgrass cultivation.

Agronomic factors such as sowing date and seed burial depth significantly influenced switchgrass establishment and biomass productivity in the present study. Similar observations were reported by Parrish & Fike (2005), who emphasized the importance of successful crop establishment for long-term biomass formation in switchgrass cultivation systems. Mitchell et al. (2008) also noted that agronomic management practices play an important role in maintaining stable biomass productivity of perennial bioenergy crops. In the present study, optimization of sowing parameters contributed to increased biomass yield and energy output per unit area.

Early sowing allows plants to utilize soil moisture accumulated during the winter period and ensures more favorable temperature conditions for seed germination and early plant development. Similar conclusions were reported by Parrish & Fike (2005), who noted that the successful establishment of switchgrass crops largely depends on sowing conditions during the initial growth stages.

Figure 2

Conceptual scheme of agronomic management of switchgrass biomass and energy potential



The results obtained in this study also demonstrate that inappropriate seed burial depth may negatively affect plant emergence and stand density. Seeds placed too shallow may suffer from insufficient soil moisture, while deeper placement may delay germination and reduce plant emergence. The optimal burial depth of 1.0–1.5 cm observed in this research corresponds with recommendations reported in previous studies on switchgrass cultivation (Mitchell et al., 2008).

The gradual increase in biomass yield during the second and third years of vegetation observed in the experiment is consistent with the biological characteristics of switchgrass as a perennial energy crop. Several studies have demonstrated that maximum biomass productivity is usually achieved after full establishment of the stand, typically in the third or fourth year of cultivation (Fike et al., 2006). The results of the present study confirm this pattern, as the highest biomass yields were recorded in the third year of plant growth. The tendency toward increased biomass productivity during the first years of cultivation is consistent with the findings of Fike et al. (2006), who reported gradual stabilization and enhancement of switchgrass yield potential in perennial production systems.

In addition to agronomic factors, environmental conditions during the growing season also influence biomass accumulation. Variations in temperature and precipitation observed during the experimental years

likely contributed to differences in biomass formation between years. According to Sharma et al. (2022), climatic factors together with agronomic management practices significantly influence biomass yield formation in perennial bioenergy crops such as switchgrass.

The results obtained also confirm that improving agronomic management practices can significantly enhance the energy potential of switchgrass biomass. The calculated solid biofuel yield and energy output demonstrate that optimization of sowing parameters contributes to increased biomass production and consequently higher energy yield per unit area.

Overall, the findings of this study emphasize the importance of optimizing sowing technology for switchgrass cultivation. Proper selection of sowing time and seed burial depth ensures better crop establishment, higher biomass productivity, and improved energy potential of this promising bioenergy crop.

The proposed conceptual approach to managing switchgrass biomass productivity can be applied not only at the field level but also for planning and optimization of bioenergy systems. By adjusting key agronomic parameters such as sowing date and seed burial depth, it is possible to influence biomass yield and, consequently, the energy output per unit area in a predictable manner. According to Sharma et al. (2022), optimization of agronomic factors remains one of the most effective approaches for improving the productivity and bioenergy efficiency of perennial energy crops, including switchgrass.

This creates opportunities for integrating agronomic management decisions into energy planning models, where biomass yield can be considered as a controllable parameter rather than a fixed value. As a result, agricultural land used for switchgrass cultivation can be more efficiently utilized to achieve higher and more stable energy production.

Thus, the management of agronomic practices should be regarded as an essential component of bioenergy system optimization, linking crop production with energy generation efficiency.

Conclusions

1. The results of the conducted research confirm that agronomic management practices play an important role in the formation of switchgrass (*Panicum virgatum* L.) biomass productivity and, consequently, in the energy potential of cultivated areas intended for bioenergy production.
2. It was established that both sowing date and seed burial depth significantly influence the formation of switchgrass biomass. Early sowing created more favorable conditions for plant establishment and development, which contributed to higher biomass yields during the experimental period. At the same time, the optimal seed burial depth was determined to be 1.0–1.5 cm, which ensured better seed germination and uniform plant stand formation.
3. The highest average biomass yield over 3-year study period of 11.9 t ha^{-1} was obtained under the conditions of early sowing combined with a seed burial depth of 1.0–1.5 cm. This variant also provided the highest calculated yield of solid biofuel (20.91 t ha^{-1}) and the highest energy output (386.83 GJ ha^{-1}).
4. Thus, the implementation of scientifically substantiated agronomic practices in the cultivation of switchgrass as an energy crop can significantly improve biomass production efficiency and increase the overall energy yield of agricultural land used for bioenergy purposes.

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DO FLOWERING PLANTS CONTRIBUTE TO BUTTERFLY DIVERSITY ALONG THE FOREST ROADS IN LATVIA?

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Abstract
The extent of anthropogenically created and impacted ecosystems is increasing globally, and forest roads can be considered as an example of such ecosystems. Despite their numerous negative impacts on biodiversity, recently, roads have been increasingly recognized for their potential role as habitats for butterflies. This study was aimed at exploring how flowering plant abundance and richness are related to butterfly diversity along forest roadsides. Differences in species richness and abundance were investigated along forest roads subject to different management regimes. Additionally, we assessed the effect of vegetation composition on butterfly diversity. We selected two study sites, representing 25 km of differently managed roadsides. The active sampling line–transect method was used to survey butterflies in the summer of 2024 and 2025. In total, 51 butterfly species were recorded along all studied roads, including six grassland indicator species and two protected species. While the highest species richness and abundance were observed along managed roadsides and roadsides with higher cover of flowering plants, we did not observe higher diversity of butterflies along roads with wider verges. In addition, the managed road verges were represented by plant species from nectar plant families that support high butterfly richness. The current study confirms the importance of maintaining flowering plant diversity on forest road verges.
Keywords: pollinators, forest road verges, managed roadsides, nectar sources.

Introduction

It has been shown that forest roads are expanding (Ring et al., 2024), thus facilitating changes in plant and animal populations, introducing exotic elements, modifying material flows in the area and availability of resources such as water, light and nutrients (Coffin, 2007). Despite their numerous negative impacts on biodiversity (Lugo & Gucinski, 2000), recently roads are increasingly recognized for their potential role as habitats for pollinators (Meinzen et al., 2024). Forest roads that are anthropogenically created landscape structures could serve as dispersal corridors and linear habitats for pollinator species (Phillip et al., 2020). Furthermore, verges along the roads may provide an important place of refuge for pollinators, including butterfly species (Phillip et al., 2020), thus contributing to the maintenance of butterfly species diversity in forested landscape (Schmitt et al., 2024). Butterflies are one of the most important pollinator species groups which are exposed to a global decline in the last decade (Potts et al., 2010; Ulyshen & Horn, 2023), with mostly specialist species decreasing (Schmitt et al., 2024). The plant species along forest roads could serve as nectar sources, breeding place (Munguira & Thomas, 1992), or larval hostplants for butterflies (Dennis, 2010). The complexity of vegetation structure, such as species composition, number of species, height of plants, and abundance of floral resources, can positively affect butterfly populations (Han et al., 2022). In particular, the nectariferous flowers' abundance could be one of the key factors influencing the diversity of butterflies along the forest roadsides (Barberis et al., 2025).

In this study, the potential of forest road verges as a nectar resource habitat for butterflies was explored. The relationship between flowering plant species diversity and adult butterfly diversity was assessed along forest road verges of varying widths.

Materials and Methods

The study was carried out at two forest areas in Latvia – in the central part (Jelgava) and central-eastern part (Kalsnava) of the country. The surrounding landscape was predominantly composed of production forests dominated by Scots pine (*'Pinus sylvestris'*), Norway spruce (*'Picea abies'*) and birch (*'Betula sp.'*). In total, 25 km of roads were selected to represent three distinct verge types: verges wider than 5 m (totaling 10 km), verges narrower than 5 m (totaling 5 km), and vegetation-covered roads without managed roadsides (totaling 10 km). The studied managed road verges were mowed once yearly. The active sampling line-transect method was used to survey butterflies in the summer of 2024 and 2025. Each kilometer of selected forest road was represented by two 200 m transects located along both sides of the road. In total, butterflies were observed along 50 transects. Butterflies were studied at each studied area five times in 2024 and four times in 2025, once during the following periods: 17 – 20 May, 30 May – 1 June, 16 June, 28 June, 16 July in 2024 and 30 May, 15 June, 2 July, 17 July in 2025. All individuals within a range of 2.5 m on both sides and 5 m in the front were recorded (Pollard & Yates, 1993) during the slow walk along the transects. Butterflies that could not be identified instantly or from a distance were captured using a butterfly net and released following identification (Tolman & Lewington, 2008). Butterflies were noted during days with no precipitation and temperatures above 17 ºC and wind below 10 m s^{-1}. The nomenclature of butterfly species followed Arvik et al. (2017, 2021, 2025). Flowering plant species diversity was counted using the transect-plot method. In total, one butterfly transect was characterized by three vegetation transects (10×2 m) located perpendicular to the road axis at the beginning, middle, and end of the butterfly transect. All flowering

plant species and their relative cover were recorded in 20 squares (1×1 m) within one transect three times per summer. In total, 180 vegetation plots described one butterfly transect. Butterfly abundance (total number of individuals) and species richness (total number of species) were calculated for each transect as the sum of records across all surveys. Flowering plant cover and richness were estimated for the same transects as the total flowering plant cover and number of species recorded across all vegetation plots in three surveys.

The effects of road type (categorical predictor) and flowering plant cover on butterfly species richness and abundance were analyzed using generalized linear models with a negative binomial error distribution (nbGLM) due to overdispersion in the count data. The study site was included as an additional categorical predictor in each model to account for site-level differences. Flowering plant richness among road types was also tested using nbGLMs, while variation in flowering plant cover was analyzed using a linear model (LM). The significance of models was assessed using analysis of variance (ANOVA). When significant effects of the categorical predictor (road type) were detected, pairwise comparisons of estimated marginal means were performed using Tukey-adjusted p-values. All analyses were performed in R version 4.4.3 (R Core Team, 2025). Negative binomial models were fitted using the MASS package (Venables & Ripley, 2002), and pairwise comparisons of estimated marginal means were obtained using the emmeans package (Lenth, 2025). A significance level of $\alpha = 0.05$ was applied.

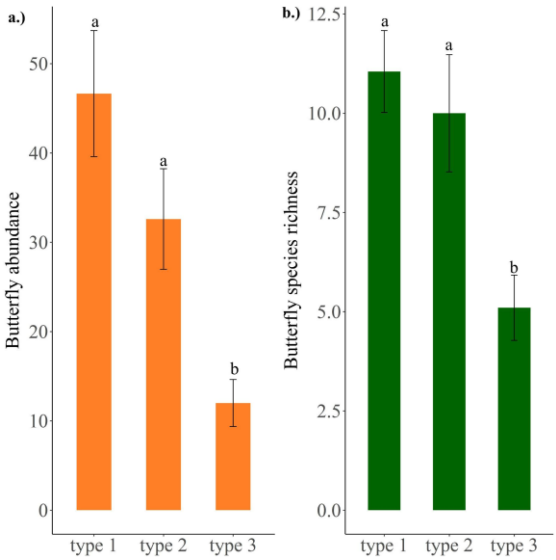
Results and Discussion

In total, 51 butterfly species were recorded along the studied road verges, the most common being *Aphantopus hyperantus, Pieris napi*, and *Argynnis paphia.* Overall, six grassland indicator species and two protected species were found (Table 1). The majority of species were recorded in less than 20% of the studied transects (Table 1).

Mean butterfly species richness per transect was the highest along roads with verges more than 5 m (11.0 ± 1.03 species), followed by roads with verges narrower than 5 m (10.0 ± 1.48), and the lowest along vegetation-covered roads without managed roadsides (5.1 ± 0.82; Figure 1b). A negative binomial generalized linear model (nbGLM) indicated a significant effect of road type on butterfly species richness (χ^2 = 23.09, p < 0.001). Mean butterfly abundance per transect showed a similar pattern, being the highest along roads with verges more than 5 m (46.6 ± 7.06 individuals), followed by roads with verges narrower than 5 m (32.6 ± 5.63), and the lowest along vegetation-covered roads (12.0 ± 2.63; Figure 1a). The nbGLM likewise indicated a significant effect of road type on butterfly abundance (χ^2 = 29.99, p < 0.001). Tukey-adjusted pairwise comparisons indicated significantly lower butterfly richness and abundance along vegetation-covered roads than along roads with managed verges (p < 0.05), while no significant differences were detected between the two managed road types (p > 0.05).

Figure 1

Mean butterfly abundance (a) and species richness (b) across three forest road types. Bars represent observed mean values ± standard errors. Type 1 - roads with verges more than 5 m; type 2 - roads with verges narrower than 5 m; type 3 - vegetation-covered roads without managed roadsides. Different lowercase letters denote significant differences among road types, as determined from estimated marginal means of nbGLM (Tukey-adjusted post hoc test, p < 0.05)



The nbGLM indicated a significant increase in butterfly species richness with increasing flowering plant cover (χ^2 = 38.58, p < 0.001; Figure 2a). Similarly, butterfly abundance increased significantly with flowering plant cover (χ^2 = 32.49, p < 0.001; Figure 2b).

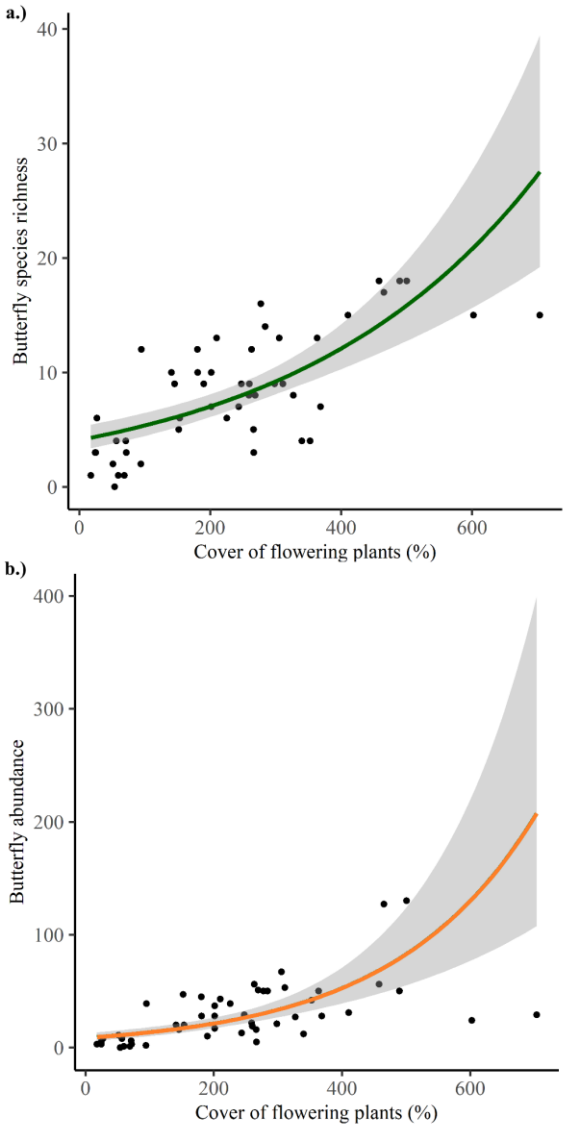
A total of 173 flowering plant taxa were recorded in the studied plots, representing 32 plant families, with the highest number of taxa in the families Asteraceae (33), Caryophyllaceae (17), and Fabaceae (13). The nbGLM indicated significant differences in flowering plant richness among road types (χ^2 = 55.5, p < 0.001), with the lowest richness along vegetation-covered roads, while no significant differences were detected between the two road types with managed verges (Tukey-adjusted comparisons; p > 0.05). Similarly, the linear model (LM) indicated that flowering plant cover differed among road types ($F_{2,46}$ = 24.5, p < 0.001) and was also the lowest along vegetation-covered roads.

In all previously described models, the study site was also included as a predictor to account for site-level differences. In the models including road type as a predictor, butterfly species richness differed significantly between the study sites (χ^2 = 5.41, p = 0.02), whereas butterfly abundance did not (χ^2 = 0.04, p = 0.85). Flowering plant richness and

cover also differed significantly not only among road types but also between study sites ($\chi^2 = 6.13$, $p = 0.013$; $F_{1,46} = 5.15$, $p = 0.028$). These differences may partly reflect the uneven distribution of road types between the two study sites, as road type 2 was absent in one site. However, in the models including flowering plant cover as a predictor, the study site had no significant effect on butterfly richness or abundance ($p > 0.05$), suggesting that differences in butterfly communities between sites were largely associated with differences in flowering plant cover.

Figure 2

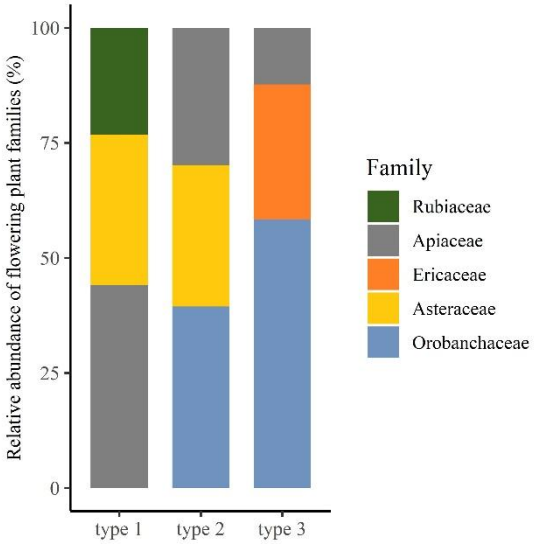
Relationship between flowering plant cover and butterfly species richness (a) and abundance (b) estimated using negative binomial generalized linear models with 95% confidence intervals. Flowering plant cover (%) represents the sum of the percentage cover of flowering plants across all surveys and plots within each transect



The relative cover of dominant flowering plant families was different among road types, with roads with managed verges dominated by Apiaceae and Asteraceae, whereas vegetation-covered roads were dominated by Orobanchaceae and Ericaceae (Figure 3).

Figure 3

Mean relative abundance (%) of flowering plant families across three forest road types. Stacked bars indicate the proportional contribution of the three most abundant plant families within each road type. Type 1 - roads with verges more than 5 m; type 2 - roads with verges narrower than 5 m; type 3 - vegetation-covered roads without managed roadsides



Our study indicates that managed forest road verges may provide suitable habitat for diverse butterfly species. At our research sites, 51 out of 120 butterfly species occurring in Latvia (Aarvik et al., 2017, 2021) were recorded along the forest roads. Furthermore, considering the species composition, the road verges were able to support not only widespread grassland indicator species but also forest species as 18 of all recorded species mainly occur in the forest landscape and have host plants related to forest structures such as trees or understory plants (Viljur et al., 2020). However, we did not record any specialist species, and also the two protected species we found were widespread butterflies according to IUCN classification (Teļnovs, 2025) and have a low risk of extinction.

It has been shown that wider road verges may support higher butterfly species diversity (Meinzen et al., 2024). Although our results did not show a significant difference, there was an observed tendency to have higher richness and abundance of butterflies and of flowering plant species along roads with wider verges. The possible explanation that the width of verges did not affect species diversity significantly could be related to similar environmental conditions of adjacent forests in the studied areas (Saarinen et al., 2005). On the other hand, our results could indicate that exactly five meters is the part of the managed roadsides that

support this high diversity of flowering plants, as there were no significant differences between flowering plant richness and abundance between the two types of managed road verges.

Nevertheless, our study revealed that managed forest roadsides have a positive effect on butterfly diversity and that there is a positive interaction between flowering plant diversity and butterflies. Forest verges create open canopy conditions which increase structural complexity and floral species diversity due to better light conditions, thus promoting a more favourable environment for flowering plant species, including nectariferous flowers (Muscolo et al., 2014). Consequently, the positive association between nectariferous flowers' abundance explains a greater increase in butterfly richness and abundance (Ohwaki et al., 2017). However, not only the abundance of flowering plants but also their composition is an important aspect, because plant-pollinator interactions depend on nectar sugar composition in plant species, which differs between plant orders and families (Liu et al., 2024). According to our findings, the managed road verges were represented by an abundance of such nectar plant families as Asteraceae and Apiaceae that support high butterfly richness (Denis, 2010). The plant species of these families were less common along unmanaged forest roads. Overall, the present study findings support the assumption that high nectar abundance along the forest road verges could increase the number and abundance of butterflies (Saarinen et al., 2004).

The study site significantly affected the butterfly species richness between different road types, thus indicating that species number per site is determined not only by the road corridor itself, but by the various surrounding forest characteristics. The most important of those could be forest site type and forest cover abundance adjacent to the studied roadsides (Viljur et al., 2020). In addition, the fluctuation in the number of butterflies between studied sites could also be driven by meteorological factors (Schmitt et al., 2024) as the assessment in each site was conducted in separate summers.

Overall, the results from the present study showed that road verges could be important linear structures for supporting butterfly species, especially widely common species. Furthermore, in line with other findings (Dániel-Ferreira et al., 2023; Horstmann et al., 2025), we suggest that it is important to maintain flowering plant diversity along the forest road verges to support the conservation of butterflies. However, our study mainly focused on one aspect - flowering plant species' relations to butterflies. Thus, our results should be considered in the context of other essential local and landscape factors important for butterflies (Viljur et al., 2020), for example, microclimate, forest road density, vegetation heterogeneity, and forest structural characteristics. Furthermore, there is need for more research to understand the significance of forest road verges in supporting forest and semi-natural grassland butterfly communities in managed forest landscapes.

Table 1

Occurrence (%) of recorded butterfly species across all transects (n=50). Grassland indicator species are marked with [1] (European Environment Agency, 2025), and protected species according to Regulation of Government of Latvia Nr. 396 (2000) are marked with [2]

Species name	%	Species name	%	Species name	%
Aphantopus hyperantus (Linnaeus, 1758)	86	*Lycaena virgaureae* (Linnaeus, 1758)	14	*Aglais urticae* (Linnaeus, 1758)	4
Pieris napi (Linnaeus, 1758)	70	*Speyeria aglaja* (Linnaeus, 1758)	12	*Eumedonia eumedon* (Esper, 1780)	4
Argynnis paphia (Linnaeus, 1758)	60	*Carterocephalus palaemon* (Pallas, 1771)	12	*Cupido argiades* (Pallas, 1771)	4
Gonepteryx rhamni (Linnaeus, 1758)	54	*Maniola jurtina* (Linnaeus, 1758)[1]	12	*Lycaena tityrus* (Poda, 1761)	4
Araschnia levana (Linnaeus, 1758)	46	*Thymelicus lineola* (Ochsenheimer, 1808)	12	*Pieris rapae* (Linnaeus, 1758)	4
Brenthis ino (Rottemburg, 1775)	46	*Aporia crataegi* (Linnaeus, 1758)	10	*Agriades optilete* (Knoch, 1781)	4
Melitaea athalia (Rottemburg, 1775)	46	*Argynnis laodice* (Pallas, 1771)	10	*Polyommatus icarus* (Rottemburg, 1775)[1]	4
Vanessa atalanta (Linnaeus, 1758)	42	*Celastrina argiolus* (Linnaeus, 1758)	10	*Pyrgus malvae* (Linnaeus, 1758)	4
Boloria selene (Denis & Schiffermüller, 1775)	36	*Lycaena alciphron* (Rottemburg, 1775)	10	*Vanessa cardui* (Linnaeus, 1758)	4
Ochlodes sylvanus (Esper, 1777)[1]	30	*Coenonympha glycerion* (Borkhausen, 1788)	8	*Apatura ilia* (Denis & Schiffermüller, 1775)	2

Species name	%	Species name	%	Species name	%
Leptidea sinapis (Linnaeus, 1758) / juvernica (Williams 1946)	24	*Plebejus argus* (Linnaeus, 1758)	8	*Boloria dia* (Linnaeus, 1767)	2
Pararge aegeria (Linnaeus, 1758)	20	*Polygonia c-album* (Linnaeus, 1758)	8	*Carterocephalus silvicola* (Meigen, 1829)	2
Lasiommata maera (Linnaeus, 1758)	18	*Polyommatus amandus* (Schneider, 1792)	6	*Limenitis populi* (Linnaeus, 1758)	2
Thymelicus sylvestris (Poda, 1761)	18	*Fabriciana addipe* (Denis & Schiffermüller, 1775)	6	*Lopinga achine* (Scopoli, 1763)[2]	2
Anthocharis cardamines (Linnaeus, 1758)[1]	14	*Coenonympha hero* (Linnaeus, 1761)[2]	6	*Melitaea diamina* (Lang, 1789)	2
Callophrys rubi (Linnaeus, 1758)	14	*Lycaena phlaeas* (Linnaeus, 1761)[1]	6	*Nymphalis polychloros* (Linnaeus, 1758)	2
Coenonympha pamphilus (Linnaeus, 1758)[1]	14	*Pieris brassicae* (Linnaeus, 1758)	6	*Satyrium pruni* (Linnaeus, 1758)	2

Conclusions

1. Forest roadsides may serve as habitats supporting flowering plant and butterfly species diversity, including grassland indicator and rare species.
2. The cover and richness of flowering plants positively contribute to butterfly species diversity along forest roadsides.
3. The variation of butterfly species diversity along differently managed forest road verges could be attributed to the availability of nectar plants.

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STAND DENSITY EFFECTS ON GROWTH AND STEM QUALITY OF HYBRID LARCH IN LITHUANIA

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Abstract
Initial planting density is a key factor influencing stand development, productivity, and stem quality in plantation forests. This study aimed to assess the effect of different initial planting densities on growth characteristics, stem quality, and sanitary condition of hybrid larch stands. The study was conducted in the Vaišvydava forest district (Lithuania) and included seven stands established under different initial densities. In total, 455 trees were measured. The analysis focused on dendrometric indicators (mean diameter, mean height, stand volume) as well as stem quality and sanitary condition parameters. Descriptive statistics were used to compare stands of different densities, and principal component analysis (PCA) was applied to integratively evaluate relationships among growth, quality, and sanitary indicators. The results revealed clear density-related differences in stand structure. Increasing initial planting density was associated with decreasing mean tree diameter, while mean height and stand volume increased, indicating stronger competition in denser stands. Low-density stands were characterized by larger diameters but poorer stem quality, including thicker branches and less straight stems. The most favourable combination of productivity and stem quality was observed in stands of intermediate density (3000–5000 trees ha^{-1}). PCA results confirmed a clear separation of stands along gradients of productivity and stem quality, highlighting the trade-off between individual tree growth and overall stand performance. The findings demonstrate that intermediate initial planting densities provide a balanced compromise between stand productivity and stem quality in hybrid larch stands, supporting their importance for sustainable plantation management.
Keywords: hybrid larch, stand density, dendrometric characteristics, productivity, principal component analysis (PCA).

Introduction

Modern forest management is increasingly oriented toward solutions that allow the reconciliation of stand productivity, wood quality, and long-term stability under changing climatic and economic conditions. In recent years, growing attention has been directed toward tree species diversification and the use of alternative, highly productive species in order to reduce risks associated with the climate sensitivity of traditional species, particularly Norway spruce (Lindner et al., 2014; Puettmann et al., 2009). In this context, European larch (*Larix decidua* Mill.) and its hybrids are considered a promising species for sustainable forest bioeconomy development (Matras & Pâques, 2008).

Recent studies indicate that European larch exhibits high growth potential and favorable wood quality under Northern and Central European conditions, especially on fertile sites and former agricultural land, where in some cases it surpasses Norway spruce in both increment and physical wood properties (Zeidler et al., 2022; Debryniuk et al., 2022). Moreover, recent research emphasizes that larch wood in more mature stands demonstrates advantageous mechanical and strength properties, which are important for evaluating economic returns and rotation length (Gil-Moreno et al., 2023).

At the same time, it is emphasized that long-term development outcomes of larch stands are closely linked to early forest establishment decisions. One of the most important of these decisions is initial planting density, which determines stand structure, growth dynamics, and the formation of wood quality. It has been established that high initial density promotes the height growth and total stand volume accumulation but often restricts diameter increment and may negatively affect stem quality, whereas excessively low density creates conditions for increased branchiness and lower commercial timber value (Juodvalkis, 2004). As noted by Malinauskas (2003), these effects are particularly pronounced in larch plantations, as planting density significantly influences branch thickness, stem straightness, and the formation of merchantable logs.

Although the effects of planting density have been widely examined in young and middle-aged stands, recent studies emphasize the importance of long-term observations for assessing stand stability, sanitary condition, and the sustainability of productivity at more advanced developmental stages (Sagar et al., 2025). Long-term analyses of stands established under different initial planting densities remain limited under Baltic region conditions, particularly in hybrid larch stands, which may become an important component of forest management diversification.

Under Lithuanian conditions, larch remains a niche species; however, it is attracting increasing interest, as its productivity and stem quality potential – especially on fertile sites – may represent an important component of forest adaptation to climate change and species diversification strategies.

In this context, the aim of the present study was to assess how different initial planting densities of hybrid larch stands determine the long-term balance between stand productivity, stem quality, and sanitary stability, in order to support rational decision-making in sustainable forest management practice.

Materials and Methods

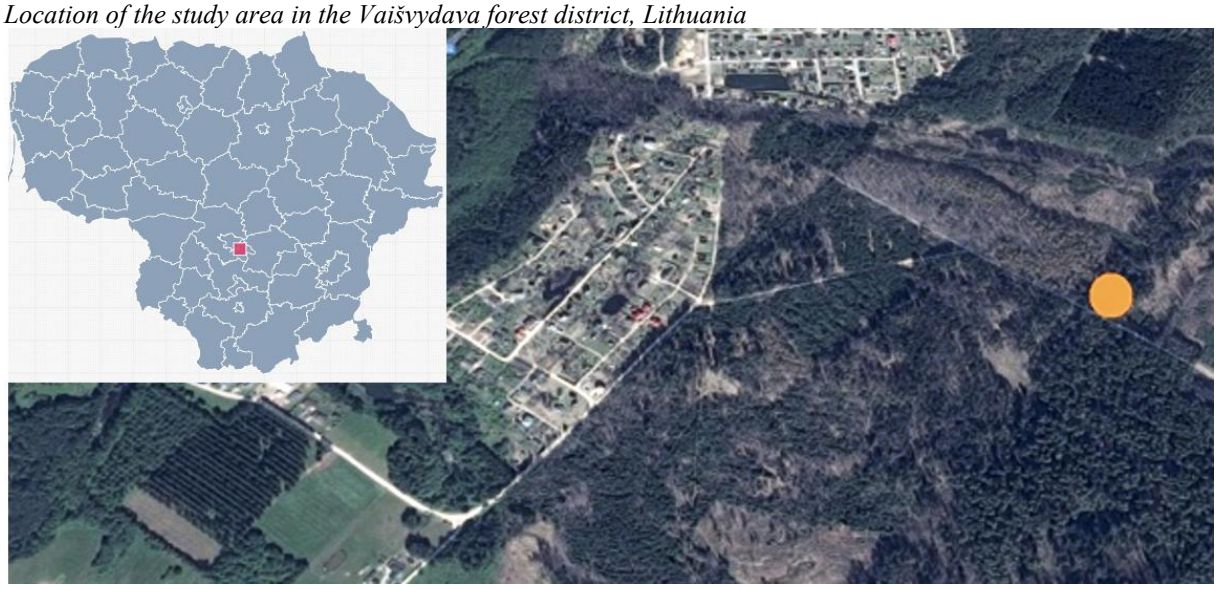
The study area is located in southern Lithuania within the Vaišvydava forest district and comprises an experimental hybrid larch plantation designed to assess

the effects of initial planting density on stand development. The location of the experimental plots is presented in Figure 1.

The plantation was established in 1983 in compartment 39 (stand 16) on a total area of 2.0 ha. The experiment consisted of six initial planting density treatments: 500; 1,000; 1,500; 2,000; 5,000 and 10,000 trees ha^{-1}. Planting spots were arranged in a square layout. The area of each density variant was 0.12 ha, except for the 5,000 and 10,000 trees ha^{-1} treatments, which covered 0.05 ha each.

Figure 1

Location of the study area in the Vaišvydava forest district, Lithuania



Field measurements were carried out during the winter of 2024–2025. In total, 455 trees were measured across all experimental plots. For each plot, dendrometric, stem quality, and sanitary condition indicators were recorded. The following indicators were measured for each tree: diameter at breast height (1.3 m), total tree height, height to dead branches, Kraft class, stem straightness, branch thickness, sanitary condition, and stand volume per hectare.

Diameter at breast height was measured using callipers, and tree height was determined using a hypsometer. Height to dead branches was measured using a measuring tape.

Kraft class was determined according to a five-class system, where 1 indicates dominant trees and 5 indicates dead or strongly suppressed trees. Kraft class values presented in the tables represent mean values calculated from individual tree classifications. Stem straightness was assessed using a five-point scale, where 1 indicates a very straight stem, 3 indicates moderate curvature, and 5 indicates a strongly curved stem. Branch thickness was evaluated using a five-point scale, where 1 indicates very thin branches, 3 indicates moderate thickness, and 5 indicates very thick branches. Sanitary condition was assessed visually using a five-point scale, where 1 indicates very good condition, 3 indicates moderate condition, and 5 indicates very poor condition.

Stand volume (m^3 ha^{-1}) was calculated based on standard volume equations using tree diameter and height.

All collected data were compiled and processed using Microsoft Excel and the R statistical environment. Descriptive statistics (mean ± standard deviation) were calculated to compare growth and quality characteristics among stands with different initial planting densities. To integratively evaluate relationships between growth parameters, stem quality indicators, and sanitary condition in relation to initial density, principal component analysis (PCA) was applied. Statistical analyses were performed using R software with base functions. Prior to PCA, all variables were standardized, and interpretation was based on the loadings and scores of the first two principal components.

Results and Discussion

Pronounced differences in dendrometric characteristics and stem quality were identified among hybrid larch stands established at different initial planting densities. With increasing initial stand density, mean tree diameter decreased, while mean tree height and total stand volume increased, indicating intensified inter-tree competition in denser stands. Mean values of tree diameter, height, and stand volume across different initial planting densities are presented in Table 1. The largest mean diameters were recorded in low-density stands (500–1,500 trees ha^{-1}), where mean diameter ranged from 29.1 to 31.1 cm. As stand density increased to 3,000–10,000 trees ha^{-1}, mean diameter decreased to 26.5–26.8 cm. In contrast, mean tree height and stand volume increased with increasing density, with the highest heights (25.2–25.65 m) and stand volumes (466–536 m^3 ha^{-1}) observed in the densest stands.

The effects of initial planting density on stem quality and sanitary condition indicators are presented in Table 2. In the lowest-density stands (500–1,000 trees ha^{-1}), higher branch thickness scores and poorer stem straightness were recorded. Stands of intermediate density (3,000–5,000 trees ha^{-1}) exhibited more favourable stem formation characteristics, including thinner branches, improved stem straightness, and better sanitary condition. In stands with very high density (10,000 trees ha^{-1}), some quality indicators remained good; however, they were not consistently superior to those observed in stands of intermediate density.

Table 1

Dendrometric characteristics of hybrid larch stands under different initial planting densities

Initial density, trees ha^{-1}	Mean diameter, cm	Mean height, m	Stand volume, m^3 ha^{-1}
500	29.5±3.2	23.20±1.1	280±40
1,000	29.1±3.0	23.20±1.0	422±55
1,500	31.1±3.5	23.10±1.2	409±50
2,000	27.2±2.8	23.35±1.1	390±45
3,000	26.8±2.6	24.10±1.3	464±60
5,000	26.6±2.5	25.65±1.5	466±65
10,000	26.5±2.4	25.20±1.4	536±70

Table 2

Stem quality and sanitary condition indicators of hybrid larch stands under different initial planting densities

Initial density, trees ha^{-1}	Kraft class	Branch thickness score	Height to dead branches, m	Stem straightness score	Sanitary condition score
500	2.2	3.3	2.0	2.5	1.4
1,000	2.1	3.1	1.8	2.0	1.1
1,500	2.2	3.5	1.1	2.1	1.2
2,000	2.4	3.1	2.2	1.9	1.2
3,000	2.2	2.9	1.1	1.8	1.0
5,000	2.0	2.9	2.5	1.6	1.0
10,000	2.2	3.2	1.8	1.7	1.1

The relationships identified between initial planting density, tree diameter, height, and stand volume are consistent with general density-related patterns reported in studies of plantation and coniferous stands. Previous research indicates that increasing stand density intensifies competition for light and promotes height growth and total biomass accumulation, while simultaneously limiting radial growth and increasing the risk of unfavourable stem formation (Tymińska-Czabańska et al., 2022; Li et al., 2025).

In stands of intermediate density, improved commercial stem structure was observed, characterised by reduced branching and more favourable stem straightness. This finding is consistent with previous studies highlighting the advantages of intermediate density levels compared with very sparse or extremely dense stands (Jiang, 2007).

Principal component analysis (PCA) was applied to integratively assess growth, stem quality, and sanitary condition indicators in hybrid larch stands established at different initial planting densities. The results showed that the first principal component (PC1) explained 65.7% of the total variance, while the second component (PC2) accounted for 19.5%, with the first two components together explaining 85.2% of the overall data structure. This level of explained variance indicates that PCA is an appropriate and informative method for interpreting the effects of planting density on stand structure and productivity.

The PCA loading analysis revealed that the first principal component (PC1) was primarily influenced by stand volume and mean tree height, whereas mean diameter and branch thickness loaded in the opposite direction. The second principal component (PC2) was mainly associated with height to dead branches and sanitary condition, reflecting stem quality and structural characteristics (Table 3).

The PCA biplot clearly demonstrated the separation of hybrid larch stands with different initial planting densities according to productivity and structural characteristics (Figure 2). This structure reflects a gradient from low-density stands, characterised by more intensive radial growth and increased branching, to high-density stands, which exhibit enhanced height growth and greater total stand volume. Similar relationships between stand density and productivity have been reported in other coniferous and plantation forests, where increasing density intensifies competition for light and promotes height growth and biomass accumulation (Thurm & Pretzsch, 2021).

The second principal component (PC2) mainly reflected stem quality and sanitary condition attributes. The positive direction of PC2 was associated with a greater height to dead branches and better sanitary condition, whereas the negative direction was related to increased branch thickness and poorer stem structural characteristics.

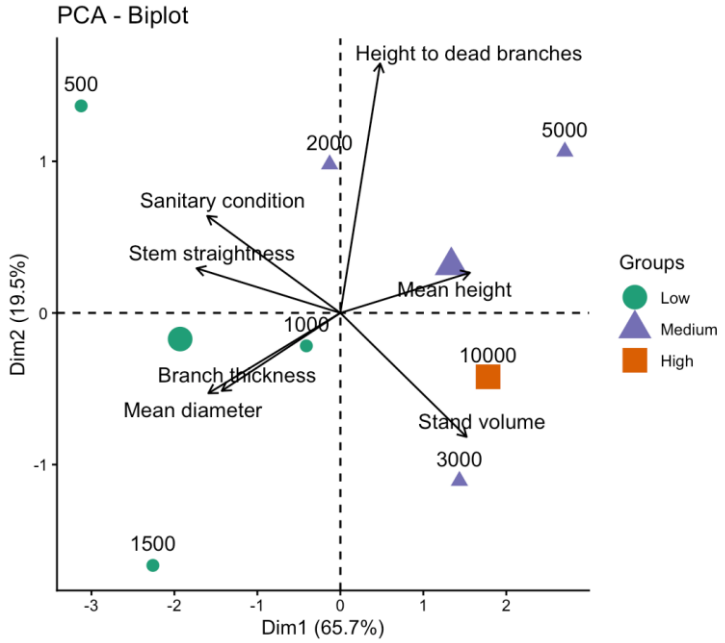
Table 3

Loadings of variables on the first two principal components (PC1 and PC2)

Variable	PC1	PC2
Mean diameter	-0.86	-0.32
Branch thickness	-0.82	-0.41
Stem straightness	-0.55	0.48
Sanitary condition	-0.49	0.62
Mean height	0.61	0.18
Stand volume	0.79	-0.36
Height to dead branches	0.12	0.87

Figure 2

Principal component analysis (PCA) biplot of hybrid larch stands based on growth, stem quality and sanitary indicators. The first principal component (PC1) explains 65.7% of the total variance, while the second component (PC2) explains 19.5%



In the PCA space, extreme initial density variants were clearly distinguished. Low-density stands (500–1,000 trees ha^{-1}) were associated with larger mean tree diameters and thicker branches but exhibited poorer stem straightness and sanitary condition. This is consistent with findings reported by other authors, indicating that excessively low initial stand density, although promoting individual tree growth, often results in inferior commercial timber structure and a higher occurrence of defects (Li et al., 2024). In contrast, very high-density stands (10,000 trees ha^{-1}) were positioned closer to the productivity axis in the PCA space; however, their location suggests that high stand volume does not necessarily ensure optimal stem quality.

Stands with intermediate initial densities (3,000–5,000 trees ha^{-1}) occupied an intermediate position between the productivity and stem quality axes in the PCA biplot, reflecting a more balanced relationship between growth and structural attributes. Such a balance between productivity and structural heterogeneity is widely discussed in the literature and is considered one of the key challenges in long-term forest stand management (Zeller et al., 2021).

The obtained PCA results are also consistent with studies on larch growth conducted in other regions, where interactions between stand density and age significantly influence growth trajectories and structural characteristics at more advanced developmental stages (Tian et al., 2023). This indicates that the patterns identified in the present study are neither local nor incidental but reflect general mechanisms governing the development of hybrid larch stands.

Conclusions

1. The effect of initial planting density on the development of hybrid larch stands was clearly expressed in both growth and stem structural indicators. With increasing initial density, mean tree diameter decreased, while tree height and total stand volume increased, reflecting intensified inter-tree competition in denser stands.

2. Stands established at low initial planting densities exhibited larger individual tree diameters; however, poorer stem quality indicators were also recorded, particularly increased branching and reduced stem straightness, which limit the formation of merchantable timber. In contrast, stands with a very high initial density achieved the highest stand volume, although this volume was not consistently associated with optimal stem quality.
3. Stands with intermediate initial planting densities were characterised by a balanced relationship between growth and structural attributes, combining sufficiently high stand productivity with more favourable stem quality and sanitary condition indicators. This suggests that intermediate initial density provides the most favourable conditions for the formation of hybrid larch stands.
4. Principal component analysis further confirmed that the effect of initial planting density on stand development is expressed through a clear gradient between productivity and stem quality, allowing intermediate density to be identified as an optimal balance between stand volume and stem structural characteristics.

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INDOOR SEED PRODUCTION OF SILVER BIRCH (*BETULA PENDULA* ROTH): CURRENT KNOWLEDGE AND RESEARCH NEEDS

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Abstract
Silver birch is the most economically important deciduous tree species in the Nordic and Baltic countries and represents a key raw material for the rapidly expanding plywood and wood-based panel industries. Although birch, as a pioneer species, primarily regenerates naturally, the use of genetically improved reproductive material can substantially increase stand productivity and improve stem quality. Reliable production of genetically superior seed is therefore a critical prerequisite for sustainable birch forestry. A technology for intensive birch seed production in plastic-covered seed orchards, originally developed in Finland, has been adopted across Northern Europe, enabling seed production within only a few years after orchard establishment. However, operational experience in Latvia and other countries indicates large variation in seed yield, regularity, and quality between years and orchards. These inconsistencies are largely driven by poorly understood interactions between orchard microclimate, genetic background (clone composition), and reproductive phenology, as well as by limitations in pollination processes under controlled environments. This narrative review synthesizes current knowledge on birch seed production in plastic-covered orchards with a specific focus on Nordic and Baltic conditions. We summarize existing management practices, experimental findings, and ongoing research efforts, and identify critical knowledge gaps related to flowering induction, pollination efficiency, microclimate regulation, and clonal selection. The review defines priority research directions required to achieve earlier, more regular, and higher seed yields, and provides a scientific basis for improving seed supply systems supporting large-scale forest regeneration under changing climatic conditions.
Keywords: reproductive phenology, forest tree breeding, seed orchards, seed yield stability, flowering induction.

Introduction

Forests provide a wide array of ecosystem services that are essential for human well-being and sustainable economic development, including the provisioning of timber as a key resource for the bioeconomy and long-lived wood products. In Europe, boreal and temperate forests not only contribute to climate regulation, water purification, and biodiversity conservation, but also underpin regional industrial sectors such as wood-based panel and plywood manufacturing (European Environment Agency, 2023, 2024; Eurostat, 2026). The strategic importance of forest ecosystems is reflected in national and international policies recognising forests as multifunctional landscapes that supply both ecological and socio-economic benefits (Ministry of Agriculture of the Republic of Latvia, 2018).

Improving forest productivity and adaptive capacity under changing climatic conditions has become a central objective of forestry research and practice. Historically, tree breeding and genetic improvement efforts have focused on enhancing growth, wood quality and vitality, particularly in conifer species such as Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) in the Northern European context (Danell, 1991; Egbäck et al., 2018). However, there has been an increasing emphasis on broadening breeding goals to include genetic diversity and resilience to environmental change, reflecting the need to support ecosystem health and long-term sustainability under global change pressures (Li et al., 2025).

Within this broader framework, deciduous tree species have received growing attention in breeding and forest management programmes (Gailis, 2026; Liziniewicz et al., 2022; Rosvald, 2011). Among these, silver birch (*Betula* pendula Roth) and downy birch (*Betula pubescens* Ehrh.) are ecologically and economically significant across the Baltic Sea region (Hynynen et al., 2009). Birches occur widely in boreal and temperate forests, contribute to biodiversity and soil functioning, and play a role in early successional dynamics, while their wood is highly desired in plywood production and bio-based material value chains (Cakiroglu et al., 2019; Dubois et al., 2020; Jonczak et al., 2020).

The heightened demand for high-quality birch timber, driven by both domestic industry and bio-refining innovation, has stimulated interest in advancing reproductive and silvicultural systems that can deliver improved seed supply. Additionally, ensuring sustainable domestic supply chains is of strategic importance in many countries, as disruptions caused by global geopolitical and trade uncertainties underscore the vulnerability of imported reproductive material and wood resources.

Compared with conifer species, breeding cycles in birch can be completed substantially faster due to its earlier onset of flowering and shorter generation intervals, allowing more rapid genetic gain (Hynynen et al., 2009; Koski & Rousi, 2005). In addition, the establishment of seed orchards in indoor facilities, such as plastic-covered greenhouses, enables intensive management and has been shown to result in abundant seed yields already a few years after orchard establishment (Ahtikoski, 2000; Lepisto, 1973).

Plastic-covered greenhouse seed orchards enable high genetic control and regulated seed production through pollen isolation and controlled environments, their high costs, technical complexity, limited integration with field forestry, and potential risks related to seed quantity, viability and clonal balance represent important constraints (Wilson, 2015).

Indoor birch seed orchards were first developed in

Finland in early seventies of last century, where this technology was introduced to accelerate seed production and improve genetic control, and it has since been adopted in several countries like Sweden, Baltic countries, Iceland, Germany and China (Poykko, 2007). Although general management principles for birch seed orchards have been described by Finnish specialists (Poykko, 2013), the physiological thresholds and reproductive conditions underpinning regular and abundant seed production remain insufficiently defined.

Despite decades long use of plastic-covered greenhouse seed orchards and the availability of general management guidelines, practical experience demonstrates that seed production in birch orchards often remains irregular (Isio, 2024). Substantial inter-annual variation is frequently observed not only in seed yield but also in seed quality parameters, such as viability and germination capacity. These fluctuations indicate that the biological regulation of flowering, pollination success and seed development under controlled greenhouse conditions is still incompletely understood. In particular, the relative roles of internal physiological factors and external environmental conditions in driving year-to-year variation in reproductive output have received limited empirical attention.

This knowledge gap constrains the optimisation of intensive birch seed production systems and limits the predictability and reliability of genetically improved seed supply, which is increasingly critical for both breeding programmes and forest regeneration strategies.

The aim of this review is to synthesise existing knowledge on birch seed production in plastic-covered greenhouse seed orchards and to identify key research gaps limiting the predictability, regularity and quality of seed yields. By evaluation of current management approaches, biological processes and environmental controls described in the literature, this review seeks to define priority directions for future research needed to optimise intensive birch seed production systems and support reliable supply of genetically improved reproductive material for forest regeneration.

Materials and Methods

Literature search

This review is based on a comprehensive survey of peer-reviewed scientific literature focusing on Silver birch (*Betula pendula* Roth) flowering, seed production and the management of plastic-covered greenhouse seed orchards. Literature searches were conducted primarily using the bibliographic databases Scopus and Web of Science, which were selected due to their broad coverage of forestry, plant physiology and applied silviculture research. Additional sources were identified through reference list screening of key publications and relevant monographs, conference materials and institutional reports where appropriate.

Search queries combined terms related to species, reproductive biology and seed production systems. The core search strings included, but were not limited to: ‘birch flowering’, ‘flower induction’, ‘reproductive phenology’, ‘seed orchard management’, ‘plastic-covered greenhouse’, ‘controlled environment seed production’, and ‘*Betula* seed yield’.

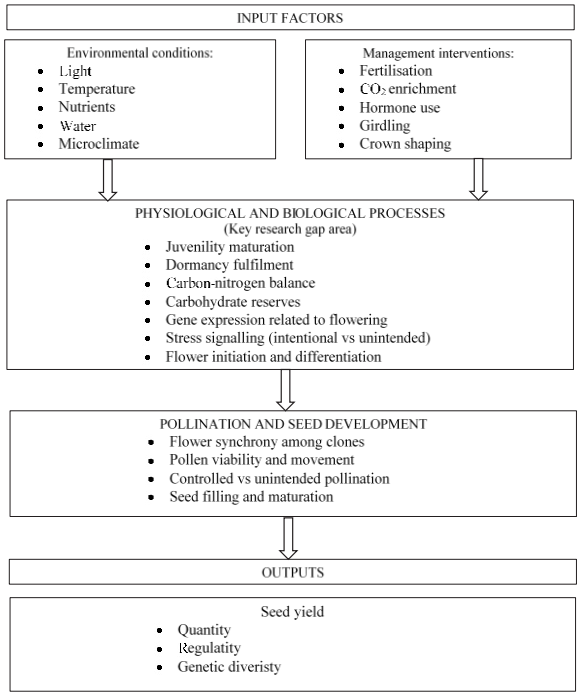
Search terms were applied in various combinations and adjusted iteratively to ensure comprehensive coverage of the topic.

Scope and synthesis approach

The review follows a structured narrative approach, integrating findings from experimental studies, applied seed orchard research and physiological investigations. Particular emphasis was placed on identifying consistencies and discrepancies among studies, as well as areas where empirical evidence remains limited or fragmented. In total, 58 literature sources were systematically reviewed and synthesised in this study.

Figure 1

Interactions among environmental conditions, management interventions and genetic factors influencing flowering initiation and seed crop in plastic-covered birch seed orchards



Conceptual framework

To support synthesis and interpretation, this review proposes the development of a conceptual framework illustrating the principal biological, environmental and management-related factors influencing seed yield and quality in plastic-covered birch seed orchards. Such a schematic representation is intended to clarify interactions among flowering induction, pollination processes, clonal effects and controlled environmental conditions, and to assist in identifying priority directions for future research.

Figure 1 synthesises the key environmental, management

and genetic factors influencing reproductive processes in plastic-covered birch seed orchards. Environmental conditions (light, temperature, nutrients and water regime) interact with silvicultural interventions such as fertilisation, CO_2 enrichment, crown management and controlled stress treatments, while clonal genetic characteristics determine inherent flowering capacity and phenological patterns.

These inputs act through underlying physiological processes, including maturation status, dormancy fulfilment, carbohydrate dynamics and gene activity related to flowering induction, which ultimately regulate pollination success, seed development and reproductive allocation. The resulting outputs are expressed as seed yield, yield stability and seed quality. Regulatory requirements concerning genetic diversity and reproductive material zoning operate across all levels of the system. The framework highlights the central role of physiological mechanisms as a key area where further research is needed to improve the predictability and efficiency of intensive birch seed production systems.

Results and Discussion

Reproductive cycle of silver birch

Silver birch is a monoecious, wind-pollinated tree species whose reproductive ecology is well documented. The initiation of reproductive primordia takes place during the preceding growing season, typically in mid- to late summer, when male and female inflorescences are differentiated within axillary buds on current-year shoots. Male catkins develop earlier and overwinter as externally visible structures, whereas female inflorescences remain enclosed within buds (Sarvas, 1952; Vakkari, 2009). Following winter dormancy, flowering occurs in early spring, often shortly before or concurrently with leaf flushing, with pollen release from male catkins and subsequent wind-mediated pollination of receptive female flowers (Atkinson, 1992; Hynynen et al., 2010).

Successful pollination, fertilisation and seed development depend on synchrony between pollen shedding and female receptivity, favourable spring weather conditions and adequate physiological status of the trees. Seed development proceeds throughout the summer, with maturation and dispersal occurring in late summer to early autumn. This reproductive strategy results in pronounced inter-annual variability in seed yield, as reproductive success is influenced by environmental conditions during both the year of floral initiation and the subsequent flowering and seed development phases (Hynynen et al., 2010; Pelham et al., 1984; Sarvas, 1956). Birch typically produces some seed annually, while abundant seed crops often occur at intervals of approximately two to three years (Cameron, 1996; Holm, 1994).

Genetic diversity and reproductive synchrony in seed orchards

The conservation of genetic diversity is a key consideration in the design and management of forest tree breeding and seed production systems (Ivetić et al., 2016). In seed orchards established for the production of forest reproductive material, it is essential to ensure adequate representation of selected genotypes and effective cross-pollination among them. Consequently, seed orchards typically include multiple superior clones selected for desirable traits such as growth performance, vitality and stem quality. For these orchards to function as intended breeding populations, however, it is crucial that the participating clones contribute to gene exchange through successful flowering and pollination (Eriksson et al., 2013; Lindgren & Prescher, 2005).

Even when several dozen clones are represented within a seed orchard, effective cross-pollination may remain limited if flowering intensity is low or uneven among clones. Differences in reproductive characteristics including the age at first flowering, flowering intensity and the temporal pattern of reproductive development are known to have a strong genetic component in many forest tree species (Kang, 2003; Owens & Blake, 1985). In addition, the phenology of flowering may vary substantially among clones. In wind-pollinated species such as birch, the flowering period of individual trees may be very short, sometimes lasting only a few days, meaning that asynchronous flowering among clones can significantly reduce opportunities for cross-fertilization and lead to unequal parental contributions to the seed crop (Sarvas, 1952).

Plastic-covered seed orchards offer important advantages for controlling pollination processes. The physical barrier created by the plastic covering can effectively reduce contamination from external pollen sources, while the warmer microclimate often accelerates reproductive development and leads to earlier flowering compared with natural stands. These conditions may substantially increase the genetic value of the produced seed by ensuring that pollination occurs primarily among the selected orchard clones (Harju & Nikkanen, 1996; Ruotsalainen, 2014). However, such controlled systems also place greater responsibility on orchard design and management to maintain adequate genetic diversity and balanced parental contributions over time.

For this reason, the selection of clones for seed orchard establishment should consider not only breeding traits such as productivity and quality but also reproductive characteristics, including flowering capacity and phenological compatibility.

Juvenile phase and reproductive maturity in birch

One of the key biological advantages of birch in forest reproductive material production is its relatively short juvenile phase compared with many economically important conifer species. In natural stands, silver birch typically begins producing flowers and viable seeds at approximately 10–15 years of age (Perala & Alm, 1990). This contrasts with species such as Norway spruce and Scots pine, where the onset of regular seed production often occurs several decades after stand establishment. The relatively early onset of

seed production in birch therefore represents an important advantage for breeding programmes and seed orchard establishment, enabling shorter breeding cycles and earlier availability of genetically improved reproductive material.

The transition from the juvenile vegetative phase to the generative phase represents a critical developmental threshold in woody plants. During the juvenile stage, trees are physiologically incapable of forming reproductive structures regardless of environmental conditions (Zimmerman, 1972). Only after this phase has been completed do trees acquire reproductive competence and become capable of initiating floral buds (Hackett & Murray, 1993).

Shortening the juvenile phase through the induction of early flowering has been identified as an important objective in the breeding of woody perennials (Khan et al., 2025). Experimental studies indicate that flowering in birch can occur at a very early developmental stage: under controlled conditions, reproductive structures have been observed in individuals as young as 8–30 months after germination (Longman, 1976; Longman & Wareing, 1959).These observations suggest that reproductive competence may develop early in the ontogeny of birch, although under natural conditions flowering usually occurs later, once sufficient crown development and resource accumulation have been achieved.

Understanding the factors that regulate the transition from vegetative growth to reproductive development is therefore essential for improving the efficiency of birch seed production systems.

Environmental and physiological triggers of flowering

The transition from vegetative growth to reproductive development in woody plants is controlled by a complex interplay of environmental cues and internal physiological signals (Khan et al., 2025; Wang et al., 2024). In temperate tree species, floral initiation is typically regulated by seasonal changes in environmental conditions, including photoperiod, temperature and resource availability, which interact with endogenous developmental processes to determine the timing and intensity of flowering (Wilkie et al., 2008). In birch, reproductive buds are generally initiated during the previous growing season (Dahl & Strandhede, 1996), indicating that environmental conditions experienced during summer may play a crucial role in determining the following year's flowering intensity and seed crop.

Light availability and temperature are among the most important environmental factors influencing flowering in trees. Long photoperiods and favourable temperature conditions during the growing season can promote the formation of reproductive buds (Almqvist, 2018; Tooke & Battey, 2010).

Carbon availability and the carbon–nitrogen (C:N) balance are widely considered important physiological factors influencing the initiation of flowering in woody plants. Classical plant physiology concepts suggest that relatively high carbon availability, or a higher C:N ratio, tends to favour reproductive development, whereas high nitrogen availability typically promotes vegetative growth. Early studies on woody plant development noted that the accumulation of carbohydrates in shoots and buds often coincides with periods of floral bud initiation (Kozlowski & Pallardy, 1997; Zimmerman, 1972). In forest trees, stored carbohydrates provide both energy and structural carbon for the formation of reproductive organs, and several studies indicate that greater carbon reserves may contribute to increased flowering intensity in subsequent seasons (Hoch, 2005).

Hormonal and genetic regulation of floral initiation

The transition to flowering in woody plants is regulated by complex genetic networks integrating environmental signals and internal physiological status. Among the genes associated with floral induction in birch, particular attention has been given to the MADS-box transcription factor BpMADS4, which is homologous to floral identity genes involved in the regulation of reproductive development in many angiosperms. Experimental overexpression of BpMADS4 in silver birch has been shown to induce precocious flowering, with transgenic trees producing inflorescences within the first year of growth (Elo et al., 2007; Lemmetyinen et al., 2004).

In addition to genetic regulation, plant hormones are widely known to influence floral initiation in woody perennials. Applications of gibberellins, cytokinins, or other growth regulators have been successfully used to stimulate flowering in several forest tree species, particularly conifers such as *Picea* and *Pinus* in seed orchard management (Owens & Blake, 1985; Pharis & King, 1985). However, comparable experimental evidence for effective hormone-induced flowering in birch is limited.

Stress-induced flowering responses

Stress-related physiological responses are known to influence the transition from vegetative to reproductive development in many woody plants. Numerous studies demonstrate that abiotic and biotic stressors can modulate hormonal signalling networks regulating floral induction, including changes in gibberellins, cytokinins, auxins and abscisic acid, which affect meristem identity and the initiation of floral buds (Li et al., 2024; Sun et al., 2022). Moderate stress often reduces vegetative vigour, thereby altering internal resource allocation in ways that favour reproductive development. Such conditions are frequently associated with increased carbohydrate accumulation in buds and shoots, shifts in the carbon–nitrogen balance, and changes in assimilate partitioning, all of which are recognised as important physiological cues for floral initiation in woody perennials (Song et al., 2024; Sun et al., 2022).

Stress-inducing silvicultural practices that simulate drought or disrupt vascular transport such as stem or branch girdling are widely used to manipulate reproductive development in conifer seed orchards

(Wheeler et al., 1985). Experimental studies on silver birch have shown that partial root excision and soil-drying treatments significantly alter stomatal conductance, root-to-shoot signalling and carbon allocation patterns, creating physiological conditions associated with moderate stress (Fort et al., 1998). Although these studies primarily examined physiological responses to water stress, they suggest that stress-induced changes in resource allocation and hormonal signalling may potentially influence reproductive activity in birch grown under controlled seed orchard conditions.

Future research directions for improving flowering and seed production in birch seed orchards

Despite considerable knowledge about the reproductive biology of silver birch, several important aspects of flowering regulation and seed production remain insufficiently understood. Context of intensive existing studies provide valuable insights into the ecological, physiological and molecular mechanisms underlying flowering in woody plants, however, the integration of these processes into practical seed production systems remains limited. This is especially relevant for plastic-covered seed orchards, where environmental conditions, pollination dynamics and tree physiology differ substantially from those in natural stands.

Identifying the physiological thresholds that trigger reproductive bud formation in birch is a critical research need. Although environmental cues such as photoperiod, temperature and resource availability are known to influence flowering, the specific combinations of factors required to consistently initiate floral development remain poorly defined. In particular, further research is needed to clarify the role of carbohydrate reserves, carbon–nitrogen balance and tree nutritional status in regulating flowering intensity under orchard conditions.

Another important research direction relates to the synchronisation of flowering among clones in seed orchards. Genetic variation in flowering phenology and reproductive capacity can lead to unequal parental contributions to the seed crop, potentially reducing the effective population size and genetic diversity of the produced reproductive material. Future studies should therefore investigate the extent of clonal variation in flowering timing and intensity in birch seed orchards.

Further research is also needed to evaluate the effectiveness of stress-based management practices for stimulating flowering in birch. While techniques such as drought stress, root pruning or girdling have been widely used to enhance reproductive activity in conifer seed orchards, comparable experimental studies in birch remain scarce. Investigating how controlled stress treatments influence hormonal signalling, resource allocation and floral induction in birch could provide valuable tools for improving reproductive performance in intensive seed production systems.

Overall, advancing knowledge in these areas will be essential for developing more reliable and efficient birch seed production systems capable of supporting forest regeneration and tree breeding programmes under changing environmental and socio-economic conditions.

Conclusions

1. Silver birch possesses several biological characteristics that make it particularly suitable for intensive seed production systems, including early reproductive maturity and relatively short breeding cycles compared with many economically important conifer species. The initiation of flowering in birch is controlled by a complex interaction of developmental stage, environmental conditions and internal physiological processes, including carbon balance, hormonal regulation and genetic control mechanisms.
2. Plastic-covered seed orchards provide important opportunities to improve the genetic quality and reliability of birch seed production by enabling control of pollination and orchard microclimate. However, several key knowledge gaps remain. In particular, further research is required to determine the physiological thresholds that trigger floral initiation in birch, to understand the genetic and phenological variation in flowering among clones and its impact on reproductive synchrony, and to evaluate the potential of stress-based management practices to stimulate flowering under controlled orchard conditions.
3. Addressing these research gaps will be essential for developing management strategies that ensure both regular seed production and balanced genetic contributions among clones, thereby maintaining the genetic diversity and long-term sustainability of birch seed orchard systems.

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EFFECT OF ALNUS GLUTINOSA (L.) GAERTN. AND BETULA PENDULA ROTH. PLANTATIONS ON GROUND COVER PLANT DIVERSITY

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Abstract
Afforestation of low-value agricultural lands is one of the most important actions to ensure climate neutrality. There are several alternatives, one of which is short rotation cycle forests, aimed at maximizing timber production. The research aims to characterize changes in ground-cover vegetation diversity in deciduous tree plantations. The study was conducted in two black alder sites and two silver birch sites - plantation stands at a young age (12 years old). In each site, 24 sample plots of 2x1 meters were established. In each sample plot, the number of ground cover vegetation plant species, their projective cover (%), occurrence, constancy classes, and Ellenberg indicators were assessed. The average number of ground cover species (species richness) in black alder sites is 44.0, whereas in birch sites it is 35.5. The difference in the number of plant species is not statistically significant; no significant differences were observed in the average projective cover (%) of ground cover plants. Based on the study results, it is recommended to grow black alder in plantations with a greater diversity of ground-cover species. In the black alder and one silver birch plantations, no significant impact of deciduous tree species on ground cover plant diversity has been found.
Keywords: *Alnus glutinosa* (L.) Gaertn., *Betula pendula* Roth., ground cover, diversity.

Introduction

Since the 1930s, forest areas in Latvia have doubled, due to the afforestation of pastures and low-fertility arable land, as well as the urbanization process. Unused and shrub-covered agricultural land areas in Latvia are mainly located in regions with low soil fertility and a small population (Kaktiņš & Arhipova, 2005). The issue of rational and sustainable land management is topical worldwide. This issue must be addressed comprehensively by assessing the quality of the environment, economic sustainability, profitability, and social benefits. One way to manage land not used for agriculture is afforestation, which provides significant economic and ecological benefits. It limits and controls rainwater runoff and soil erosion, while reducing water, soil, organic and nutrient losses, thereby promoting the accumulation of organic matter and preservation soil biological activity. These benefits are largely determined by the proportional presence of trees in the system.

A plantation is a stand of one or two species of even age class, established with local or introduced species to obtain the maximum amount of a certain type of wood or other products in the shortest possible time. The establishment, registration, and management of plantation forests are regulated by the Forest Law (Saeima, 2000) and Cabinet of Ministers Regulation No. 308 'Regulation on Afforestation, Forest Establishment and Plantation Forests' (Ministru kabinets, 2012). The Latvian regulatory framework not only allows for the application of different management measures in these areas, but also does not exclude the possibility of returning them to agricultural production in the future (Liepiņš et al., 2013). Biomass from tree plantations is an essential component of the transition to more sustainable energy production. Increasing forest areas and establishing new plantations help limit CO_2 emissions into the atmosphere (Liepiņš, 2022). Plantation trees not only produce wood and related by-products, but also significantly improve the ecological condition of the surrounding environment. Forest plantations provide up to 33% of the total industrial roundwood used worldwide, and it is predicted that this share will reach 50% by 2040 (Liu et al., 2018).

Studies show that forest plantations, when properly managed, can preserve biodiversity by increasing the diversity of different plant and animal habitats, as well as reducing the impact of logging on commercial forests (Liu et al., 2018). Species for plantation crops should be selected not only based on the wood growth rate, but also on the suitability of the species for growth in open areas and resistance to adverse abiotic and biotic factors.

In Latvia, from 2019 to 2023, there was an upward trend in the afforestation of plantation stands. Deciduous tree species have a greater capacity to promote soil organic carbon sequestration, since they have a higher ratio of root biomass to aboveground biomass. In general, deciduous tree species have a faster growth rate and a larger, deeper root system, which, in turn, creates greater input of soil organic carbon through root litter into deeper soil layers. From the perspective of climate change mitigation, it is recommended that tree species that produce the greatest biomass in the shortest possible time will be selected for establishing forest stands. In this way, those tree species would sequester most CO_2 (Bārdulis, 2022). Black alder *Alnus glutinosa* (L.) Gaertn. is a fast-growing tree species with the largest annual growth at 20-25 years old (Mauriņš & Zvirgzds, 2009). It is a very soil-demanding species but can also grow in poor, sandy soils if oxygen-rich groundwater is nearby (Mangalis, 2004), as it is a nitrogen (N)-fixing species (Ahmed et al., 2016). Recent studies show that black alder also plays an important role in plantation forestry, since it grows well in periodically overmoist areas or in areas with high groundwater levels, forming a deep and extensive root system also in anaerobic conditions (Daugaviete et al., 2017). Silver birch,

Betula pendula Roth, is a fast-growing, highly light-requiring, and highly resistant to climate extremes tree species. It grows well in well-drained, humus-rich soils. Birch has a relatively shallow but extensive root system that can reach depths of up to 2 m in loose soils. Due to its rapid growth, care for birch crops is minimal or unnecessary (Mangalis, 2004). Birch is the most commercially important deciduous tree species in Latvia. It is widely used for afforestation of agricultural lands (Liepiņš, 2011). The rapid growth characteristic of birch in its juvenile stage persists until 40-50 years of age (Daugaviete et al., 2017). Birch stands on agricultural soils are faster-growing and more productive than on forest soils, and the trees for the production of veneer logs in plantations of agricultural soils can reach the required parameters already at the age of 40 (Liepiņš, 2011). Scientists from Nordic countries consider birch a key energy tree species due to its ability to produce significant biomass in a relatively short period (15-20 years).

The ground vegetation in the forest is mainly determined by soil type and the dominant tree species, which in turn influence light intensity, its variability during the growing season, and the chemical composition of dead plant litter. Established plantations can increase plant diversity in agricultural landscapes by functioning as an additional element that provides a habitat for new species. Consequently, the resulting plant communities are highly diverse, comprising a mix of meadow, ruderal, and typical forest species. Studies have shown that plant diversity in the established plantations can be even richer than in coniferous and mixed forests (Dimitriou & Rutz, 2015). Intensive management of short-rotation timber plantations often results in soil depletion. To preserve soil fertility, it is recommended to use species that fix atmospheric nitrogen when establishing plantations, either in admixture or through species rotation. Tree species of the genus *Alnus* are characterized by symbiosis with nitrogen-fixing actinobacteria, which fix atmospheric nitrogen and deposit it in the soil in the form of nitrates available to plants. Thus, alder also increases the growth rates of other trees in the immediate vicinity (Liepiņš K. & Liepiņš J., 2010). The study aims to characterize the diversity of ground cover vegetation in deciduous tree plantations.

Materials and Methods

The research object is located in Ķeipene parish, Ogre municipality (Figure 1). The established plantation is an experimental plantation owned by the Latvian State Forest Research Institute 'Silava'. In the study, *Betula pendula* Roth and *Alnus glutinosa* (L.) Gaertn. plants planted in 2012 were selected as sample groups, with 2 plots per species. The total number of trees planted in each plot was 200. The distance between the trees was four meters. Vegetation data were collected in the summer season of 2024. A 2x1 m^2 sample plot was placed one meter away from two trees, continuing to arrange them in strips - a total of 24 sample plots in each plot (Figure 2). In each sample plot, the ground cover was characterized - the total projective cover of vegetation in %, all plant species were counted and recorded, and the projective cover of each plant species in % was determined.

Figure 1
The location of the research object

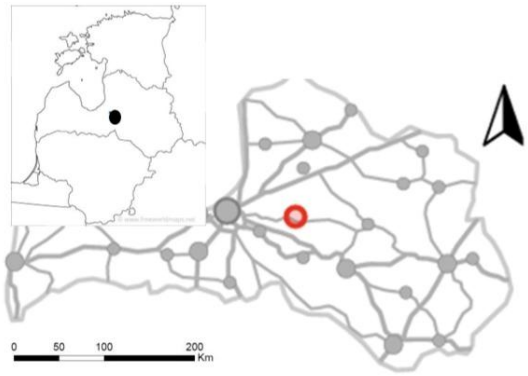
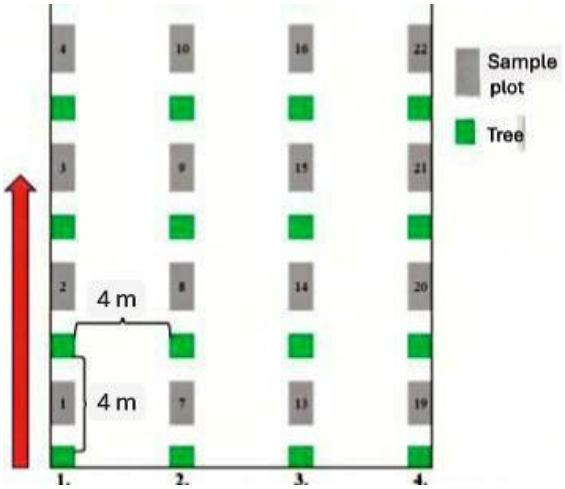


Figure 2
The sample plot scheme



Using Raunkiaer's formula, the occurrence coefficient was calculated for all vegetation species, which shows the frequency of occurrence of each species in the sample plots. The occurrence coefficients correspond to 5 constancy classes (percentage frequency): class I (1-20%), class II (21-40%), class III (41-60%), class IV (61-80%), and class V (81-100%). Ellenberg's ecological indicators were determined for the species of the herbaceous plant layer. They were determined for four environmental factors – moisture, light, soil reaction, and nitrogen (Ellenberg et al., 1992). Analysis of variance was performed using the ANOVA tool (Arhipova & Bāliņa, 2006).

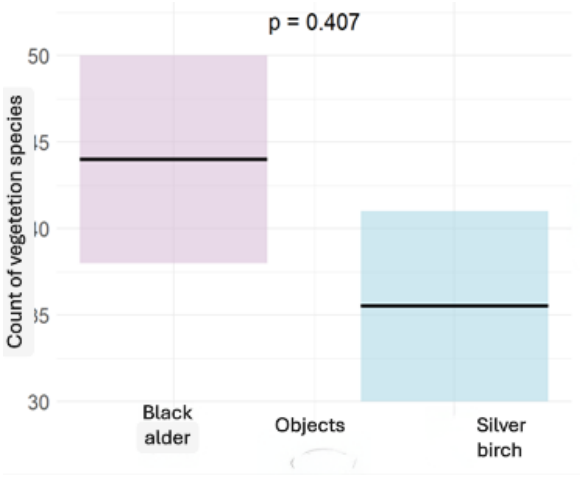
Results and Discussion

Number of species

In *Alnus glutinosa* (L.) Gaertn. plots, 38 and 50 vascular plant species were counted and recorded,

respectively, with an average of 44 species. In *Betula pendula* Roth plots - 30 and 41 vascular plant species, respectively, with an average of 35.5 species (Figure 3). When performing an analysis of variance, it was found that the difference in the number of species across different deciduous tree plots was not statistically significant (p-value = 0.407 > 0.05).

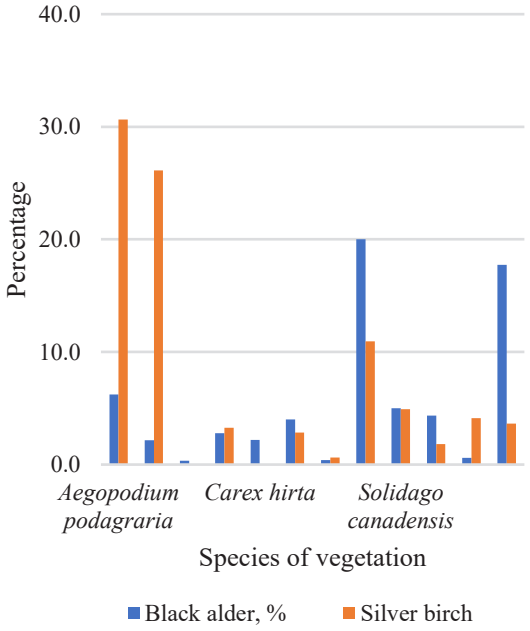
Figure 3
The number of plant species at each site and the average number of plant species



Species occurrence
The occurrence of a plant species indicates how often it is represented in a plant community. Plants with an occurrence of at least 50% (a plant occurs in at least two plots) and their constancy class from III-V were used for data analysis. As a result, we obtain an indicator that 31.3% of plant species from the total number of species occur in two plots - the constancy class of these plants is III (occurrence is 41-60%); 23.9% of plants are found in three plots and their constancy class is IV (occurrence 61-80%), but plants that are found in all plots (in all sample plots) are 19.4% from the total number of plants, respectively, form constancy class V (occurrence 81-100%).

Average projective cover of plants (%)
In *Alnus glutinosa* plots, the largest projective cover in a single plot is occupied by Aegopodium podagraria, indicating nitrogen-rich soil, *Veronica chamaedrys,* and *Poa sp*. In contrast, in the other *Alnus glutinosa* plot, the largest average projective cover is *Poa sp., Equisetum arvense,* and *Ranunculus repens.* In *Betula pendula* plots, the ground cover vegetation is predominantly composed of *Aegopodium podagraria*, with an average cover of 30% and 17%, respectively, as well as *Poa sp.* and *Dactylis glomerata*. In all results of the analysis of variance, the calculated p-value is >0.05, indicating that there are no significant differences in the average projective cover of ground cover vegetation across plots. Fertile soils, additional levels of plant-available nutrients lead to the increased development of aggressive herbs with high competitive ability – such as *Aegopodium podagraria*, which inhibit the immigration of woodland herbs (Orczewska, 2009). A study on the influence of tree species on the diversity and conservation of ground cover vegetation in Germany indicates that the correct choice of tree species is a practical tool to increase biodiversity in the ground cover, thus contributing to the conservation of endangered and rare species (Oijen et al., 2005) (Figure 4).

Figure 4
The comparison of the average percentage cover of the most important species



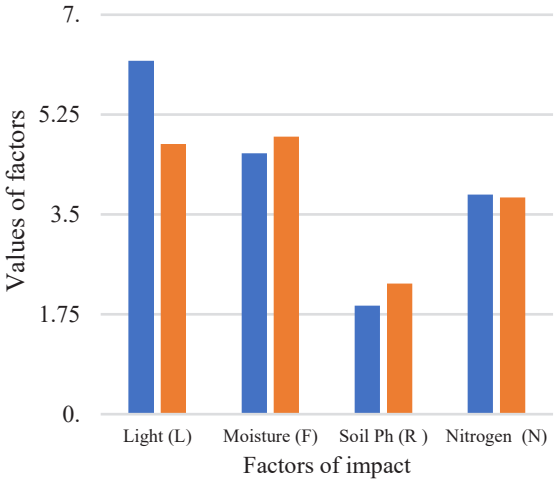
Assessing the Ellenberg ecological indicator values
Species with similar ecological factor values can be included in a single ecological group. Ecological groups provide information about environmental conditions that affect the entire plant community. The simplest way to use the indicator values of all representatives of the plant community is to calculate average factor values, which assess the relative importance of various environmental factors. According to the Ellenberg scale evaluation, the corresponding value for the specific influencing factor was found for each plant. The conditions evaluated were the following: light (L), moisture (F), soil pH (R), nitrogen (N), or nutrient concentration. Based on the numerical values of the Ellenberg scale for each plant, average values were calculated for each influencing factor in each plot (Figure 5).
The development of ground cover is not only driven by the combined influence of edaphic and light conditions, but also by the availability of water. Most woodland herbs avoid habitats with extreme hydrological conditions, both too wet and too dry, but show a clear affinity for sites with a moderate level of this abiotic factor (Orczewska, 2009). When evaluating the average values of Ellenberg's influencing factors, it can be observed that the highest

light requirements are shown by the ground cover in the second *Alnus glutinosa* plot (6.39); this indicator is also very close in the second *Betula pendula* plot (6.33). The sites with lower average light values are in the first plots (6.14 and 6, respectively). It can be concluded that in all plots there are conditions of semi-light, and no statistically significant differences were found (p-value > 0.05).

Soil moisture is one of the most important environmental factors that determine the composition, structure, and functionality of vegetation in dryland ecosystems. Studies have shown that species diversity increases with greater water availability. When assessing the impact of moisture, it can be seen that the highest average indicator is in the second *Betula pendula* plot (5.21), followed by the second *Alnus glutinosa* plot (4.97). In the first plots, the average moisture factor values are 4.17 and 4.52, respectively, indicating that all plots have moderately moist soil conditions. The impact of former agricultural land-use on forest soils has become an object of growing interest because historical land-use can influence present-day soil characteristics and, through that, also the diversity patterns of forest plant species (Orczewska, 2009).

Studies have shown a significant positive relationship between vascular plant diversity and soil pH in moderately moist to moist soils. The pH response index in plots varies from 1.87 to 2.38, indicating acidic soil conditions. Plant diversity is positively related to soil pH – higher soil pH, or more alkaline soil, is associated with a greater number of plant species (Partel et al., 2004). Former arable soils have higher nutrient concentrations resulting from previous agricultural fertilization (Lutter et al., 2016). Soil acidification has been identified as one of the main risks in fast-growing tree stands or plantations (Rajapaksha, 2012). Average values of nitrogen presence or soil nutrient content are relatively equivalent and characterize moderately rich soils. Studies show that biodiversity after the establishment of a tree plantation depends on the land use before its establishment (Bremer & Farley, 2010). The influence of initial ground cover vegetation decreases with increasing tree age. Light-demanding species most often form the ground cover plant composition at the early age of the stand, while as the stand age increases, the number of shade-tolerant plant species increases (Pučka et al., 2016).

Figure 5
The average values of environmental factors



Conclusions

1. The differences between the number of plant species and the average projective cover (%) indicators in *Alnus glutinosa* (L.) Gaertn and *Betula pendula* Roth plots are not statistically significant.
2. Greater plant species diversity was found in *Alnus glutinosa* plots.
3. Ellenberg values in all plots indicate semi-light conditions, moderately moist and acidic soil, and moderately rich in nutrients.
4. In *Alnus glutinosa* and *Betula pendula* stands, no significant effect of a tree species was found on the diversity of ground cover vegetation.

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OCCURRENCE PATTERNS OF KEY NON-TIMBER FOREST PRODUCTS: EVIDENCE FROM THE NATIONAL FOREST INVENTORY IN LATVIA

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Abstract
Non-timber forest products (NTFPs) are a significant forest ecosystem service, especially with the growing societal importance of forests not only as a timber source but as a multifunctional ecosystem. However, quantitative information on the topic in Latvia is still scarce. Drawing on an extensive National Forest Inventory dataset (4,916 plots), we explored the occurrence, mean cover, and mean height of eight ground vegetation species commonly used as NTFPs and correlated these indices with the forest site characteristics (trophic conditions and soil moisture level) and stand parameters. The most frequently recorded species were *Vaccinium myrtillus, Vaccinium vitis-idaea,* and *Rubus idaeu*s, found in 31.8%, 23.8%, and 19.5% of all plots, respectively. The cover and height of NTFPs were significantly influenced by both site conditions (soil fertility and moisture) and stand structure (age, density, and tree species composition), with strong interdependencies between these factors. The projective cover of most species was significantly influenced by the dominant tree species, stand density, and site trophic level. In contrast, the hydrological factor had a significant effect only on *Vaccinium myrtilus, Fragaria* spp, and lichens. The cover of *Vaccinium vitis-idaea* and *Calluna vulgaris* was statistically significantly negatively affected by stand age and stand density. The cover of *Vaccinium* species, *Fragaria* spp., lichens, and also *Calluna vulgaris* was positively influenced by the dominant tree species *Pinus sylvestris.* Furthermore, data on the overall status of NTFPs in the country provide a foundation for evaluating how different forest management approaches influence the long-term availability and dynamic trends of these resources.
Keywords: ground vegetation, forest berries, stand structure, site conditions.

Introduction

Forests, the most widespread terrestrial ecosystems, offer a wide range of benefits for society. While timber and firewood are most closely associated with the term 'forest resources', non-timber forest products (NTFPs) contribute significantly to people's well-being globally and in the Nordic-Baltic region. FAO defines these products as 'goods of biological origin other than wood derived from forests and other wooded land and trees outside forests' (FAO, 1999), and they include food and food additives, medicinal, cosmetic and decorative resources and fibres. These products are highly important in the European context - at least 100 million Europeans consume various NTFPs, but at least 65 million engage in their collection (Schulp et al., 2014). NTFPs are a crucial part of multi-purpose forestry, even though conflicts with certain forest management approaches exist (Lõhmus & Remm 2017; Kurttila et al., 2018). Foraging for NTFPs often creates a synergy with forest recreation (Kangas & Niemeläinen, 1996; Stryamets et al., 2015; Wiersum, 2017). Moreover, mushroom and berry picking are deeply rooted cultural practices, widely studied in Northern Europe, the Baltics, Central Europe and Western Europe (Pouta et al., 2006; de Aragon et al., 2011; Sisak et al., 2016; Grivins & Tisenkopfs, 2018). In Latvia, NTFPs have high socioeconomic and cultural meaning. According to previously published data from various sources, over 60% of households engage in NTFP gathering (Lovrić et al., 2020; Donis, 2020, 2024). According to Lovrić et al. (2020), *Vaccinium vitis-idaea* and *Vaccinium myrtillus* are the most frequently picked wild berries in Northern Europe. Other species with good potential for picking are *Vaccinium uliginosum* and *Rubus idaeus*. In Latvia, historically important NTFP resources in swampy areas are *Oxycoccus palustris* and *Oxycoccus microcarpus*. While repeated surveys show decreasing NTFPs retail sales (Bārdule et al., 2020), a minor part of the population, especially in the rural areas, still largely rely on the added income provided by the sales of forest berries and mushrooms (Donis, 2024). For the majority of NTFP foragers, however, this activity bears both provisioning and recreational meaning and constitutes a lifestyle aspect rather than a practical necessity (Lībiete, 2023).

While foraging may be a predominantly recreational activity, the availability of the NTFPs is still an essential factor determining the forest visitors' satisfaction with the outdoor experience. The occurrence and abundance of plants, mushrooms, and other organisms depend on the habitat, as well as meteorological conditions. Light availability, site fertility, and soil moisture, as well as management-induced disturbances, are the major factors determining the composition of ground vegetation, including NTFPs (Tonteri et al., 2016, Eldegard et al., 2019; Matisone et al., 2023).

Despite their acknowledged importance, nationwide data on the actual occurrence and cover of NTFPs are scarce. Our study aims to address this knowledge gap by examining the relationships among site conditions, stand structure, and the cover and height of the eight most common NTFPs—*Vaccinium myrtillus, Vaccinium vitis-idaea, Vaccinium uliginosum, Rubus idaeus*, other *Rubus* species*, Fragaria* spp., *Calluna vulgaris*, and lichens.

Materials and Methods

The study is based on data from the NTFP assessment

of the Latvian National Forest Inventory (NFI). The NFI in Latvia is a systematic, nationwide grid-based network of permanent sample plots measured at five-year intervals (circular plots with 500 m² area, 4 plots per tract, tracts are located in 4 × 4 km grid). Within the 500 m² plot, all trees with a diameter at breast height (DBH) ≥ 14.1 cm are measured; within the inner 100 m² circular plot, all trees with DBH ≥ 6.1 cm are measured; within one quarter of the inner plot (25 m²), trees with DBH ≥ 2.1 are measured.

NTFPs have been assessed on NFI plots since 2008. The assessment is conducted in 3 × 3 m rectangular plots located at the center of the 500 m² circular plot. Following species, comprising edible, medicinal, and decorative plants, are recorded*: Vaccinium myrtillus, Vaccinium vitis-idaea, Vaccinium uliginosum, Rubus idaeus, Rubus caesius, Rubus nessensis, Rubus plicatus, Rubus odoratus, Fragaria vesca, Fragaria viridis, Calluna vulgaris* and lichens (*Cladonia sp., Cetraria islandica*). Although *Fragaria vesca* is the most likely species in forest habitats, the NFI field assessments identify these species only at the genus level. Within each subplot, species-level projective cover (%) is recorded, along with modal height (in 0.05 m classes) and, during the reproductive season, the presence of flowers or fruits (berries).

This study used data from one complete NFI cycle (2019–2023), comprising 4916 plots located in forest land and clear-felling areas (forest land categories 10 and 14). The sample covered a wide range of site conditions, including gradients of soil fertility (from oligotrophic to eutrophic) and soil moisture (dry, mesic, and wet), as well as variation in stand age and stand density. Species' projective cover and height were analysed using generalized linear mixed models (*GLMMs)* fitted in R (version 4.2.2) with the *glmm*TMB package. Because the cover data were strictly positive and right-skewed, a *Tweedie* distribution with a log link function was applied, which is suitable for continuous, positive ecological data with heterogeneous variance.

For cover-intensity analyses, only positive observations (cover > 0) were included, thereby modelling cover magnitude conditional on species presence. Fixed effects comprised site characteristics—soil fertility (from oligotrophic to eutrophic) and soil moisture (dry, mesic, and wet)—as well as stand structural variables: relative density of the first and second canopy layers, stand age, and dominant tree species group. Tract identity was included as a random intercept to account for repeated measurements and potential non-independence of observations within plots.

Inference was based primarily on effect size estimates and their 95% confidence intervals. Where multiple comparisons were performed, p-values were adjusted using the false discovery rate (FDR) approach.

All data processing and visualization were done in RStudio, version 4.2.2.

Results and Discussion

At least one of all studied NTFPs was found on 2978 plots (60.6% of all plots). The most frequently recorded species were *Vaccinium myrtillus*, *Vaccinium vitis-idaea* and *Rubus idaeus*, found on 1,609, 1,173, and 931 plots (31.8%, 23.8%, and 19.5%, respectively). Other species were recorded on less than 10 percent (from 7.6% to 0.8%) of the plots (Table 1). The highest mean cover was recorded for *Rubus* spp. *Vaccinium myrtillus*, *Vaccinium uliginosum*, and *Rubus idaeu*s. The mean height varied most for *Rubus idaeu*s (from 0.05 m to 2.2 m), indicating that these species might rely the most on varying site conditions and stand parameters.

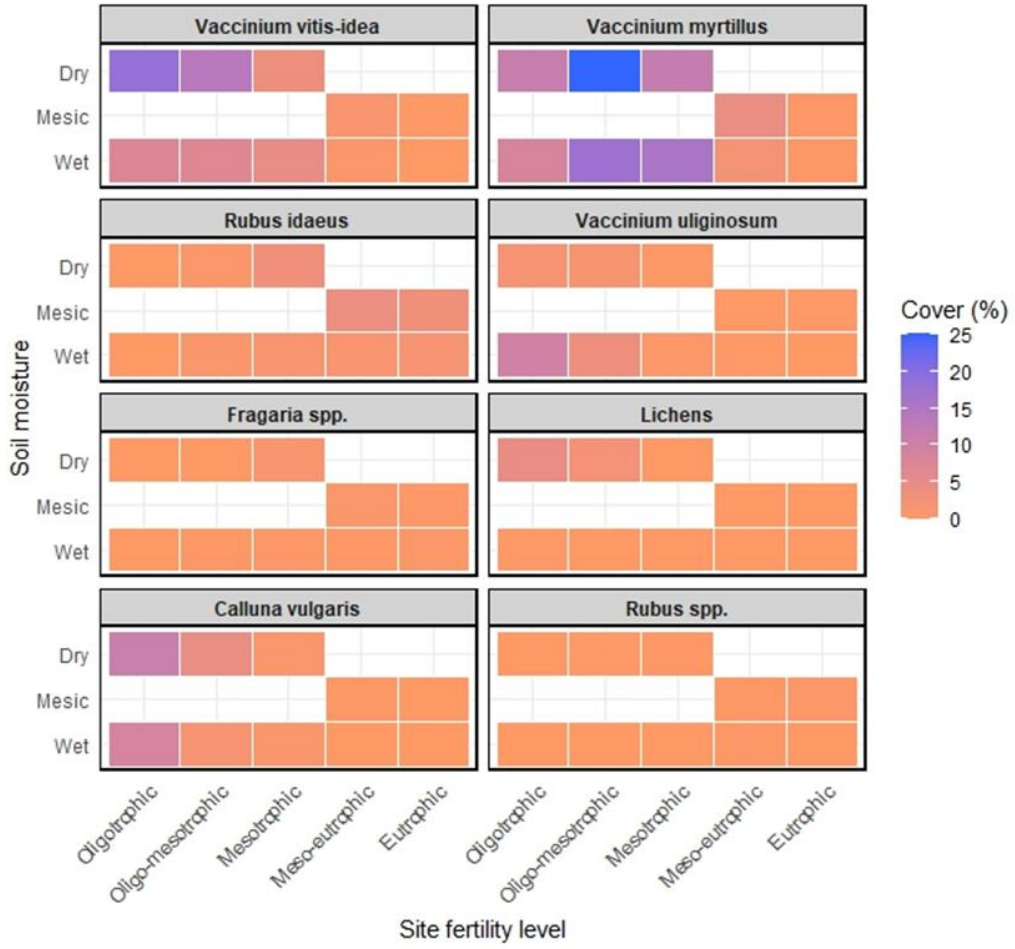
Table 1

Occurrence, mean cover, mean height, and predominant site conditions characterizing the studied NTFPs

NTFP	Occurrence, % (number of plots)	Mean cover, %, where species was present	Mean height, cm	Predominant site conditions (fertility level/moisture)
Vaccinium myrtillus	31.81/1609	25.22±0.44	20.55±0.17	Mesotrophic/Dry
Vaccinium vitis-idaea	23.82/1173	14.72±0.27	12.63±0.14	Oligo-mesotrophic/Dry
Vaccinium uliginosum	4.39/216	18.93±0.35	40.31±0.79	Oligo-mesotrophic/Wet
Rubus idaeus	19.47/931	16.31±0.33	64.5±1.15	Meso-eutrophic/Mesic
Rubus spp.	0.85/43	38.7±2.19	46.78±0.4	Meso-eutrophic/Wet
Fragaria spp.	7.57/369	9.62±0.18	12.56±0.02	Meso-eutrophic/Mesic
Calluna vulgaris	6.98/337	18.25±0.38	25.14±0.1	Oligo-mesotrophic/Dry
Lichens	1.52/73	17.46±0.38	-	Oligo-mesotrophic/Dry

The highest occurrence and cover were determined by each species' ecological requirements and adaptive capacity. *Vaccinium vitis-idaea* was one of the most frequently observed (and with the highest cover) in dry oligotrophic forest stands. In contrast, *Vaccinium myrtillus* was characteristic of slightly more fertile sites and occurred in both dry and wet conditions (Figure 1).

Figure 1
Predicted cover (%) of the studied NWFPs, by soil moisture and site fertility level, %



The model results indicated that the significant factors affecting projected cover differed across the analysed species. For example, for *Vaccinium myrtillus*, in contrast with the other species, the factor that positively influenced cover was the dominance of *Pinus sylvestris* in the main stand compared to spruce (β= -0.385, $p < 0.001$), birch (β=-0.950, $p < 0.001$), and other species (β=, -1.887, $p < 0.001$) (Figure 2). This is consistent with the results from Northern European studies where higher *Vaccinium myrtillus* cover was found in *Pinus*-dominated forests compared to *Picea*-dominated ones (Eldegard et al., 2019; Miina et al., 2009), while deciduous trees decreased *Vaccinium myrtillus* cover, especially on the most fertile mineral soil sites. (Turtiainen et al., 2016). In our study, stand age showed a weak but significant positive effect on *Vaccinium myrtillus* cover ($\beta = 0.012$, $p < 0.001$), whereas, compared to the reference trophic group (eutrophic forest soils), the cover of *Vaccinium myrtillus* was significantly higher in the mesotrophic group ($\beta = 3.305$, $p < 0.001$), the mesoeutrophic group ($\beta = 2.318$, $p < 0.001$), the oligomesotrophic group ($\beta = 3.539$, $p < 0.001$), and the oligotrophic group ($\beta = 2.334$, $p < 0.001$).

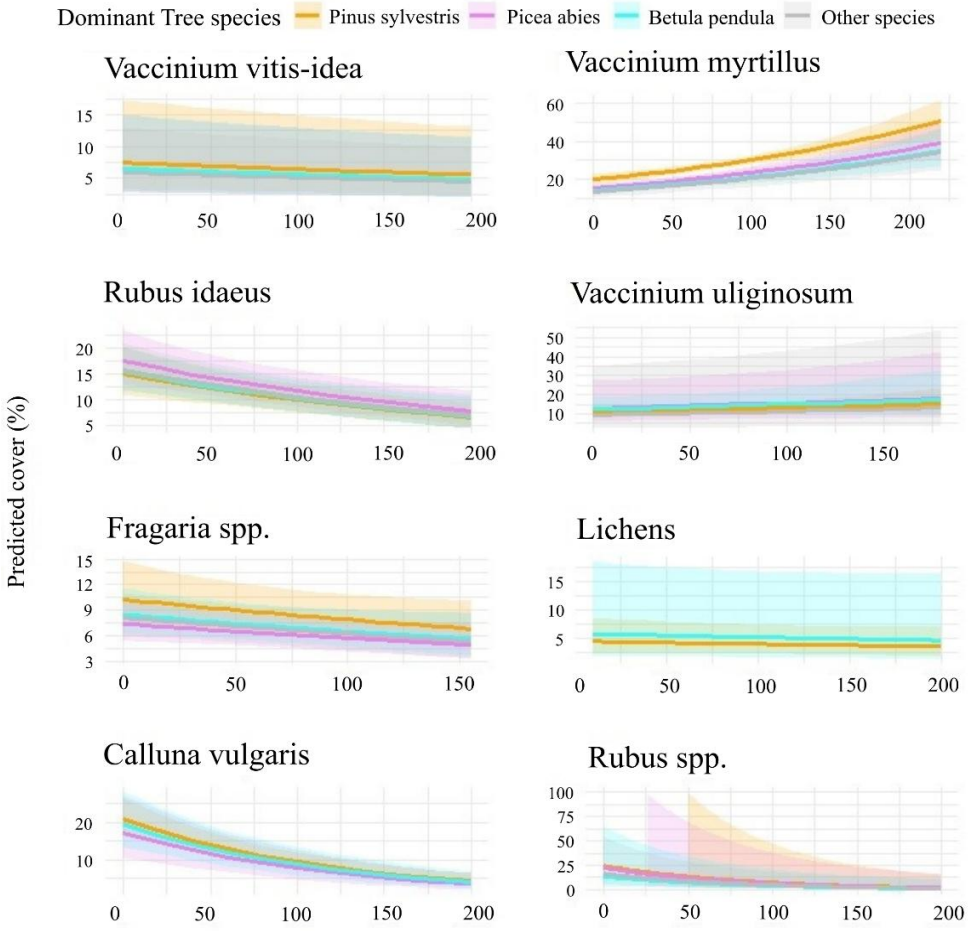
The predicted increase was gradual, indicating that older forests provided more favourable conditions for *Vaccinium myrtillus*. Similar results have been reported by Eldegard et al. (2019) in a Norwegian study, where an increase in *Vaccinium myrtillus* cover was observed in older stands. For *Rubus idaeus*, however, the negatively influencing factor was stand age (β = -0,173, $p < 0.001$) – its cover declined as stand age increased, and the trend was similar in oligotrophic and oligo-mesotrophic conditions. This confirms that this species is characteristic for early successional stages of the forest. *Rubus idaeus* often becomes dominant within 2–3 years after major over-story disturbances (e.g., clear-cutting) in mesic temperate forests (Donoso & Nyland, 2006). The abundance of shrubs decreases rapidly as the stand canopy closes at 30 years of age (Kardell, 1979). However, our results indicate a more gradual and consistent decline rather

than an abrupt reduction.

Calluna vulgaris is commonly found in dry pine forests, clear-cuts, bogs, and acidic, nutrient-poor soils. In our study, it was positively associated with *Pinus sylvestris* stands, compared to *Picea abies* ($\beta = -1.995$, $p < 0.001$) or *Betula* spp. ($\beta = -1.736$, $p < 0.001$), but negatively associated with stand density and stand age ($\beta = -0.016$, $p < 0.001$).

Figure 2

Predicted cover (%) of the studied NTFPs depending on the age of the dominant stand tree species. Graphs show the results of the glmmTMB models



Note: the scales for predicted cover (%) and stand age (years) differ among species.

Comparing changes in projective cover in relation to stand age and stand density, it was evident that stand density did not significantly affect ($\beta = 0.161$, $p < 0.001$) the *Vaccinium myrtillus* cover.

A study conducted in Lithuania on the vegetation succession in pine stands concluded that the highest cover of *Calluna vulgaris* occurred in the early stages of stand development, when stand density was relatively low (Gustienė et al., 2022). It has been found that the optimal stand relative density for *Vaccinium vitis-idaea* ranges from 0.1 to 0.3, at which the species attains its highest projective cover (Timoshok, 2000).

The model results indicated that the factors significantly affecting the projected height differed among the analyzed species and the dominant tree species. For *Vaccinium myrtillus*, a gradual increase in predicted height was observed with increasing stand age ($\beta = 0.161$, $p < 0.001$). Statistically significant differences between stand age and height were observed for *Vaccinium myrtillus* ($\beta = 0.001$, $p < 0.001$), *Rubus idaeus* ($\beta = 0.001$, $p < 0.001$), other *Rubus* spp. ($\beta = 0.001$, $p < 0.001$), and *Calluna vulgaris* ($\beta = -0.001$, $p < 0.001$) (Figure 4).

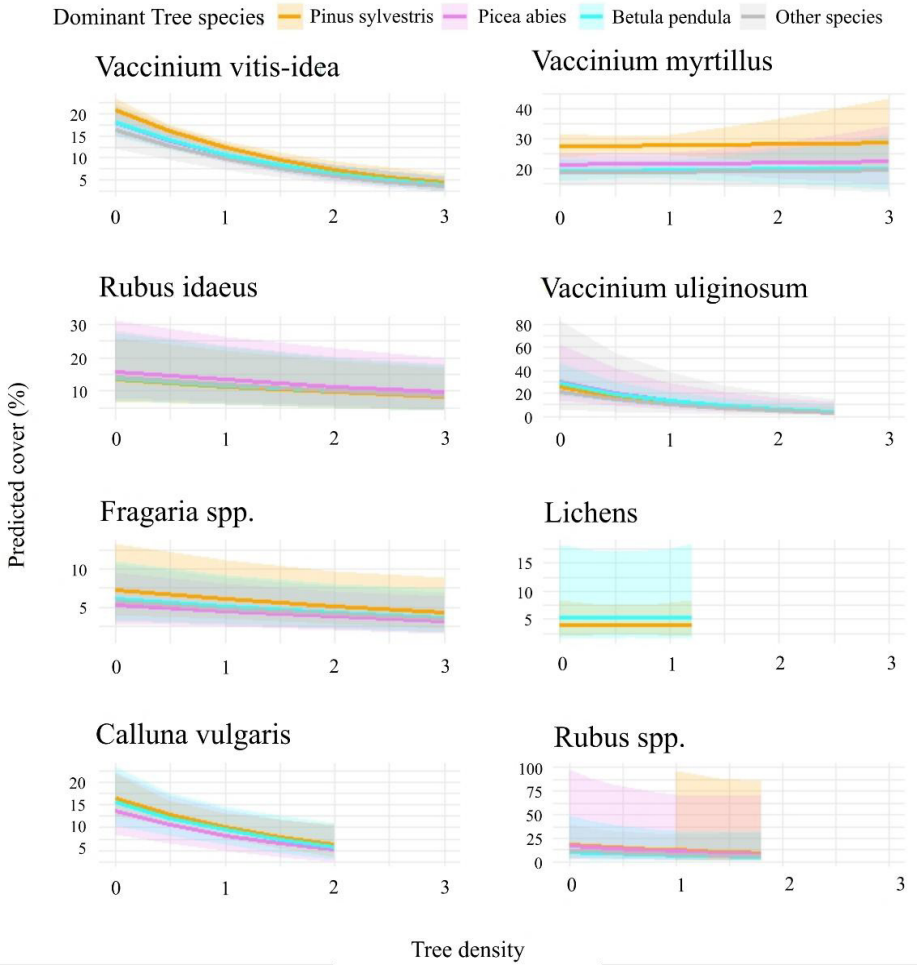
Predicting optimal forest characteristics for NTFPs is of general ecological interest and importance for sustainable and well-balanced forest management. Based on a nationwide dataset of sample plots across different forest type groups, we demonstrate that the effects of stand age and stand density on species cover and height are also influenced by tree species composition, hydrological conditions, and trophic groups.

Due to data availability and time constraints, this

study primarily focused on forest berries and did not include other important non-wood forest products, such as mushrooms, which require significantly longer time series due to high yield variation resulting from a complex interaction of meteorological factors (Dahl et al., 2008, Olah et al., 2020). Nevertheless, the results indicate the presence of non-wood forest products in Latvian forest stands, including those where clear-cut regeneration has been applied.

Figure 3

Predicted cover (%) of the studied NTFPs depending on the tree density (relative tree density according to local legislation) of the dominant stand tree species. Graphs show the results of the glmmTMB models



Note: the predicted cover (%) scale differs among species.

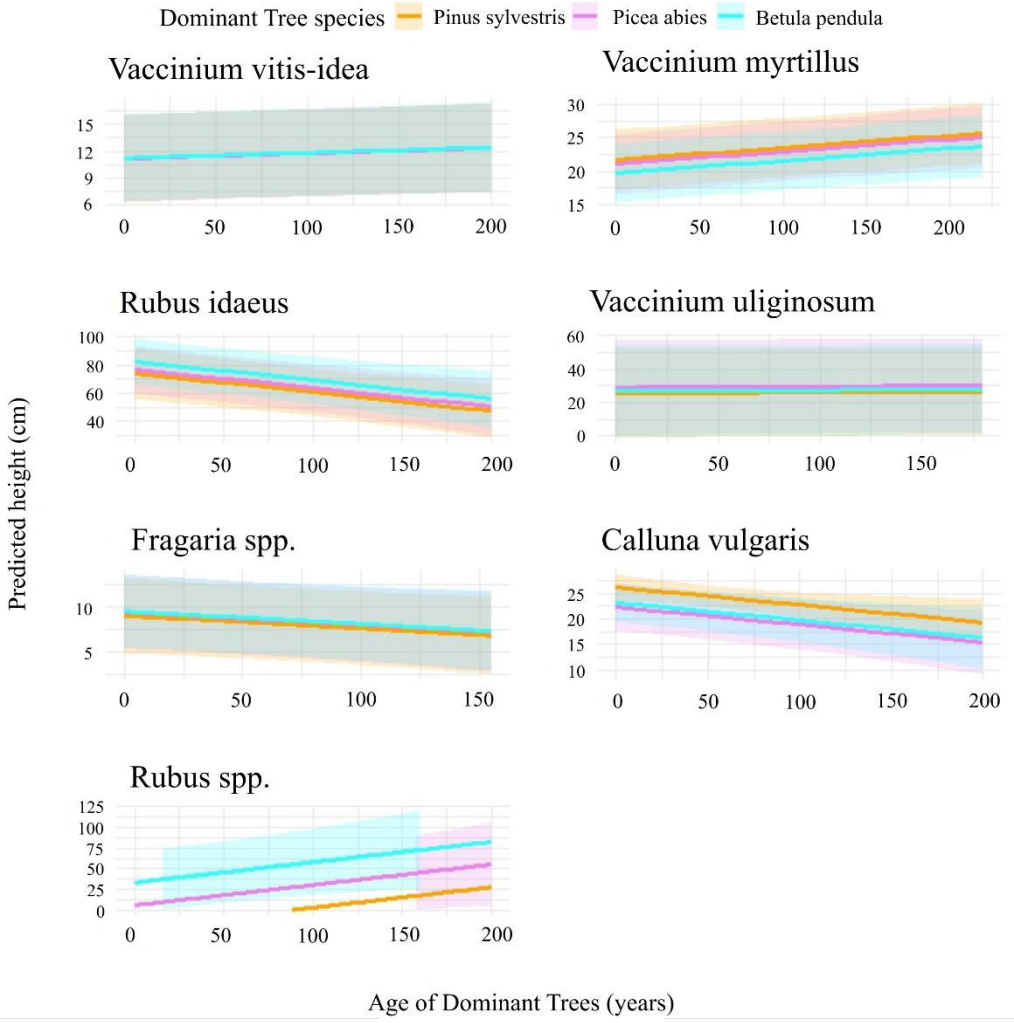
The findings of this study represent the overall condition of NTFPs in the country. These data can serve as a baseline, complemented by berry yield data and factors driving annual variation, for further analysis and assessment. Furthermore, the data on the overall status of NTFPs in the country provide a foundation for evaluating how different forest management approaches influence the long-term availability and dynamic trends of NTFPs.

Conclusions

1. Most frequently recorded forest berry species in Latvia are *Vaccinium myrtillus*, *Vaccinium vitis-idaea*, and *Rubus idaeus,* while the remaining species are recorded much less frequently, reflecting their narrower ecological niches.
2. The highest average projected cover of *Vaccinium myrtillus* and *Vaccinium vitis-idaea* is observed in the dry forest group, from oligotrophic to mesotrophic forests.
3. Both tested variables (projective cover and height) of the studied NTFPs vary significantly among the tested sites. The cover of NTFPs is explained by a broader range of factors than height, suggesting that cover is a more sensitive indicator of changes in environmental conditions and stand structure
4. Strong relationships exist between site conditions and stand structure: specific site conditions determine the formation of characteristic stand types (e.g., the dominance of pine on nutrient-poor soils), which, in turn, affect the cover and height of NTFP species. The cover and height of NTFPs are significantly influenced by both site conditions and stand structure, which are closely interrelated and collectively influence NTFP occurrence and characteristics.

Figure 4

Predicted height (cm) of the studied NTFPs depending on the age of the dominant stand tree species. Graphs show the results of the glmmTMB models



Note: the scales for predicted cover (%) and stand age (years) differ among species.

Acknowledgements

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SNOW, WATER, AND TERRAIN AS DRIVERS OF FOREST SCENIC BEAUTY

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Abstract
Understanding outdoor visitors' preferences can support spatial planning and management of nature areas. Prior research suggests that distinct environmental features—such as snow cover, topographic variation, and nearby water—can increase visual appeal by adding contrast, depth, and recognizable focal points. To assess the effects of these three elements on the aesthetic evaluation of five forest landscape types among the Latvian population, we conducted a nationwide representative online survey (CAWI; n = 1001). Respondents rated photographs on a 7-point Likert scale using paired comparisons across five forest setting types: pine stand, spruce stand, broadleaved stand, clear-cut area, and forest road. For each setting type, participants evaluated matched photo pairs where one image included a target element (snow, water, or terrain variation) and the other did not. Internal consistency of ratings was examined using reliability analysis, and paired differences between image versions were tested with the Wilcoxon signed-rank test. All analyses were performed in IBM SPSS Statistics v26. Across all conditions, pine stands received the highest ratings, while clear-cut areas were rated lowest. The presence of the tested elements generally increased ratings across setting types, but effects varied in magnitude. Differences were most pronounced for spruce and broadleaved stands, where images featuring snow, terrain variation, or water were rated notably higher than their matched counterparts without these elements. Overall, the findings underline the role of salient visual features as cues that can measurably enhance perceived attractiveness, offering practical entry points for improving perceived amenity through planning and design.
Keywords: landscape amenity, visual preference, forest setting, paired comparisons, societal survey.

Introduction

Understanding preferences for different outdoor settings is essential for managing visitor flows in nature areas, particularly when the goal is to protect sensitive sites or plan management interventions in time and space. Previous research indicates that landscape elements (e.g., terrain, presence of waterbodies), seasonality (including phenological changes, notably autumn and winter), and meteorological conditions (such as snow cover or extreme temperatures) can significantly influence visitors' perceptions of natural environments (Pálsdóttir, 2009; Korpela et al., 2010; Jaal et al., 2013; Tyrväinen et al., 2017; Ebenberger & Arnberger, 2019; Wang et al., 2020).

Snow cover enhances the visual attractiveness of forested areas by creating a picturesque, peaceful environment often associated with harmony and beauty. Studies suggest that viewing snow-covered landscapes may also improve mood (Bielinis et al., 2021). In forest settings, the bright white snow contrasts with darker tree tones, increasing visual appeal. This transformation may attract more visitors during winter, as people seek scenic views, photography opportunities, and winter recreation (Xiao et al., 2015; Bausch & Unseld, 2017).

The presence of waterbodies in forests increases scenic beauty and provides opportunities for activities such as fishing, boating, and swimming. Water can enhance outdoor experiences by evoking peace and relaxation or by offering possibilities for active recreation. People are naturally drawn to water, and its presence can elevate the overall scenic quality of a landscape while supporting diverse habitats that attract wildlife enthusiasts and photographers (Kakoyannis, 2002; Mundher et al., 2022).

Terrain variability - hills, valleys, and other topographic features - also contributes to the aesthetic and recreational value of forested areas. Pronounced and diverse terrain creates a more dynamic and engaging landscape compared to flat, uniform sites. Such diversity supports activities like hiking, mountain biking, and climbing, while also increasing the variety of viewpoints and, consequently, the scenic quality of the forest (Golovets, 2011).

Although the importance of landscape elements in shaping visitors' perceptions is widely acknowledged, detailed empirical studies remain comparatively scarce. The objective of this study was to assess the effects of snow cover, waterbody presence, and terrain variability on the aesthetic evaluation of five forest landscape types among the Latvian population.

Materials and Methods

Data were collected in autumn 2024 through an online survey (CAWI; n = 1001) administered by a professional survey company to a nationally representative sample of respondents (balanced by gender, age, and place of residence). Participants evaluated photographs of forest landscapes using a 7-point Likert scale (1 – dislike a lot … 7 – like a lot). The photo set included five forest landscape types: pine forest, spruce forest, broadleaved forest, clearfelling area, and forest road. Each landscape type contained three pairs of photographs showing the presence or absence of a specific landscape element (snow, terrain variability, waterbody). All other attributes within each pair - such as forest type, stand age, stand density, and lighting - were kept as similar as possible. We selected forest types typical of Latvia (medium fertility and soil moisture) with normal stand density (7–8) and medium-aged to mature stands. To avoid copyright issues, all photographs were taken by the authors. An example photo pair is shown in Figure 1. Photographs were presented in random order, and all respondents rated all pairs.

Figure 1
Example of photos used for the evaluation in category 'Forest road' (left – with snow, right – without snow)



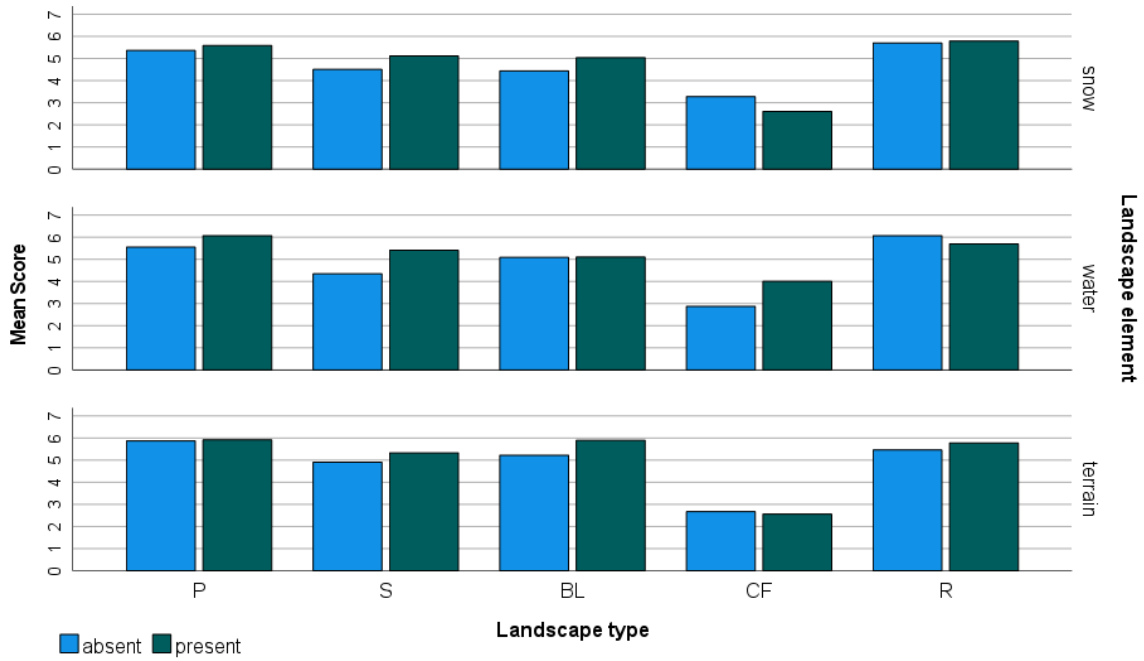
To assess the internal consistency of the evaluation items, we conducted a reliability analysis using Cronbach's alpha, which confirmed that the photo-based Likert-scale ratings were sufficiently reliable for subsequent statistical testing. Differences in perceived landscape value between photos with and without each environmental element were analysed using the Wilcoxon signed-rank test, an appropriate non-parametric method for paired ordinal data. All data processing and statistical analyses were performed in IBM SPSS Statistics v27.

Results and Discussion

Cronbach's alpha was 0.926, indicating very high internal consistency of the evaluation scores.

Across all forest landscape photographs, pine stands and forest roads received the highest ratings, while clearfelling areas were evaluated the lowest. These results align with previous findings from the Nordic–Baltic region (e.g., Silvennoinen et al., 2010; Tyrväinen et al., 2017). In most cases, the presence of a landscape element increased the assigned score. The largest difference in mean scores (1.1 points) was observed when comparing spruce forests and clearfelling areas with and without a waterbody. The smallest differences were found for forest roads with or without snow, broadleaved forests with or without a waterbody, and pine forests with or without terrain (Figure 2).

Figure 2
Mean evaluation scores with the tested landscape element absent and present across the assessed forest landscapes



Median values indicated generally positive attitudes toward all forest landscape types. For pine forests, broadleaved forests, and forest roads, the dominant rating was 'like', regardless of the landscape element. Attitudes toward spruce forests were less positive, with more frequent 'neutral' or 'rather dislike' responses. Clearfelling areas were evaluated most negatively, with dominant ratings of 'dislike' and 'rather dislike' (Table 1).

Figure 3
Distribution of the evaluation scores across forest landscape types and landscape elements

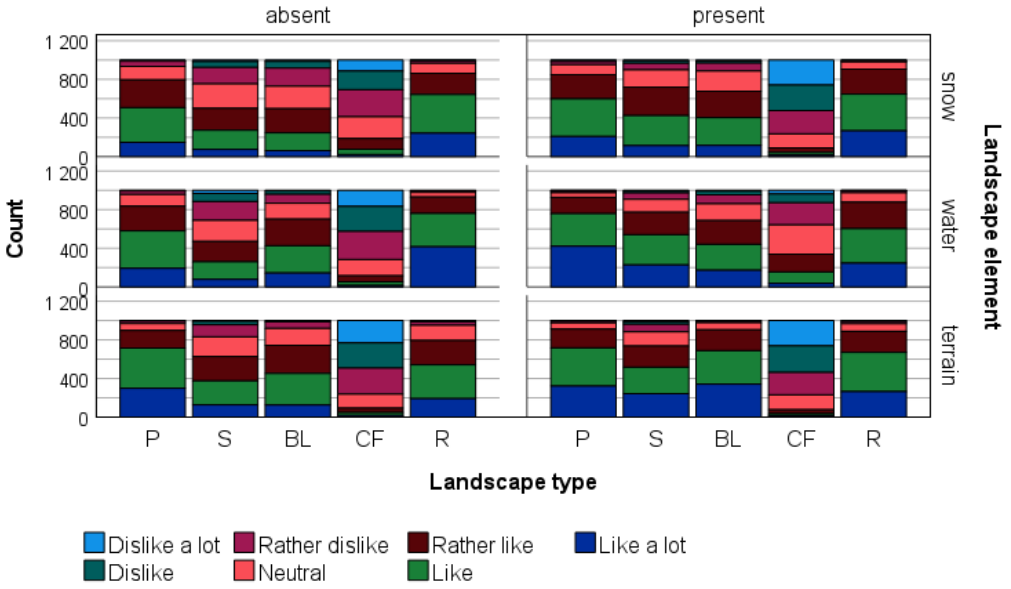


Table 1
Descriptive statistics of scores assigned to photos with or without the tested elements across landscape types

Landscape type	Element (S – snow, W – water, T – terrain)	Descriptive statistics of the scores (element present/element absent)				
		Mean	St. error of mean	Median	Mode	St. dev.
Pine forest	S	5.58/5.37	0.036/0.036	6.00/6.00	6/6	1.140/1.150
	W	6.07/5.55	0.033/0.035	6.00/6.00	7/6	1.041/1.095
	T	5.92/5.87	0.032/0.033	6.00/6.00	6/6	1.023/1.050
Spruce forest	S	5.12/4.51	0.039/0.045	5.00/4.00	6/4	1.249/1.409
	W	5.42/4.36	0.042/0.048	6.00/4.00	6/4	1.326/1.533
	T	5.34/4.92	0.045/0.043	6.00/5.00	6/5	1.422/1.375
Broadleaved forest	S	5.04/4.43	0.041/0.044	5.00/4.00	6/5	1.284/1.398
	W	5.11/5.08	0.044/0.042	5.00/5.00	6/6	1.404/1.343
	T	5.91/5.22	0.033/0.037	6.00/5.00	7/6	1.049/1.166
Clearfelling area	S	2.61/3.28	0.045/0.046	2.00/3.00	2/3	1.415/1.450
	W	4.01/2.87	0.044/0.044	4.00/3.00	4/3	1.391/1.387
	T	2.57/2.67	0.044/0.045	2.00/3.00	2/3	1.382/1.412
Forest road	S	5.79/5.70	0.032/0.034	6.00/6.00	6/6	1.026/1.087
	W	5.70/6.08	0.033/0.033	6.00/6.00	6/7	1.042/1.030
	T	5.78/5.45	0.034/0.037	6.00/6.00	6/6	1.063/1.160

Within each landscape type, pine forests showed the most consistent evaluations, with minimal differences between photos with and without snow, terrain, or water. The opposite pattern emerged for spruce forests: settings without landscape elements were often rated neutral or negative, while the presence of snow, terrain, or water substantially increased positive evaluations. A similar trend was observed for broadleaved forests. In clearfelling areas, snow cover slightly reduced ratings, whereas waterbody presence increased the proportion of neutral responses and reduced negative ones. This 'inverted' effect of snow may be explained by the thin snow cover and visible logging residues in the photographs. For forest roads, terrain had the strongest positive effect, increasing the share of moderately to highly positive ratings (Figure 3). Overall, these results suggest that landscape elements matter, but their influence is not uniform: when the 'base setting' is already well-liked, additional elements have a smaller effect than in less preferred settings such as spruce forests.

In nearly all landscape types, photos with the tested landscape element received higher ratings. In all cases except pine forests with or without terrain and

broadleaved forests with or without a waterbody, the differences were statistically significant ($p < 0.05$; Table 2). Forest roads showed the smallest influence of landscape elements: in all three photo pairs, more than 40% of respondents assigned identical scores. In contrast, for spruce forests, more than 40% of respondents rated the element-present photos higher across all three elements (snow, terrain, water).

When examining the landscape elements separately, waterbody presence emerged as the strongest driver of increased aesthetic value, raising scores by +1.14 points for clearfelling areas. Snow produced small to moderate increases in pine, spruce, and broadleaved forests and forest roads, but decreased ratings for clearfelling areas (-0.67). Terrain had the strongest positive effect in broadleaved forests (+0.69) and forest roads (+0.33), with minimal impact in pine forests and a slight negative effect in clearfelling areas. Overall, aesthetic evaluations were similar across socio-demographic groups, with some exceptions. Respondents from the capital city Riga and the surrounding Pieriga region showed larger score differences between photos with and without landscape elements, with statistically significant differences in all cases except forest roads with or without snow.

Table 2

Score differences of the photo pairs (element present vs. element absent), Wilcoxon signed-rank test results

Landscape type	Element (S – snow, W – water, T – terrain)	Z-value	p-value
Pine forest	S	-6.734	<0.001
	W	-12.556	<0.001
	T	-1.927	0.054
Spruce forest	S	-13.079	<0.001
	W	-18.479	<0.001
	T	-8.995	<0.001
Broadleaved forest	S	-13.608	<0.001
	W	-0.9	0.368
	T	-15.129	<0.001
Clearfelling area	S	-16.426	<0.001
	W	-18.359	<0.001
	T	-3.621	<0.001
Forest road	S	-2.464	0.014
	W	-10.571	<0.001
	T	-9.351	<0.001

The consistent positive effects of snow, terrain, and waterbody presence on perceived aesthetic value suggest several practical implications for forest management. Pine forests are generally well-liked (as also shown by Silvennoinen et al., 2001), but in spruce-dominated areas with monotonous views, designing for visible waterbodies or highlighting terrain features may enhance perceived attractiveness. Waterbodies may also soften negative perceptions of clearfelling areas, whereas snow does not necessarily improve their appearance - suggesting that winter recreation routes near recent clearcuts may reduce visitor satisfaction. It should be noted that the example used in this study depicted a thin snow cover, which is increasingly common under current climatic conditions; thicker snow may have a more positive effect (Tyrväinen et al., 2017). Waterbodies are widely associated with positive affect and restorative qualities in both natural and built environments (White et al., 2010). However, their aesthetic contribution depends on their recognizability as natural blue spaces; artificial ditches or straightened channels may not enhance visitor experience (Grace et al., 2023).

This study has several limitations. Although the photographs represented typical Latvian forest settings and were matched as closely as possible within each pair, it is still possible that factors other than the tested landscape element influenced the ratings. Visual materials inherently introduce additional evaluative cues such as viewing angle, composition, rhythm, colour tones, and lighting (Sevenant & Antrop, 2011). Even carefully matched photo pairs may differ subtly in attributes such as path curvature, sky visibility, or understorey structure, which can affect evaluations (Palmer & Hoffman 2001). Moreover, personal associations, memories, and value systems may shape individual responses, with some studies identifying visitor characteristics as key determinants of perceived visual attractiveness (e.g., Kearney & Bradley, 2010; Hegetschweiler et al., 2022). Homogeneity of landscape has been perceived negatively in some cases; thus, a broader, holistic study at the landscape level would be prudent in determining preferences (Schirpke et al., 2013). Photo-based surveys capture only visual information, whereas on-site experiences include sound, smell, temperature, wind, movement,

and perceived safety, all of which may influence landscape perception (Hull & Stewart, 1992). Future research on forest amenity values could therefore benefit from more immersive technologies such as 360° imagery, video, or virtual reality, which have shown promise in landscape assessment (Shi et al., 2020).

Conclusions

1. Pine forests received the highest aesthetic ratings but clearfelling areas the lowest, regardless of the presence of landscape elements.
2. Snow cover, waterbody presence, and terrain variability generally increased the stated aesthetic quality of forest landscapes, with waterbody presence showing the strongest positive effect and only a few exceptions across landscape types.
3. Among the three tested elements, waterbody presence had the strongest positive effect on aesthetic ratings; snow cover produced small to moderate increases in most forest types but reduced ratings for clearfelling areas; terrain variability had the strongest positive effect in broadleaved forests and forest roads.
4. Residents of the capital city and its surrounding region rated element-present images considerably higher than residents of other areas.
5. The aesthetic effects of snow cover, waterbody presence, and terrain variability differed across forest landscape types, with the most pronounced responses observed for spruce and broadleaved forests.

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REDUCTION OF R:FR RATIO MODULATES SHOOT ARCHITECTURE OF *BETULA PENDULA IN VITRO* WITHOUT IMPAIRING PHOTOSYNTHESIS

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Abstract
Far-red light has emerged as an important spectral component in plant tissue culture, affecting morphogenesis and physiological development. Supplementation with far-red light lowers the red:far-red (R:Fr) ratio perceived by plantlets, promoting stem elongation, internode extension, apical dominance and leaf expansion traits often desirable during the shoot multiplication and elongation phases. However, the excessive reduction of R:Fr can induce etiolation, reduced chlorophyll accumulation, and weakened structural tissues. In this study, the performance of *in vitro* cultures of three silver birch clones under LED illumination with R:Fr ratio of ~1.0 was tested. Cultivation in such conditions seemed to partially trigger the expression of shade-avoidance like traits, while maintaining the robustness and photosynthetic capacity of plantlets. More resources were allocated to main shoot growth, while lateral shoot development was inhibited, and propagation rates remained the same. At the same time, relative chlorophyll content (SPAD) was slightly lower, yet photosynthesis worked more efficiently as indicated by higher PI_{ABS}. Quantum yield efficiency (Fv/Fm) for plantlets cultivated under low R:Fr was slightly higher, yet remained above the optimum threshold (0.8) for both treatment and control. These findings demonstrate that far-red light supplementation can be used to manipulate the architecture and physiological performance of *B. pendula in vitro*, promoting elongation and potentially improving transplant-ready morphology, while maintaining efficient photochemical activity and robustness of plantlets.
Keywords: Silver birch, phytochrome signalling, micropropagation, LED, shade-avoidance.

Introduction

Light quality is a critical environmental signal regulating plant growth and development. In natural ecosystems, solar radiation is selectively filtered by vegetation: chlorophyll strongly absorbs red and blue wavelengths, while far-red (Fr) radiation (700–750 nm) is transmitted and reflected (Ballaré et al., 1990). As a result, the red:far-red (R:Fr) ratio declines beneath plant canopies and within dense stands. Plants have evolved to interpret this spectral shift as an indicator of neighbouring vegetation and impending competition for light. A reduced R:Fr ratio, therefore, functions as an ecological signal that enables plants to adjust their growth strategy to optimise light capture and survival (Tan et al., 2022).

Perception of R:Fr changes is mediated by the phytochromes, which exist in two conformations: the red-absorbing Pr and the biologically active Fr-absorbing Pfr (Tan et al., 2022). The relative proportion of these forms reflects the spectral composition of the environment and regulates downstream signalling networks, including hormonal pathways involving auxins, gibberellins, and brassinosteroids (Demotes-Mainard et al., 2016; Wang et al., 2022). Under the reduced R:Fr conditions, phytochrome signalling promotes a suite of morphological and physiological responses commonly associated with shade environments. These include stem and internode elongation, enhanced apical dominance, reduced lateral branching, and altered leaf orientation or expansion (Ballaré et al., 1990; Casal, 2012; Franklin, 2008; Tan et al., 2022). Physiologically, reduced chlorophyll content and shifts in biomass allocation may occur, accompanied by modifications to photosynthetic function (Demotes-Mainard et al., 2016; Evans & Poorter, 2001). However, the magnitude and nature of these responses depend on species, genotype, light intensity, and exposure duration (Demotes-Mainard et al., 2016). Excessive Fr enrichment can induce etiolation, characterised by fragile tissues, diminished structural integrity, and reduced acclimatisation potential (Ballaré & Pierik, 2017).

Light spectrum manipulation is an effective tool for regulating plant architecture in controlled environments (Muleo et al., 2025). In micropropagation, overly compact shoots hinder handling and acclimatisation, while moderate elongation improves transplant readiness and efficiency. The key challenge is to promote elongation without inducing etiolation or reducing physiological performance. Far-red supplementation offers a targeted approach by stimulating axial growth while maintaining structural integrity and photochemical function (Franklin, 2008; Smith, 2000).

Despite increasing interest in spectral optimisation for controlled cultivation, most studies of Fr responses have focused on herbaceous crops and model species (Casal, 2012), while woody plants remain comparatively underexplored. Silver birch (*Betula pendula* Roth.) is an ecologically and economically important forest species in northern Europe, and efficient micropropagation protocols are essential for clonal propagation and breeding programs (Ryynänen L. & Ryynänen M., 1986). However, the effects of reduced R:Fr ratios on shoot architecture and physiological performance in birch microshoot cultures are insufficiently characterised, particularly with respect to maintaining structural integrity and photosynthetic efficiency.

The present study evaluates the effects of reduced R:Fr ratio (~1.0), on the morphology and physiological

performance of *in vitro* cultures of three silver birch clones. Specifically, we examined shoot morphology, chlorophyll status, and photochemical efficiency to determine whether the reduced R:Fr ratio can promote elongation and transplant-ready morphology without inducing etiolation or impairing photosynthetic function.

Materials and Methods

In this study, we used established *in vitro* cultures of three locally bred silver birch clones 54-461, 54-89 and 55-880 from *in vitro* clone archive of Latvian State Forest Research Institute 'Silava' Laboratory of Plant Physiology. Prior to the experiment, the cultures were routinely cultivated in 100 mL glass jars covered with transparent, gas-permeable plastic lids, containing ~20 mL of Woody Plant Medium (WPM) (Lloyd & McCown, 1980) supplemented with 0.1 mg L^{-1} BAP, sucrose 20 g L^{-1} and solidified with 6 g L^{-1} plant agar (SigmaAldrich, USA). Medium pH was adjusted to 5.8 prior to autoclaving (121 °C at 200 kPa for 20 min). Subcultures were carried out by dissecting fully regenerated plantlets into 1.5 cm long explants, either from shoot apex or shoot segments containing at least two leaves. Transplanted explants were then cultivated for six weeks on a vertical shelf system under full-spectrum (control) LED luminaires (Table 1) with total photosynthetic photon flux density (PPFD) 30±2 µmol m^{-2} s^{-1} and a 16/8h (day/night) photoperiod. The temperature in the growth chamber was maintained at 25 °C and relative air humidity at 30-40%.

Table 1

Photosynthetic photon flux density (µmol m^{-2} s^{-1}) distribution over spectral regions for luminaires used in this study and the relevant light ratios analysed

Spectral regions and relevant spectral ratios	Reduced R:Fr	Control
blue (B) (400-500 nm)	3.3	5.4
green (G) (500-570 nm)	2.6	3.9
yellow + orange (570-625 nm)	2.2	3.4
red (R) (625-700 nm)	10.8	16.8
far-red (Fr) (700-750 nm)	11.1	0.5
Total PPFD in PAR region (400-750 nm)	30	30
R:B	3.3	3.1
R:Fr	1.0	31.1
B:G	1.3	1.4

To test the effect of reduced R:Fr ratio, plantlets were cultivated under full-spectrum LED luminaires supplemented with Fr LEDs emitting light at a peak wavelength of 730 nm. The amount of Fr light was adjusted so that R:Fr reduced to ~1.0, while other significant light ratios (R:B, B:G) and total PPFD were maintained the same as for the control group (Table 1). As control, plantlets under spectral composition used for routine propagation purposes were cultivated. Spectral composition and PPFD were measured using an AvaSpec ULS2048 spectrometer (Avantes, The Netherlands). All other growth conditions were maintained the same as mentioned before.

After cultivation for 6 weeks, morphological characteristics of the plantlets – main shoot traits (length, number of internodes and average internode length), lateral shoot traits (number and length of shoots) and rooting rate of plantlets were evaluated. Using measurements of morphological traits, we calculated: 1) Multiplication index, derived by dividing total shoot length by the mean explant length (1.5 cm); 2) Lateral branching, defined as the percentage of plantlets that developed lateral shoots and 3) Axis Proportion Index (API), calculated by dividing the main shoot length by the total shoot length. The API describes biomass allocation to lateral or main axis, where a value less than 0.5 indicates longer lateral shoots and a value greater than 0.5 indicates a longer main shoot.

Physiological traits were assessed in the same plants alongside morphological measurements. Relative chlorophyll content (SPAD) was measured as an indicator of photosynthetic capacity using Minolta SPAD-502 (Konica Minolta, Japan). Mean value of 5 measurements was taken from the largest of newly formed leaves for each plant, representing relative chlorophyll content for the whole plant. Chlorophyll a fluorescence was determined using HandyPea portable fluorometer (Hansatech Instruments Ltd., UK) and used to assess the photosynthetic efficiency of plants. The same leaf as for SPAD was used for fluorescence measurements, representing the whole plant. Detached leaves were first dark-acclimated for 15 min, then exposed to short and saturated (1500 µmol m^{-2} s^{-1}) pulse of red light and the reemitted light was measured. Raw data were processed with PEA PLUS v.1.13 (Hansatech Instruments Ltd., UK) and exported as data points. For further analysis, we used fluorescence parameters Fv/Fm (as sensitive indicator of stress) and performance index PI_{ABS} (as a proxy of overall photosynthetic efficiency). In addition, we analysed the dynamics of special energy fluxes ABS/RC, DIo/RC, TRo/RC, ETo/RC to assess the absorption, dissipation, trapping, and electron transport rates,

respectively, in photosystem II (PS II).

Data analysis was conducted in R (v.4.2.2) using packages 'lme4' and 'emmeans'. The effects of light treatments and clone, and the interaction of both factors on the physiological and morphological characteristics of plantlets were assessed using linear mixed-effects models or generalised linear mixed-effects models applying Poisson or Binomial residual distribution depending on the data type analysed. Model assumptions were evaluated by visual inspection of residual Q–Q plots and residual-versus-fitted plots. Variance components of random effects were estimated, and intraclass correlation coefficients (ICC) were calculated to quantify variation among experimental units. Model explanatory power was assessed using marginal and conditional R^2 values. For variables where significant effect of light treatment appeared, the estimated marginal means were compared using the Tukey's HSD multiple comparison test. Altogether, data from 336 plantlets (56 jars each containing 6 plantlets) cultivated under experimental setup and control conditions were analysed.

Results and Discussion

Random-effect variance (τ00) associated with jar identity was generally low across most physiological and morphological traits and ranged between <0.0005 to 0.1, indicating that environmental variation between culture vessels was minimal. Intraclass correlation (ICC) coefficients ranged between 0.08 and 0.26, suggesting that only a small portion of total variability could be attributed to differences between jars. This indicates that the experimental conditions were relatively homogeneous and most of the observed variation was explained by clone and light treatment, rather than microenvironmental differences between jars. Marginal R^2 values ranged from approximately 0.14 to 0.51 for most variables, indicating moderate explanatory power of the fixed effects (clone identity and light treatment), which is common in biological systems, where quantitative traits are determined by many factors simultaneously (Hill, 2010). Conditional R^2 values were only slightly higher (0.22 to 0.57), suggesting that variation attributable to jar identity was relatively small.

Changes in the R:Fr ratio influenced plant development, as indicated by a significant effect of light treatment on measured variables (Table 2). For some parameters (PI_{ABS}, TRo/RC, ETo/RC, main-to-total shoot length ratio and average internode length), a significant clone × light treatment interaction was observed, indicating clone-specific responses to changes in spectral composition. Overall, clone effects were stronger and more consistent across variables, as reflected by higher χ^2 values compared with light treatment. Genetic differences between clones have previously been shown to strongly influence the proliferation capacity of silver birch plantlets *in vitro* (Ryynänen L. & Ryynänen M., 1986). Accordingly, when optimising micropropagation performance, the clone selection may play a more important role than specific environmental treatments, such as adjustments in the R:Fr ratio.

Table 2

Significance of clone identity, light treatment, and their interaction for physiological and morphological traits based on mixed-effects models displayed as χ^2 values

Variable	Clone	Light treatment	Clone × Light treatment interaction
SPAD	15.26***	51.22***	0.43
Fv/Fm	101.44***	4.15*	2.17
PI_{ABS}	94.77***	0.29	11.56**
ABS/RC	31.27***	0.54	2.36
Dio/RC	64.87***	3.64	4.08
TRo/RC	24.92***	15.97***	7.44*
ETo/RC	1.43	6.12*	14.77***
Main shoot length, mm	174.29***	34.97***	4.67
Lateral branching, %	27.92***	21.23***	4.76
Number of lateral shoots	23.11***	15.22***	2.51
API	29.93***	32.26***	11.83**
Multiplication index	250.09***	0.31	2.37
Number of internodes of main shoot	21.86***	0.32	3.02
Mean internode length, mm	54.31***	47.41***	11.94**
Rooting rate, %	35.79***	15.42***	1.79

*** - significant at p<0.001; ** - significant at p<0.01; * - significant at p<0.05.

Although the effect of clone was generally stronger, light treatment played an important role in shaping plant morphology. In particular, the R:Fr ratio exerted pronounced effects on morphology compared to physiology, as indicated by a significant effect of light treatment on 6 of 8 morphological variables versus 4 of 7 physiological variables (Table 2). Such decoupling of architectural adjustment from the

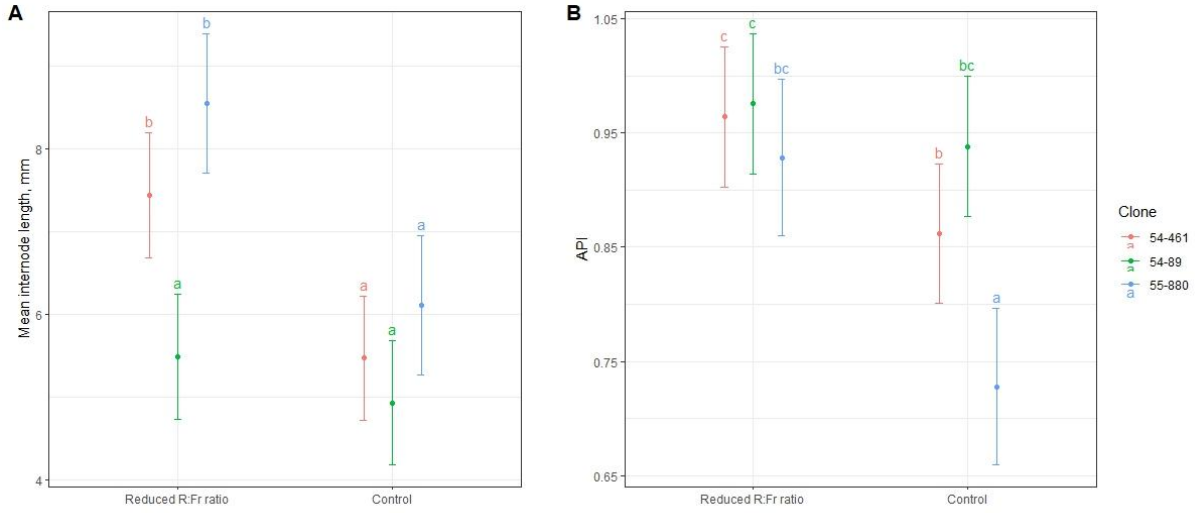
photosynthetic performance is characteristic to phytochrome-mediated shade-avoidance responses under low R:Fr conditions (Ballaré & Pierik, 2017; Casal, 2012; Franklin & Whitelam, 2005). Under such conditions, plants respond primarily through elongation and modifications in shoot architecture that improve access to light, while changes in the efficiency of the photosynthetic apparatus are secondary and are maintained within an optimal range (Franklin, 2008; Smith, 2000). Nonetheless, changes in the R:Fr ratio affected morphological traits associated with the growth of the main shoot (main shoot length, mean internode length), the formation of lateral shoots (number of lateral shoots, proportion of plants forming lateral shoots, and the ratio of main to total shoot length), and rooting rate (Table 2), whereas the number of internodes of the main shoot and the multiplication index remained unchanged. Considering that the ratio of main to total shoot length was significantly affected by light treatment, the stability of the multiplication index suggests that the overall growth was not substantially altered but rather redistributed among plant organs. Such observation is consistent with typical shade-avoidance responses where low R:Fr primarily modifies biomass allocation rather than increasing total carbon assimilation (Ballaré & Pierik, 2017; De Wit et al., 2016; Franklin, 2008).

Although the effects were more pronounced for morphological traits, light treatment also influenced chlorophyll content and the functional performance of PSII, as reflected by changes in SPAD values and chlorophyll *a* fluorescence parameters Fv/Fm and PI_{ABS}, as well as in the specific energy fluxes describing electron trapping (TRo/RC) and electron transport (ETo/RC) in PSII reaction centres (Table 2). In contrast, the energy absorption (ABS/RC) and dissipation (DIo/RC) were not affected, suggesting that the applied light conditions did not induce photoinhibitory stress, which is typically associated with increased energy dissipation and reduced PSII efficiency (Kalaji et al., 2012; Maxwell & Johnson, 2000). Changes in chlorophyll content under altered R:Fr ratios are frequently reported in shade environments, where plants adjust pigment composition and leaf optical properties while maintaining relatively stable photosynthetic efficiency (Ballaré & Pierik, 2017; Casal, 2012; Franklin, 2008). However, such responses are not exclusively associated with shade-avoidance signalling and may also reflect photosynthetic acclimation to broader variations in spectral environment, including adjustments in chlorophyll concentration that optimise light-harvesting efficiency under altered light conditions (Demotes-Mainard et al., 2016; Evans & Poorter, 2001; Walters, 2005).

Plantlets cultivated under illumination with reduced R:Fr ratio developed longer main shoots estimated at 36.0 mm (95% Confidence Interval ($CI_{95\%}$): 34.0-37.9 mm) compared to 28.5 mm ($CI_{95\%}$: 26.6-30.5 mm) for the control group, while the elongation occurred on account of longer internodes (Figure 1A), as the internode number remained stable.

Figure 1

Changes of the mean internode length (A) and API (B) of silver birch clones cultivated under illumination with different R:Fr ratios



Such responses are widely observed across plant species and reflect an evolutionary adaptation to canopy shade, where rapid architectural adjustments enable plants to escape unfavourable light environments (Ballaré & Pierik, 2017). At the molecular level, this response is initiated by phytochrome inactivation under low R:Fr conditions, which stabilises phytochrome-interacting-factor (PIF) transcription and promotes auxin transport and gibberellin biosynthesis, ultimately driving stem and internode elongation (Demotes-Mainard et al., 2016; Wang et al., 2022). At the same time, node initiation at the shoot apical meristem is controlled largely by the developmental regulation of leaf initiation rather than

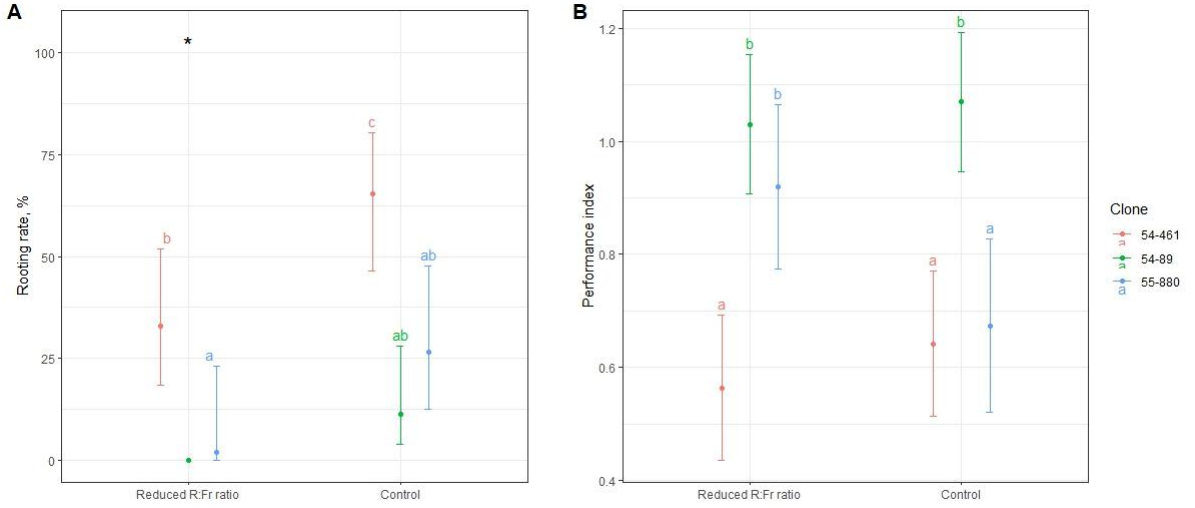
elongation processes, and is therefore less sensitive to changes in spectral quality, including the R:Fr ratio (De Wit et al., 2016).

Despite main shoot length being increased, changes in total shoot length were not observed, indicating that decreased R:Fr ratio did not stimulate overall biomass accumulation but instead induced redistribution of growth resources within the shoot system. Reduced R:Fr ratio stimulated resource allocation from lateral shoots to the main axis, as indicated by reduced lateral branching estimated at 14.5% ($CI_{95\%}$: 8.8-14.5%) versus 40.1% ($CI_{95\%}$: 31.1-49.8%) for the control group, and increased API (Fig. 1B). The mean number of lateral shoots was higher under the control condition, with an estimated value of 0.388 ($CI_{95\%}$: 0.287–0.524), compared with 0.149 ($CI_{95\%}$: 0.089–0.250) under the treatment, indicating a significant reduction in lateral shoot formation. Observed responses represent typical shade-avoidance mechanism regarding biomass allocation within plants (Franklin & Whitelam, 2005), and have been widely reported in herbaceous plants (Casal, 2012; Smith, 2000). From the practical perspective, such a shift towards stronger apical dominance may be beneficial for micropropagation by reducing excessively bushy phenotypes and improving the structural quality of shoots during subculture (Ballaré & Pierik, 2017; Demotes-Mainard et al., 2016; Franklin, 2008). Sustainable changes in biomass allocation should, however, be confirmed over several subcultures to ensure consistency of the response for practical applications.

Considering that Fr enrichment modulates auxin metabolism via phytochrome-mediated signalling, enhanced adventitious rooting could be expected, as demonstrated with the cuttings of watermelon (Wu et al., 2023) and lavender (Muleo et al., 2025), where reduced R:Fr ratios accelerated root initiation and increased root biomass. We observed that the rooting rate of silver birch clones under decreased R:Fr ratio was lower (Figure 2A) compared to the control group. Reduced rooting can result from an excessive reduction in the R:Fr ratio (Sessa et al., 2018). However, because the R:Fr ratio used in this study was moderate, the reduced rooting was likely caused by other factors. This could include the application of cytokinins to the culture medium, which are characterised by their inhibitory effect on rooting (Jing & Strader, 2019). Cytokinins may have also interacted with elevated levels of Fr, as reduced rooting was observed in comparison to the control, where the R:Fr ratio was elevated (Table 1). This, however, remains speculative, and should be tested experimentally to verify.

Figure 2

Changes of rooting rate (A) and Performance index PI_{ABS} (B) of silver birch clones cultivated under illumination with different R:Fr ratios



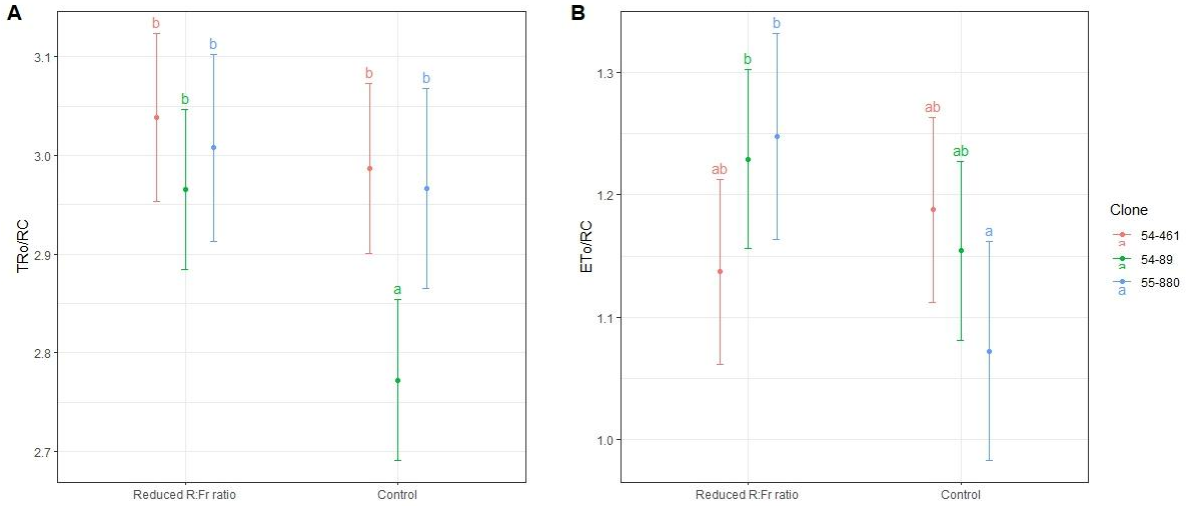
*Note – no rooting was observed for clone 54-89 cultivated under reduced R:Fr ratio, dispersions were therefore removed to improve graphic representation.

In terms of photosynthetic performance, reduction of the R:Fr induced only minor changes. Exposure to illumination with reduced R:Fr ratio resulted in slightly reduced photosynthetic capacity, as indicated by significantly lower SPAD for the plantlets with estimated value 20.6 ($CI_{95\%}$:19.7-21.4) versus estimate 24.2 ($CI_{95\%}$:23.3-25.0) for the control group. Unlike etiolation, the shade avoidance does not induce complete suppression of chlorophyll accumulation (Demotes-Mainard et al., 2016). Accordingly, photosynthetic capacity is usually maintained with only a slight decrease in performance, allowing plants to sustain carbon assimilation while reallocating resources toward elongation growth (Tan et al., 2022). Reduced R:Fr treatment also resulted in significantly higher Fv/Fm value with 0.809 ($CI_{95\%}$:0.801-0.817) compared to 0.797 ($CI_{95\%}$:0.789-0.805) control group, indicating higher quantum yields in response to the

reduced R:Fr. Nonetheless, both groups remained at the range that is estimated as optimum (Maxwell & Johnson, 2000), suggesting that illumination did not induce photoinhibition for plantlets in both groups. The reduction of R:Fr ratio also resulted in a significantly higher PI_{ABS} for clone 54-89 (Figure 2B), indicating a slight increase of overall photosynthetic efficiency; increased electron trapping in PS II for clone 54-89, as indicated by higher TRo/RC (Figure 3A) and increased electron transport beyond Q_A for clone 55-880, as indicated by higher ETo/RC (Figure 3B). Changes in Performance Index and electron fluxes (TRo/RC and ETo/RC) were, however, clone specific and seemed random, without exhibiting a distinguishable pattern, thus further reinforcing relative stability of photosynthesis under the reduced R:Fr ratio, characteristic to shaded environment (Casal et al., 2014; Franklin, 2008).

Figure 3

Changes of special electron fluxes TRo/RC (A) and ETo/RC (B) for silver birch clones cultivated under illumination with different R:Fr ratios



Conclusions

1. Silver birch clones exhibit typical shade-avoidance responses under the reduced R:Fr environment.
2. Morphological responses of silver birch to the reduced R:Fr ratio are more pronounced than physiological changes.
3. The reduction of R:Fr ratio enhances growth of main axis by reducing resource distribution to lateral shoots, thus improving transplant-ready morphology.
4. Physiology of plantlets adjusted to the reduced R:Fr environment via optimisation of photosynthetic capacity and efficiency, while maintaining the overall stability of photosynthetic performance.
5. The reduced R:Fr ratio has the potential to optimise micropropagation of silver birch.

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CASE STUDY OF BIRD'S-FOOT TREFOIL (*LOTUS CORNICULATUS*), WOOD FIBER, PEAT FOR SAND AND GRAVEL QUARRY RECLAMATION

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Abstract
After sand and gravel extraction, mined areas must be reclaimed. The most common reclamation practice is afforestation; however, the remaining soil after extraction is usually nutrient-poor, dry, unstable, and low in organic matter, making it highly susceptible to erosion. Bird's-foot trefoil (*Lotus corniculatus*), a legume, is a promising species for reclamation. The aim of the study was to evaluate two measures for gravel quarry reclamation: (i) vegetation establishment by sowing *Lotus corniculatus* between tree rows in a gravel quarry (Kapusils, Latvia), and (ii) the effect of wood fiber–peat mulch on tree growth in a nursery (Kalsnava, Latvia) and in the gravel quarry. Two growing seasons after sowing, approximately 14.5% of bird's-foot trefoil plants were classified as large, 30% as medium-sized, and the remaining plants as small. In most cases, root dry mass exceeded aboveground dry mass. The combined application of wood fiber–peat mulch at tree planting spots together with bird's-foot trefoil sown between tree rows may reduce wind erosion while improving soil stability, moisture availability, and nutrient supply for newly planted trees. As a result, this approach can contribute to soil improvement, reduce erosion, provide resources for pollinators, and enhance biodiversity in reclaimed areas.
Keywords: bird's-foot trefoil, biomass, wood fiber, peat, sandy soil recultivation.

Introduction

Sand and gravel are among the most widely extracted construction materials worldwide (Gavriletea, 2017). In Latvia, approximately 3 million m³ of sand and about 2.6 million m³ of sand–gravel are extracted annually (Latvian Environment, Geology and Meteorology Centre, 2025), mainly for concrete production, road construction, and other building activities. However, extraction significantly disturbs the natural landscape, removing vegetation and topsoil and exposing loose sediments (Bradshaw, 2000). After mining operations cease, these disturbed surfaces become highly vulnerable to erosion, particularly during the early stages before reclamation measures stabilize the site (Bendixen et al., 2021). Because exposed sand and gravel have low cohesion, rainfall runoff and wind can easily mobilize and transport sediments, contributing to land degradation and dust pollution (Morgan, 2005).

Various methods are used to control erosion and sedimentation in post-mining areas, including vegetation establishment (Navarro-Ramos et al., 2022), mulch application (Fan et al., 2023), silt fences, sediment ponds (Kincl, 2022), and surface runoff diversion (Martín-Moreno et al., 2016). Among these approaches, vegetation establishment is particularly promising because it provides multiple ecological benefits, including improved soil stability, enhanced biodiversity, habitat creation (Bradshaw, 2000), carbon sequestration (Zhu et al., 2024), and improved soil nitrogen (N) availability through legumes (Junia et al., 2020). One legume species with strong potential for the reclamation of degraded soils is bird's-foot trefoil (*Lotus corniculatus*), which can form stable ground cover while improving soil fertility through biological N fixation (Knežević et al., 2022).

In addition to vegetation establishment, soil amendments may improve conditions for plant, including trees, establishment on nutrient-poor sandy substrates. A mixture of wood fibre and peat may create favorable conditions for the early growth of planted trees because each component provides complementary functions. Peat improves water retention due to its high porosity, which is particularly important during the early establishment stage when seedlings are sensitive to drought stress (Rezanezhad et al., 2016). Wood fiber decomposes more slowly and forms a coarse surface matrix that stabilizes sandy soils by trapping moving particles and reducing surface erosion. Wood-based mulches have also been shown to effectively stabilize soil surfaces during the early stages of vegetation establishment (Girona-García et al., 2022; Neris et al., 2017). Together, these materials may enhance nutrient availability, improve moisture conditions, and stabilize the soil surface, thereby supporting vegetation establishment and reducing erosion in sandy post-mining landscapes.

The aim of the study was to evaluate the suitability of two measures for gravel quarry reclamation (afforestation): (i) the incorporation of bird's-foot trefoil between tree rows in a gravel quarry; and (ii) the effect of wood fiber and peat mix mulching on tree growth, both in the nursery and in the gravel quarry. The specific focus of the study regarding bird's-foot trefoil as a ground cover species was its growth performance, root biomass development, and potential for natural reseeding in nutrient-poor substrates.

Materials and Methods

Bird's-foot trefoil incorporation effect

Bird's-foot trefoil (*Lotus corniculatus*) was sown in the end of May 2024 in 15 cm wide rows at a reclaimed sand–gravel quarry site (Kapusils study site) in Latvia, located approximately 250 km northwest of Riga (57.33136, 25.95272). Total area of study site is 10 ha. In autumn 2025 (after two growing seasons since sowing), biomass samples of bird's-foot trefoil were collected from five sampling plots (area of each

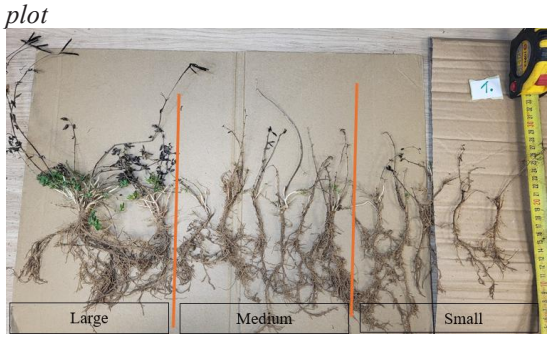
sampling plot 225 cm^2, distance between sampling plots 5 m), and the number of individuals as well as the dry biomass of roots and aboveground parts were determined. Since bird's-foot trefoil was sown in rows and its root system is known to expand spatially, a 15 × 15 cm area within each sampling plot was selected as the representative sampling unit (Figure 1).

Figure 1
The selected 15x15 cm area for collecting bird's-foot trefoil



After excavation, the soil was carefully shaken off and the number of large (>10 cm), medium (5–10 cm), and small (<5 cm) bird's-foot trefoil individuals within the sampling plot was recorded (Figure 2).

Figure 2
Bird's-foot trefoil individuals counted in the sampling plot



The proportion (%) of large, medium, and small individuals was determined for each sampling plot. Root and aboveground biomass were oven-dried at 70 °C to constant mass and weighed. The proportion of root and aboveground biomass in each sampling plot was then calculated.

Soil samples from 0 – 5cm depth (5 replicates) were collected from the bird's-foot trefoil row adjacent to the biomass sampling plot. Control set of soil samples were taken from the unsown soil next to the row. All soil sample analyses were carried out at the laboratory of the Latvian State Forest Research Institute 'Silava'. Soil pH was determined in a water (H_2O) suspension. The concentrations of potassium (K), calcium (Ca), magnesium (Mg), zinc (Zn), iron (Fe), manganese (Mn), phosphorus (P), aluminium (Al), nickel (Ni), copper (Cu), lead (Pb), boron (B), sodium (Na), and sulfur (S) were measured after microwave-assisted digestion using a CEM MARS 6 iWave system (Matthews, USA); elemental analysis was performed with an inductively coupled plasma optical emission spectrometer (ICP-OES; Thermo Fisher Scientific iCAP 7200 Duo, Waltham, USA) following the ISO 11885:2009 standard. Total carbon (TC) and total nitrogen (TN) contents were determined by the dry combustion method using an Elementar El Cube analyzer (Langenselbold, Germany) in accordance with ISO 10694:2006 and ISO 13878:1998, respectively. Carbonate content determined using FOGII Digital Soil Calcimeter, while organic carbon (OC) content calculated as a difference between TC and carbonate content. Statistical analysis was performed using the R software (version4.4.0). To compare the chemical indicators of soil samples collected under bird's foot trefoil with those from the control sites, Welch's two-sample t-test for independent samples was used. Since multiple soil chemical parameters were analyzed simultaneously, the p-values were adjusted using the Benjamini–Hochberg method to control the false discovery rate (Benjamini & Hochberg, 1995). Differences were considered statistically significant at $p < 0.05$.

Wood fiber and peat mix mulching effect

The substrate/mulch formulation was designed with the consideration that adding wood fiber also known as trade mark 'forest gold' (FG) would stimulate the activity of wood-decomposing bacteria, which consume mineral N; therefore, substrates with higher wood fiber content received more mineral N (Table 1). Additional N was added using NPK (12-14-24)+TE (0.5 kg m^{-3} of peat) in all treatments; in substrates containing wood fiber, slow-release N fertilizer containing urea and crotonylidene diurea (CDU) was added.

At the Kapusils study site, individual planting spots were mulched in 2024, applying 0.4 kg of natural wet mulch per planting spot. The height of planted bare-root and container-grown Norway spruce seedlings at the Kapusila study site was determined in 2024.

But in Kalsnava nursery wood fiber and peat mulching (3 t ha^{-1}) effect on spruce growth had been tested in production of Plough+ *Norway spruce* seedlings in 2024. In nursery, the measurement of trees was done after one year. For each type of mulch material, tree height (classified into height groups at 10 cm intervals: 10-20 cm, 20-30 cm, 40-50 cm, 50-60 cm, and 60-70 cm) was measured and the proportion of seedlings within each 'height class' was calculated.

Results and Discussion

Bird's-foot trefoil individuals and biomass

The proportion of large, medium, and small bird's-foot trefoil individuals varied among the five sampling plots (Figure 3). Small individuals represented the largest share in most plots, indicating that a considerable part of the population consisted of less developed plants. On average across all sampling

plots, small individuals constituted the largest proportion of the population 55.4 ± 9%, while medium individuals accounted for 30.1 ± 8% and large individuals for 14.5 ± 5%.

Table 1

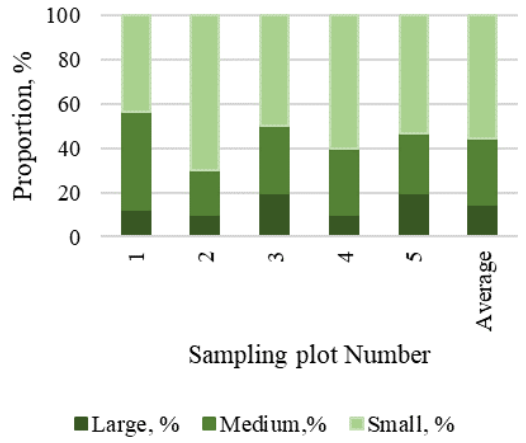
The amount of additional nitrogen fertilizers added to the standard substrate recipe of SIA Pindstrup

Source of nitrogen	Amount of additional nitrogen added, g m^{-3}			
	0% wood fiber (FG)	15% wood fiber (FG)	30% wood fiber (FG)	50% wood fiber (FG)
NO_3 – N	35	35	35	35
NH_4 – N	25	25	25	25
UREA – N	-	2.7	5.40	7.5
CDU Nitrogen	-	25.20	50.40	70

These results indicate that the *L. corniculatus* population at the study site was dominated by smaller, less developed individuals.

Figure 3

Proportion of different size Bird's-foot trefoil individuals in the sampling plots

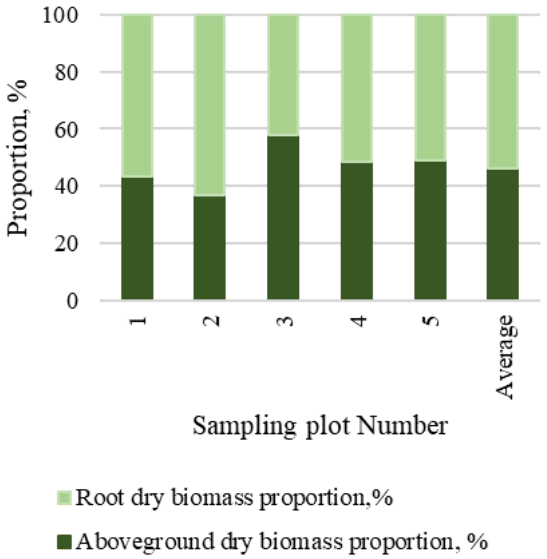


In the early stages of reclamation, relatively low vegetation height, even within pioneer plant communities, is considered a typical characteristic. During this phase, many plant species allocate a greater proportion of their resources to root development (Boldt et al., 2012) and survival strategies rather than to rapid above-ground growth. Well-developed root systems enable plants to access limited soil moisture and nutrients while simultaneously stabilizing loose substrates like sand and gravel, thereby reducing erosion (Vannoppen et al., 2017).

The biomass allocation of bird's-foot trefoil varied among the five sampling plots, with the proportion of aboveground dry biomass ranging from approximately 37% to 58% (1.85…4.05g), while root biomass ranged from about 42% to 63% (1.95…5.68g). The highest proportion of aboveground biomass was observed in sampling plot 3, whereas sampling plot 2 showed a relatively greater allocation of biomass to roots (Figure 4). Differences in biomass allocation among sampling plots may also reflect local variations in microsite conditions such as soil moisture, nutrient availability, or substrate composition. For example, the higher proportion of aboveground biomass observed in sampling plot 3 may indicate more favorable moisture conditions that allowed greater investment in shoot growth. Similar patterns have been reported in other studies of leguminous species, where biomass allocation shifts depending on resource availability and environmental stress (Poorter et al., 2012).

Figure 4

Proportion of bird's-foot trefoil oven dry biomass



Bird's-foot trefoil impact on soil quality

Among the analyzed soil chemical indicators—OC, TC, TN, the C/N ratio, K, Ca, Mg, Zn, Fe, Mn, Ni, Cu, lead Pb, B, Al, Na, S, and P concentrations—no statistically significant differences were found between the control soil and the soil beneath bird's-foot trefoil ($p > 0.05$). This can be explained by the fact that reclamation and the recovery of soil fertility are long-term processes, and measurable improvements in soil chemical properties often require several years or even decades to develop. In the early stages of reclamation, soil systems are still undergoing physical stabilization and biological colonization, while processes such as organic matter accumulation,

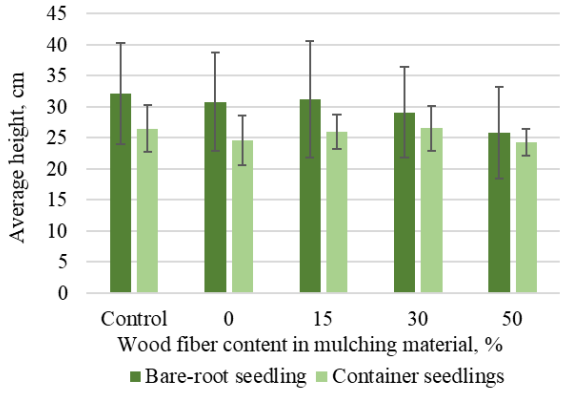
nutrient cycling, and the development of microbial communities are only beginning to establish (Navarro-Ramos et al., 2022; Li et al., 2025). However, significant differences were detected in the content of carbonate carbon (Ccarb.; p = 0.0016) and calcium carbonate ($CaCO_3$; p = 0.0016), less Ccarb. contain noncovered soil what could be result of wind erosion – material accumulation or removing on topsoil.

Tree growth with wood fiber mulch

In the Kapusils sand mining recultivation area, after the first growing season, no visible differences in seedling height were observed among seedlings, regardless of whether the planting spots were mulched or not. Unsignificant shorter seedlings developed in planting spots mulched by material containing 50% of wood fibre (Figure 5).

Figure 5

Average height (cm) of Norway spruce seedlings (bare-root and container-grown) under different wood fiber contents in the mulching material (0%, 15%, 30%, and 50%), compared to the control. Error bars represent standard deviation (SD)



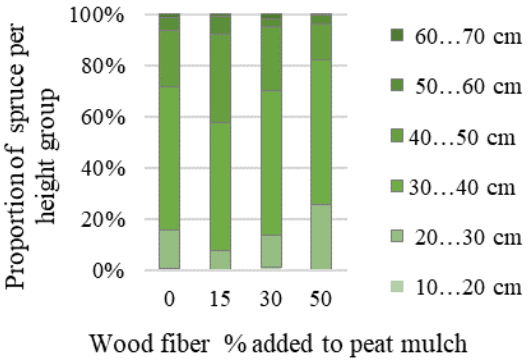
At this stage, the mulch layer had become covered by sand, and the root collars of the planted seedlings were also covered, which may have contributed to their protection against wind erosion.

In experimental planting on sandy soils in Kalsnava nursery, we found that peat+15-30% wood fiber improve seedling quality (Figure 6). Mulching of nursery-ploughed soil bare-root Norway spruce seedlings showed better results when 15 and 30% wood fibre was added to the peat mulch for improving soil organic material content, less higher seedlings with 50/50 peat / wood fiber mulch.

In summary, the current observations suggest that the future combination of localized mulching at planting spots and a living legume cover in inter-rows may be particularly suitable for tree establishment on erosion-prone sandy soils. In such environments, the immediate challenge is often not nutrient limitation alone, but rather the physical instability of the surface substrate, including sand deflation, burial of planting spots, and exposure of the root collar. Vegetation cover is known to reduce wind erosion by increasing surface roughness and decreasing near-surface wind velocity, while mulch-based surface protection can provide an immediate barrier before living cover is fully established (Zhang et al., 2021; Girona-García et al., 2022).

Figure 6

Distribution of Picea abies seedlings among height classes according to the proportion of wood fiber added to peat mulch in a sandy soil field at the Kalsnava nursery



In this context, bird's-foot trefoil can be viewed as a biologically persistent, cumulative erosion-control component. Once established, it is expected to maintain soil cover over time and thereby contribute to longer-term suppression of aeolian sand movement. At the same time, as a perennial legume, it may also contribute N to the system through biological fixation; however, the transfer of legume-derived N to neighboring non-legume plants generally occurs gradually and is often mediated by decomposition of root residues and other belowground pathways rather than by an immediate fertilizer-like effect (Thilakarathna et al., 2016; Reilly et al., 2022).

By contrast, a mulch composed of wood fiber, peatwould be expected to act immediately after planting by physically stabilizing the planting microsite. This is especially relevant under sandy conditions, where the root collar may be either exposed by deflation or buried by wind-blown material. Mulches are widely used to reduce erosion and protect the soil surface during the vulnerable establishment phase, and woody amendments may additionally improve water retention and soil physical conditions in degraded coarse-textured soils (Jourgholami & Etehadi Abari, 2017; Li et al., 2018). Soil physical improvement is particularly important because better aggregation, porosity, and infiltration can moderate moisture stress and improve aeration in sandy substrates (Bronick & Lal, 2005).

The temporal contrast between the effects of living cover and woody mulch is central to the proposed interpretation. Wood-based materials typically have a high C/N ratio and therefore may temporarily immobilize N during decomposition, meaning that their short-term benefit is more likely to be physical than nutritional. Nevertheless, the more slowly decomposing carbon fraction may contribute to

gradual improvement of soil structure and moisture relations (Li et al., 2018; Bronick & Lal, 2005).

Latvian agroforestry studies provide additional support for the ecological logic of combining woody plants with herbaceous intercrops and recycled nutrient sources. In an agroforestry alley cropping experiment established in central Latvia, Rancāne et al. (2014) showed that systems combining hybrid aspen with perennial herbaceous plants on mineral soil could generate positive agronomic and economic outcomes, particularly, where herbaceous crops were used for seed production and organic fertilization treatments were applied. The same study also demonstrated that alley cropping was evaluated not only as a productive land-use option but also as one offering environmental benefits, including soil-protective functions and diversified biological production.

More specifically, Bārdule et al. (2013) reported from a Latvian agroforestry system on loam/sandy soils that wastewater sludge increased hybrid aspen stem length after the first growing season, while wood ash substantially increased seed yield of fodder galega, illustrating that recycled residual materials can influence tree and intercrop components differently. Their study is particularly relevant here because it demonstrates, under Latvian conditions, that wood ash can function as a meaningful nutrient source within mixed tree–herbaceous systems and that perennial intercrops can be successfully maintained between tree rows.

Overall, the proposed combination of wood fibre–peatmulch in the immediate planting spot and bird's-foot trefoil in the inter-rows appears conceptually strong because it aligns short-term and long-term mechanisms of site improvement. The mulch layer is likely to provide immediate physical protection against wind erosion and burial–exposure stress around the root collar, while the legume cover can progressively strengthen biological stabilization of the soil surface. By the time root turnover in the trefoil stand begins to release appreciable quantities of N and C, the root systems of planted trees are likely to be better developed and more capable of exploiting those resources. Thus, from a discussion perspective, the advantage of this combined approach is not that both components act identically, but rather that they act on different time scales and through complementary mechanisms: mulch offers rapid microsite protection, whereas the legume cover offers cumulative ecosystem service delivery through persistent cover, organic matter inputs, and delayed nutrient transfer (Li et al., 2018; Thilakarathna et al., 2016; Bārdule et al., 2013; Bārdulis et al., 2021).

Conclusions

1. Bird's-foot trefoil showed good suitability for the reclamation of sand and gravel mining areas, demonstrating the ability to grow in nutrient-poor conditions.
2. The population of bird's-foot trefoil was dominated by small individuals (55.4%), indicating ongoing establishment and development, while biomass allocation varied among plots but remained relatively balanced between aboveground and root biomass, reflecting adaptation to nutrient-poor soils.
3. The combined use of mulch (wood fiber, peat) at planting spots and bird's-foot trefoil in inter-rows could provide both immediate protection against wind erosion and longer-term improvement of soil stability, moisture conditions, and nutrient availability for newly planted trees.
4. Mulching during production of Plough+ Norway spruce seedlings in nursery showed better results when peat in mulch was supplemented with 15 or 30% wood fiber.
5. After the first growing season, mulching had no significant effect on Norway spruce containerized and bare-root seedlings height in the Kapusils sand mining recultivation area, while sand accumulation over the mulch and root collar provide additional protection to the planted seedlings.

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MANUAL PIPETTING: A MULTI-SECTOR STUDY WITH DRY-VERIFICATION TECHNOLOGY (ATMOS-1)

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Abstract
This study evaluated pipetting accuracy, precision, and leakage across six Estonian laboratories—including medical diagnostics, university research, and authority labs—using the Atmos-1 device, an advanced, rapid, and environmentally independent pipette verification tool. The results revealed substantial variability in pipetting performance among the different sectors. Authority and medical laboratories, which operate under strict regulatory frameworks and frequent calibration routines, demonstrated consistently higher accuracy and precision in pipetting. In contrast, university research laboratories exhibited the greatest frequency of unacceptable deviations, primarily due to inconsistent or reactive pipette verification practices. Notably, the smallest volume pipettes (10–20 µl), used mainly in academic settings, were most prone to significant inaccuracies. Leakage issues were common but often resolved by replacing incompatible pipette tips, highlighting the impact of procurement decisions on laboratory performance. In clinical and authority settings, the consequences of pipetting inaccuracies are minimized by the use of automated analysers, whereas in research environments, manual pipetting errors can directly compromise experimental validity and scientific outcomes. These findings underscore the importance of regular pipette maintenance, comprehensive staff training, and careful selection of compatible consumables. Implementing routine pipette verification, particularly in research institutions, and prioritizing quality in procurement strategies can significantly enhance data reliability and overall research quality. The Atmos-1 device proved to be a valuable tool for enabling rapid, user-friendly, and effective pipette assessment, supporting improved laboratory practices across diverse sectors.
Keywords: Atmos-1, pipetting, quality assurance, accuracy, leakage.

Introduction

Modern biology and chemistry laboratories, including those for veterinary clinical diagnostics, require precise liquid handling and making micropipette accuracy vital for reproducible results. Accurate and precise measurements begin with correct and proper sampling, labelling and sample transport (delivery) to laboratories. These preanalytical activities will be followed by in-lab work as aliquoting, preparation of necessary solutions, dilutions and finally actual analytical step. For these activities the correctness is often not controlled as it is taken as self-evident. However, this introduces unexpected risks. To mitigate these risks, it is critical to verify measuring devices (such as pipettes) and containers (Blues et al., 2004; Huber, 2025). Traditional pipette calibration methods, gravimetric and photometric methods (Lochner, 1998; Lochner et al., 1996; Pati et al., 2021), are labour-intensive and therefore often outsourced, leaving gaps in regular quality assurance. The Atmos-1 device we used in our study for pipette verification is a gamechanger; it employs advanced pressure sensors and microelectronics to assess precision rapidly, without liquid, in under a minute (Unipix, 2025). Atmos is independent of environmental conditions and can also detect leaks, ensuring optimal pipette performance prior to critical experiments. This is especially important while the user experience may vary or to be insufficient in emerging testing situation (Karus A. & Karus V., 2024), but also in development, validation, and verification of new tests (Carle et al., 2004; Cremonesi et al., 2017; Karus et al., 2017). Problems in volume measurement accuracy and precision can present unexpected obstacles, raising doubts in reliability of scientific findings, adding it to already known challenges (Batista et al., 2007; Guan et al., 2023; Karus A. & Karus V., 2018). The aim of this study was to analyze pipetting practices across different sectors involved in biochemistry and molecular biology using the novel dry measurement technology Atmos-1, to identify potential gaps in pipetting performance, provide evidence of prevalent issues, suggest solutions, and ultimately enhance the quality of pipetting and research data.

Materials and Methods

The single-channel pipette accuracy tester Atmos-1 version 2024-V4.2 was used for measuring pipette accuracy, precision and leakage in six institutions: three medical diagnostics laboratories, research laboratories of two universities and one authority laboratory in Estonia in years 2024 and 2025 on voluntary basis. In every institution, the introductory training was conducted by author on-site for one to three responsible specialists (Yamamoto et al., 2014). Following the training, the Atmos-1 was left in institution for internal evaluation for up to two months. Results were recorded in tester internal memory and downloaded using ReadATMOS software. The selection of pipettes, their volume and number were identified by laboratory personnel according to their everyday use of pipettes and the selection has no impact of authors' influence. Measurements conducted during the initial user training, as well as all measurements with fewer than three repetitions, were excluded from analyses. Results were grouped by user and pipette volume. If leakage was observed, changing pipette tips (to another producer) was recommended and thereafter the testing was subsequently repeated. Accuracy was calculated as relative deviation of the

measured volume from the set value, expressed as a percentage ($\frac{|\bar{x}-V|}{V} \times 100\%$, where $\bar{x}$ – mean of measured pipetting volume and V – set volume on pipette) with good performance defined within 1% and acceptable accuracy as within 2%. Unacceptable failure in accuracy was defined as a deviation greater than 10% and is reported separately. These limits are recommended by manufacturer. Precision was calculated as the coefficient of variation (CV) in percentage. The leakage limit of 1% is set by the instrument software (Unipix, 2025) and was used as fixed recommendation for result acceptance. Institutions are anonymized. Thus, simple descriptive statistics were used to compare different pipette types. Discriminant analysis was performed only at the highest level of generalization to evaluate differences in pipetting quality between user groups (research, medical diagnostics and authority/control laboratories). Because the number of studied pipettes differed across these groups, the Tukey-Kramer test was applied to accommodate the unequal sample sizes, as there were sufficient measurements available (Tukey, 1949; Kramer, 1956). As the ATMOS1 pipetting accuracy tester is indicated for controlling the pipettes in-between required calibration intervals, we did not limit and did not record the measurements done with pipettes recently arrived from regulated periodic calibrations.

Results and Discussion

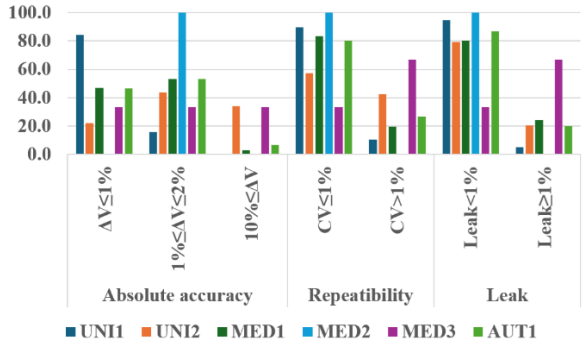
There are no earlier publications available about real-laboratory situation usage of no-liquid pipette controlling devices of ATMOS-1 or analogues. The introductory training was essential for ensuring an understanding of the basics of techniques, tips and tricks, and best practices required to obtain comparable and reliable results. Data recorded in Atmos-1 memory revealed the diversity of the pipettes in use across institutions. Table 1 provides a summary of pipettes in use in the participating laboratories. The number of other pipette sizes (300 µl and 50 µl) was insufficient for meaningful summary and thus are not shown. Study results demonstrate substantial variation in the accuracy of analysed pipettes. The number of pipettes decreased with smaller volume sizes, and it is notable that smallest volume pipets were used only in university laboratories. Pipette performance data were also analysed on the institutional level and are presented in Figure 1 and summarized in Table 2. The mean deviation values differed across the three institutional groups ($n_1 = 91$, $n_2 = 75$, $n_3 = 15$). A one-way analysis of variance (ANOVA) indicated a statistically significant overall effect of laboratory group on the measured variable ($p < 0.01$). Post hoc pairwise comparisons were performed using the Tukey–Kramer test to account for unequal sample sizes. The Tukey–Kramer analysis demonstrated that all pairwise differences between all groups were statistically significant. Specifically, UNI sector labs differed significantly from MED (medical diagnostic laboratories) ($p < 0.01$) and AUT (authority laboratory) ($p < 0.01$), while MED also differed significantly from AUT ($p < 0.01$). These results indicate that all groups are significantly distinct from one another. Superior pipette performance, and particularly accuracy, in authority and medical laboratories likely reflects regulated testing environments, where pipettes are routinely controlled and calibrated annually or semi-annually according to established rules. In two participated medical laboratories the verification is done locally by gravimetric method. In authority and one medical laboratory, calibration and verification are conducted by certified service providers. In academic (university research) laboratories, pipette calibration and verification are generally not regulated on university level. Practices vary by institute or laboratory, and verification is often only performed when there are reasonable doubts about accuracy.

Table 1

Pipette accuracies and precisions among different pipette sizes (absolute numbers)

		Absolute accuracy			Repeatability (precision)		Leak	
V (µl)	n	ΔV≤1%	1%≤ΔV≤2%	10%≤ΔV	CV ≤ 1 %	CV > 1%	Leak < 1 %	Leak ≥ 1%
1000	66	**39**	24	3	**48**	18	47	19
200	56	19	29	8	42	14	41	15
100	22	9	11	2	17	5	21	2
20	20	5	13	2	16	4	20	**0**
10	17	0	5	**12**	7	10	17	**0**
Total	181	72	82	27	130	51	146	36

Figure 1
Accuracy, repeatability and leakage rate data of pipettes in different institutions



It is also important to note that absolute accuracy deviations have a lower impact in medical and authority laboratories because manual pipetting is mainly limited to sample transfer and aliquoting. Analytical measurements are largely performed with fully automated analysers, reducing the risk of generating erroneous results; the primary concern is obtaining invalid results due to insufficient sample volume (AlShahrany & Ahmed, 2025). In contrast, in research laboratories, pipetting errors can have a greater effect, as deviation in pipetted volume may introduce systematic error. However, bigger volume pipettes tend to expose better accuracy (Lochner et al., 1996). Failures in precision (reproducibility) increase result bias, which can undermine scientific findings, especially when small differences in measured biological values are significant.

Leakage in pipettes can result from a lack of hermeticity, but is most often caused by incompatibility between the pipette and pipette tips (Art et al., 2016; Huber, 2025). Leakage problems were frequently resolved (but not always, with at least six known unresolved cases) by replacing pipette tips as already decades ago was demonstrated by Joyce & Tyler (1973).

This common issue may be partly due to purchasing practices that prioritize price, resulting in suboptimal compatibility between pipettes and tips.

Table 2
Accuracies and precisions of pipettes in different laboratory sectors (research, medical, and authority laboratories) (%)

		Absolute accuracy			Repeatability (precision)		Leak	
Sector	n	ΔV≤1%	1% ≤ΔV≤2%	10%≤ΔV	CV ≤ 1 %	CV > 1%	Leak < 1 %	Leak ≥ 1%
UNI	92	35.2	38.5	**26.4**	64.8	**35.2**	83.5	16.5
MED	74	44.0	52.0	**4.0**	78.7	21.3	76.0	25.3
AUT	15	**46.7**	**53.3**	**0.0**	80.0	20.0	86.7	**13.3**

Conclusions

1. Atmos-1 proved as reliable and easy-to-use pipette accuracy tester in all types of laboratories.
2. There is a substantial variation in pipette accuracy across sectors. Pipette accuracy and precision varied widely between laboratories, with university research labs showing the highest rates of unacceptable deviations and medical/authority labs demonstrating better accuracy and precision.
3. Authority and medical laboratories, which follow regular calibration and verification protocols, consistently maintained pipette accuracy within acceptable limits, highlighting the importance of routine, regulated quality control.
4. The smallest volume pipettes (10–20 µl), predominantly used in university labs, had the highest rates of unacceptable deviations, emphasizing the need for special attention to small-volume pipetting.
5. Pipette leakage is commonly due to tip incompatibility. Most leakage issues were resolved by switching to compatible pipette tips, suggesting that procurement practices focusing solely on cost can undermine pipetting reliability through poor tip compatibility.

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COMPARATIVE ANTIBACTERIAL AND BIOFILM-INHIBITORY ACTIVITY OF *LACTOBACILLUS HELVETICUS* CELL-FREE AND HEAT-INACTIVATED NON-FILTERED SUPERNATANTS

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Abstract
Pseudomonas aeruginosa and *Staphylococcus aureus* are opportunistic pathogens capable of forming biofilms that exhibit increased tolerance to antimicrobial interventions. Lactic acid bacteria and their metabolites have therefore attracted interest as potential sources of alternative antimicrobial compounds. This study compared the concentration-dependent antibacterial and biofilm-inhibitory effects of *Lactobacillus helveticus* cell-free supernatant (CFS) and a heat-inactivated, non-filtered supernatant (NFS) against *P. aeruginosa* ATCC 27853 and *S. aureus* ATCC 25923 using a microtiter plate model. Planktonic growth, biofilm formation, and minimum bactericidal concentration (MBC) were evaluated, together with acidified, neutralised, and medium controls. Both CFS and NFS showed strong concentration-dependent activity, with an MBC of 12.5 %. At concentrations of 12.5-50.0 %, both preparations nearly completely inhibited planktonic growth and biofilm formation. At 6.25 %, activity was lower and more variable. CFS inhibited *P. aeruginosa* planktonic growth more strongly than NFS, whereas both preparations showed similar activity against *S. aureus*. Both preparations also inhibited biofilm formation at 6.25 %. In the *S. aureus* assays, neutralisation eliminated planktonic growth inhibition, whereas NFS retained a more pronounced biofilm-inhibitory effect than neutralised CFS. Overall, the results demonstrate target and condition-dependent differences between CFS and NFS and suggest that, although acidity contributes substantially to the activity of both preparations, additional pH-independent factors may me involved, particularly in the biofilm-inhibitory activity retained by NFS after neutralisation.
Keywords: crystal violet assay, lactic acid bacteria, postbiotics, *Pseudomonas aeruginosa* ATCC 27853, *Staphylococcus aureus* ATCC 25923.

Introduction

Pseudomonas aeruginosa and *Staphylococcus aureus* are opportunistic pathogens capable of growing either as free-living planktonic cells or within structured biofilm communities. These physiological states differ substantially in their susceptibility to antimicrobial interventions, with biofilm-associated cells generally exhibiting increased tolerance to antimicrobial agents and environmental stressors. Biofilm formation therefore represents a significant challenge to public health (Ciofu et al., 2022), animal health (Howden et al., 2023), food safety, and the hygienic maintenance of food-processing environments and equipment (Elbehiry & Marzouk, 2026). Bacteria embedded within biofilms exhibit increased tolerance to cleaning and sanitation procedures, disinfectants, antimicrobial agents and adverse environmental conditions, which contributes to their persistence on biotic and abiotic surfaces and makes established biofilms difficult to eradicate (Ban-Cucerzan et al., 2025). Consequently, considerable attention has been directed toward the development of alternative and complementary approaches for preventing biofilm formation and controlling established biofilms (Elbehiry & Alajaji, 2026).

Lactic acid bacteria (LAB), including *Lactobacillus helveticus*, produce a broad range of extracellular metabolites and bioactive compounds that may exert antimicrobial and antibiofilm effects (Erdinc & Cufaoglu, 2026). Cell-free supernatants derived from LAB have been widely investigated as sources of antimicrobial activity, which may be associated with organic acids, hydrogen peroxide, peptides, and other secreted metabolites (Erdinc & Cufaoglu, 2026; Khani et al., 2024). However, less is known about whether non-filtered preparations containing potentially retained inactivated bacterial cells, cellular or subcellular material contribute to inhibition beyond the effect of soluble extracellular compounds alone (Loforte et al., 2025). This distinction is particularly relevant in the context of postbiotic research. According to the current consensus definition, postbiotics comprise preparations of inanimate microorganisms and/or their components, with or without microbial metabolites that confer a health benefit on the host (Salminen et al., 2021). Although antimicrobial activity in vitro does not by itself establish a preparation as a postbiotic, comparison of cell-free and heat-inactivated non-filtered preparations may help clarify whether components retained in the non-filtered fraction contribute to antibacterial and biofilm-inhibitory activity. Beyond that associated with soluble extracellular compounds. Such comparisons may therefore provide indirect evidence of the contribution of retained cellular, subcellular, or particulate material, although these components must be characterized directly before their role can be established. Therefore, the present study aimed to comparatively evaluate the concentration-dependent effects of *L. helveticus* cell-free supernatant and heat-inactivated, non-filtered preparation on the planktonic growth and biofilm formation of *Pseudomonas aeruginosa* ATCC 27853 and *Staphylococcus aureus* ATCC 25923 using a microtiter plate model. By directly comparing these preparations, the study sought to determine whether the non-filtered, heat-

treated preparation exhibited inhibitory effects that differed from those of the cell-free supernatant and whether such differences could indicate a contribution of components retained during the different preparation procedures.

Materials and Methods

The capacity of the supernatants to inhibit planktonic growth and biofilm formation was evaluated using a microtiter plate assay.

Preparation of supernatants

A commercially available freeze-dried culture of *Lactobacillus helveticus* THT 031102 (THT s.a., Belgium) was used to prepare the supernatants. Initially, 0.1 g of the lyophilized culture was inoculated into 45 mL of De Man, Rogosa, and Sharpe (MRS) broth (Oxoid, UK) and cultured at 37 °C with shaking at 150 rpm for 24 h. After incubation, the cultures were washed twice with deionized water and re-inoculated into fresh MRS broth at a 1:10 dilution. To prepare the supernatants, the cultures were then incubated at 37 °C at 150 rpm for 42 h.

Viable bacterial count of the *L. helveticus* 42 h old culture was determined by the microdrop plate counting technique described by Naghili et al. (2013). Serial dilutions ranging from 10^{-4} to 10^{-11} were plated on MRS agar and incubated aerobically at 37 °C for 48 h, yielding a bacterial count corresponding to an initial concentration of 7.5 x 10^7 CFU mL^{-1}.

Two types of supernatants were prepared: heat-inactivated, non-filtered supernatant (NFS) and cell-free supernatant (CFS). Initially, the *L. helveticus* culture was centrifuged (4 °C at 4,000 rpm, 10 min), and the supernatant was collected. To prepare NFS, the supernatant was heated in a water bath at 85 °C for 25 min and subsequently cooled to room temperature. To prepare CFS, the supernatant was filtered using a 0.22 µm syringe filter (Avantor, USA). Samples were stored at −30 °C until use.

The absence of viable microorganisms in the supernatants was confirmed by streaking the samples onto Columbia blood agar (Liofilchem, Italy) and MRS.

Preparation of controls

To prepare neutralised supernatants and pH-matched controls, the pH was adjusted using 1 *M* sodium hydroxide (Honeywell Specialty Chemicals Seelze GmbH, Germany), acetic acid (Carl Roth GmbH, Germany), and 1 *M* hydrochloric acid (HCl) (Honeywell Specialty Chemicals Seelze GmbH, Germany). Three types of MRS controls were used: MRS adjusted to pH 3.8 with hydrochloric acid (Control 1), MRS adjusted to pH 3.8 with acetic acid adjusted (Control 2), and MRS adjusted to pH 7.3 with sodium hydroxide (Control 3). The control conditions were assessed only in the *S. aureus* experiments and were not included in the *P. aeruginosa* assays.

Bacterial strains and preparation of preculture

The bacterial strains used in this study were *Pseudomonas aeruginosa* ATCC 27853 and *Staphylococcus aureus* ATCC 25923 (Microbiologics, USA). The cultures were stored in glycerol stock at −80 °C until use.

To evaluate the supernatant's potential to inhibit planktonic bacterial growth and to determine the minimum bactericidal concentration (MBC), firstly, *S. aureus* and *P. aeruginosa* stock cultures were inoculated onto tryptic soy agar (TSA) and incubated aerobically at 37 °C for 18 h prior to the experiment. The preculture was then prepared as follows: Two to three morphologically similar colonies were inoculated into five mL of broth—here and throughout the text, Luria-Bertani (LB) broth (LB) (Liofilchem, Italy) was used for the cultivation and dilutions of *P. aeruginosa*, and Tryptone soya broth (Oxoid, UK), supplemented with 1 % glucose (D-Glucose anhydrous, Fisher Chemical, Germany), was used for *S. aureus* (TSBG). The broth was incubated at 200 rpm for 2 to 4 hours to achieve a turbid suspension with an OD_{620} of 0.3 to 0.6, as measured with a HiPo microplate photometer (Biosan, Latvia). The bacterial count (colony forming units (CFU) mL^{-1}) in the preculture was determined by inoculating a $1:10^4$–$1:10^7$ dilution as drops onto TSA in five replicates, followed by incubation at 37 °C for 18 h. Following incubation, the *P. aeruginosa* and *S. aureus* precultures contained 2.75×10^8 CFU mL^{-1} and 2.01×10^8 CFU mL^{-1}, respectively.

Preparation of working plates

Frozen supernatants were thawed at room temperature before preparation of the working plates, and their pH was measured prior to use. Both samples had a pH 3.8. The supernatants were diluted with LB/TSBG broth to obtain concentrations of 50.0 %, 25.0 %, 12.5 %, and 6.25 %. Then 180 µL of each concentration was dispensed into 96-well polystyrene flat-bottom microtiter plates (Nunc, Thermo Fisher Scientific, Denmark) in five technical replicates.

The resulting preculture was diluted with fresh broth in a 1:10 ratio and 20 µL was added to each test well. As a result, the bacterial concentration in the test wells was approximately 10^6 CFU mL^{-1}. Similarly, a negative control (200 µL of sterile LB/TSBG broth) and a positive control (180 µL of LB/TSBG broth and 20 µL of bacterial culture) were added to the microplate. The plates were incubated at 37 °C, 200 rpm for 18 h. The experimental plate layout is illustrated in Figure 1.

Determination of antimicrobial activity

After an 18-hour incubation period, the plates were first visually inspected for the presence of clear wells, and subsequently the turbidity of the wells (OD at 620 nm) was measured to determine at which concentrations the supernatants inhibit bacterial growth.

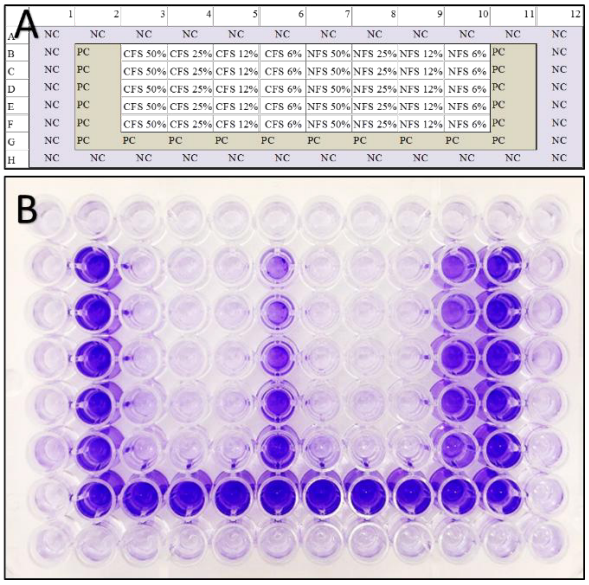
To verify the bactericidal activity of the supernatants, the MBC assay was performed according to guidelines established by the National Committee for Clinical Laboratory Standards (NCCLS, 1999). 10 µL aliquots from clear wells in three replicates were transferred to a microtiter plate and serially diluted $1:10^1$–$1:10^7$ with 90 µL of sterile broth. Each dilution was inoculated onto TSA using the spot-plating method and incubated at 37 °C for 18–24 h. Following incubation, growth on TSA was assessed, and the lowest concentration of the supernatants that achieved a 99.9 % CFU reduction of the initial inoculum of the planktonic culture was recorded as the MBC (Pankey & Sabath, 2004).

Determination of antibiofilm activity

The capacity of supernatants to inhibit biofilm formation was assessed using a crystal violet assay adapted from the methodological recommendations of Stepanović et al. (2007).

Figure 1

Microtiter plate layout (A) and assay after staining with crystal violet (B)



NC – negative control; PC – positive control; CFS – cell-free supernatant; NFS – non-filtered supernatant; supernatant concentration is indicated as a percentage (%) of the total well volume.

After plate incubation, the planktonic suspension was decanted into a discard container by flicking. The plate was washed twice with 200 µL per well of sterile 0.9 % NaCl using a multichannel pipette. Following every washing step, the wells were emptied by flicking the plate. After washing, the remaining biofilms were fixed with 200 µL per well of methanol for 15 min at room temperature, under static conditions. Following fixation, the microtiter plate was emptied by flicking and left to air-dry for 15-20 min until fully dry. The plate was stained with 190 µL of 0.1 % v/v Crystal violet (Thermo Fisher Scientific, Belgium) for 15 min at room temperature, under static conditions. After staining, the plates were washed twice with 200 µL of deionized water per well using a multichannel pipette, then left to air-dry for 5 min in a laminar flow hood. The stain was solubilized with 200 µL per well of 96 % ethanol for 30 min at room temperature under static conditions. The absorbance was measured at 570 nm using HiPo microplate photometer (Biosan, Latvia).

An interpretation of biofilm forming inhibition were performed according to the Falqueto et al. (2026). Absorbance values were corrected for background by subtracting the corresponding negative control values. Biofilm inhibition was then calculated relative to the untreated positive control according to Equation 1.

$$Biofilm\ inhibition\ (\%) = \left(1 - \frac{OD_t}{OD_c}\right) * 100 \qquad (1)$$

where OD_t represents the background-corrected OD of the treated culture and OD_c represents the background-corrected OD of the untreated positive control.

The methodological description was prepared with consideration of the minimum information guidelines proposed by Allkja et al. (2019), where applicable.

Statistical assessment and data presentation

A single supernatant preparation was tested in three independent experimental runs. For each run, bacterial cultures and microplates were prepared independently, and each sample was tested in at least five technical replicate wells. For each plate, planktonic growth inhibition and biofilm inhibition were calculated after correction for the background absorbance of the positive (bacteria without supernatants) and negative control (sterile medium). Inhibition was expressed as a percentage (%), and plate-specific mean values were calculated from the technical replicates. Values obtained from independent experiments were combined and are presented as mean ± standard deviation (SD). Planktonic growth inhibition and biofilm formation inhibition were analysed separately. Differences between selected experimental groups were assessed using Welch's independent-samples t-test, with p-values adjusted for multiple comparisons using the Holm method within each supernatant concentration. Additionally, differences between formulations across concentrations were assessed using a linear mixed model with formulation, concentration, bacterial species, and their interaction included as fixed effects. Pairwise comparisons of estimated marginal means were performed with Bonferroni adjustment for multiple comparisons. Statistical significance was set at $p < 0.05$. Figures were created using Microsoft Excel 2013 (Microsoft Corporation, USA). The statistical analyses were performed using IBM SPSS Statistics, version 32.0.0.0 (134) (IBM Corp., USA).

Results and Discussion

Planktonic growth inhibition and MBC

Both *L. helveticus* supernatant preparations showed

strong concentration-dependent antibacterial activity against the tested bacterial strains. The minimum bactericidal concentration (MBC) of both cell-free supernatant (CFS) and heat-inactivated, non-filtered supernatant (NFS) was 12.5 %, indicating a bactericidal effect at this concentration, with a reduction in viable bacterial counts of more than 99.9 % (Table 1).

Three types of controls were included to support interpretation of the antibacterial and antibiofilm effects of the *L. helveticus* supernatants. MRS medium acidified with HCl (Control 1) served primarily as a pH control and was used to assess whether lowering the pH alone was sufficient to reproduce the antimicrobial effect of the supernatants. Although lactic acid is the predominant organic acid produced by *L. helveticus*, MRS supplemented with acetic acid was used as a weak organic acid control (Control 2) to distinguish the effect of low pH from additional weak-acid-specific antimicrobial effects. Organic acids are considered important contributors to the antimicrobial activity of LAB supernatants, together with bacteriocins, hydrogen peroxide, biosurfactants, and other bioactive metabolites (Gong et al., 2026). MRS adjusted to pH 7.3 (Control 3) served as a neutral medium control to determine whether the culture medium itself contributed to inhibition under non-acidic conditions. This control was particularly relevant because the *L. helveticus* supernatants were obtained after cultivation in MRS.

Table 1

Minimum bactericidal concentration (MBC), % (v/v)

pH condition	Supernatant / control	*P. aeruginosa MBC, %*	*S. aureus MBC, %*
Native pH	Cell-free supernatant (CFS)	12.5	12.5
	Non-filtered supernatant (NFS)	12.5	12.5
Acidic controls	MRS + HCl acid (Control 1)	ND	50.0
	MRS + acetic acid (Control 2)	ND	≤ 6.25
Neutralised controls	MRS + NaOH (Control 3)	NA	NA
	CFS and NFS + NaOH	NA	NA

ND - Not determined; NA - Not applicable.

The acidic controls differed markedly in their antibacterial activity. MRS supplemented with acetic acid showed particularly strong bactericidal activity, with an MBC of ≤ 6.25 %, whereas the MBC of HCl-acidified MRS was substantially higher (50 %) and exceeded that of both CFS and NFS. In contrast, MRS adjusted to pH 7.3 did not inhibit planktonic growth of *S. aureus* (Table 2). These observations indicate that extracellular acidification alone was insufficient to account for the activity of the supernatants and also demonstrate that the antimicrobial effects of weak organic acids cannot be considered equivalent to those of a strong inorganic acid at low pH.

Table 2

The inhibition (%) of planktonic growth of S. aureus ATCC 25923

Controls and supernatants	Sample code	Concentration of controls and supernatants, %			
		50	25	12.5	6.25
Native cell-free supernatant (CFS), pH 3.8	A	97.0±0.2 ^{BCEF}	98.1±0.2	97.6±1.9 ^{CE}	46.5±0.6 ^{CEF}
Native non-filtered, heat-inactivated supernatant (NFS), pH 3.8	B	94.8±0.5 ^{ADEF}	97.3±0.4 ^{D}	96.7±1.1 ^{DE}	46.0±3.6 ^{DEF}
Neutralised cell-free supernatant (CFS-N), pH 7.3	C	-39.9±0.7 ^{AG}	-43.3±3.5 ^{G}	-0.1±1.4 ^{AG}	-9.3±3.2 ^{AG}
Neutralised non-filtered, heat-inactivated supernatant (NFS-N), pH 7.3	D	-69.9±7.58 ^{B}	-82.8±6.94 ^{B}	-93.5±2.11 ^{B}	-55.0±3.21 ^{BG}
MRS + HCl acid, pH 3.8 (Control 1)	E	82.6±0.3 ^{AB}	37.5±16.9	-16.6±7.0 ^{AB}	-6.6±3.4 ^{AB}
MRS + acetic acid, pH 3.8 (Control 2)	F	74.7±3.2 ^{AB}	85.8±2.1 ^{B}	63.0±45.6	88.7±0.9 ^{AB}
Neutralised MRS, pH 7.3 (Control 3)	G	-60.9±10.8 ^{C}	-76.3±11.6 ^{C}	-91.0±8.7 ^{C}	-79.7±9.1 ^{CD}

Values are presented as mean ±SD. Superscript capital letters indicate the supernatants from which the corresponding value differed significantly in predefined pairwise comparisons (Welch's tests with Holm adjustment, adjusted $p<0.05$). Comparisons were performed separately within each concentration. The predefined comparisons were A vs B, A vs C, B vs D, A vs E, B vs F, C vs G, and D vs G.

The difference is consistent with the distinct antimicrobial mechanisms of weak organic acids. Undissociated acetic acid crosses bacterial membranes and dissociates within the cytoplasm, disrupting intracellular pH and cellular homeostasis to exert antibacterial and antibiofilm activity (Feng et al., 2022). HCl, in contrast, primarily imposes extracellular acidification and proton stress. Consequently, MRS supplemented with acetic acid showed greater antimicrobial activity then HCl-acidified MRS, consistent with the additional weak-acid-specific effects described for organic acids (Yoon et al., 2024).

Despite the strong activity of the acetic acid control at the lowest concentrations, both CFS and NFS produced near-complete inhibition, whereas their activity became less pronounced and more variable at 6.25 %. Thus, the antibacterial effect of the supernatants was clearly concentration dependent.

Neutralisation further showed that acidic conditions were important for inhibiting planktonic growth. After neutralisation, both CFS and NFS no longer showed detectable antimicrobial activity against planktonic *S. aureus*. Therefore, an MBC could not be determined for the neutralised preparations within the tested concentration range.

These findings support an important contribution of low pH and/or pH-dependent antimicrobial metabolites to the activity of the native supernatants. However, the loss of detectable planktonic growth inhibition after neutralisation does not necessarily imply complete loss of biological activity, as LAB supernatants may contain additional bioactive compounds whose effects are not directly reflected by planktonic growth measurements (Ibrahim et al., 2021).

At concentrations of 25-50 %, CFS and NFS showed similarly strong antibacterial effects against *S. aureus* (Table 2) and *P. aeruginosa* (Table 3) planktonic growth. Differences became more apparent at the lowest tested concentration of 6.25 %, which was below the determined MBC. At this concentration, CFS inhibited planktonic growth of *P. aeruginosa* by 64.0±5.8 %, whereas NFS showed little or no mean inhibitory effect. Pairwise comparison confirmed significantly greater inhibition by CFS than by NFS, with a mean difference of 67.482 percentage points ($p < 0.001$; 95% Cl 63.577-71.387).

Table 3

The inhibition of planktonic growth and biofilm formation of P. aeruginosa ATCC 27853

Controls and supernatants	Planktonic growth inhibition				Biofilm formation inhibition			
	Concentration of controls and supernatants, %							
	50	25	12.5	6.25	50	25	12.5	6.25
Native cell-free supernatant (CFS), pH 3.8	98.0±0.0 ^{B}	98.9±0.2 ^{B}	99.8±0.2	64.0±5.8 ^{B}	97.8±0.4	98.2±0.7	98.8±0.4	75.2±14.3
Native non-filtered, heat-inactivated supernatant (NFS), pH 3.8	96.8±0.4 ^{A}	97.3±0.4 ^{A}	99.4±0.5	-3.3±6.0 ^{A}	97.2±0.6	98.3±0.2	98.9±0.4	56.2±34.7

Values are presented as mean ±SD. Superscript capital letters indicate the formulation from which the corresponding value differed significantly according to Welch's independent-samples t-test ($p<0.05$). Comparisons were performed separately within each concentration.

In contrast, inhibition of *S. aureus* remained similar for the two preparations, reaching 46.5±0.6 % for CFS and 46.0±3.6 % for NFS (Table 2).

At 6.25 %, differences between CFS and NFS against *P. aeruginosa* became more apparent, likely because the overall antibacterial effect was weaker at this concentration. The greater activity of CFS may indicate that heat treatment affected one or more components contributing to growth inhibition. Heat treatment has been reported to reduce the antimicrobial activity of some LAB-derived cell-free supernatants against planktonically growing bacteria, suggesting a contribution of heat-sensitive compounds (Singh et al., 2025). However, this effect is not universal, as LAB-derived antimicrobial components differ in thermal stability and the antimicrobial activity of cell-free supernatants may either decrease following heat treatment (Singh et al., 2025) or remain largely preserved (Scillato et al., 2021). The similar activity of CFS and NFS against *S. aureus* at 6.25 % further suggests that the consequences of heat treatment may depend on the target bacterial species.

Inhibition of biofilm formation

At concentrations of 12.5-50.0 %, both *L. helveticus* preparations inhibited planktonic growth by approximately 94.8 % to 100.0 % and concomitantly reduced biofilm formation by approximately 95.7-98.9 % in both bacterial strains. Because bacterial growth and viability were already strongly suppressed at these concentrations, the reduction in biofilm biomass cannot be interpreted as a specific, standalone antibiofilm effect.

At the lowest tested concentrations of 6.25 %, which was below the determined MBC, the response was

different. At this concentration, inhibition of planktonic growth was substantially lower than at concentrations of 12.5 % and above, whereas considerable inhibition of biofilm formation was still observed. CFS and NFS reduced *P. aeruginosa* biofilm formation by 75.2±14.3 % and 56.2±34.7 %, respectively (Table 3). The difference between CFS and NFS was statistically significant for *P. aeruginosa* (mean difference = 19.01 percentage points, p = 0.016, 95 % Cl 3.875-34.147), indicating a stronger antibiofilm effect of CFS at this concentration. In contrast, *S. aureus* biofilm formation was reduced by 64.6±6.5 and 63.8±3.9 % by CFS and NFS, respectively (Table 4), with no significant difference between the two supernatants (mean difference = 0.784 percentage points, p = 0.916). At 6.25 %, the response of *P. aeruginosa* was more variable than that of *S. aureus*, particularly for NFS, indicating a more heterogeneous effect below the MBC.

Thus, although substantial inhibition of biofilm formation was retained at 6.25 % despite lower inhibition of planktonic growth than at concentrations at or above the MBC, the effect was species – and supernatant-dependent. In particular, the significantly greater inhibition of *P. aeruginosa* biofilm formation by CFS compared with NFS suggest that the antibiofilm activity observed below the MBC may not explained solely by the overall inhibition of bacterial growth.

Table 4

The inhibition (%) of biofilm formation of S. aureus ATCC 25923

Controls and supernatants	Sample code	Concentration of controls and supernatants, %			
		50	25	12.5	6.25
Native cell-free supernatant (CFS), pH 3.8	A	95.7±0.4 ^{EF}	98.2±0.7 ^{EF}	98.3±0.3 ^{CE}	64.6±6.5
Native non-filtered, heat-inactivated supernatant (NFS), pH 3.8	B	97.2±1.7 ^{DEF}	95.9±5.0 ^{E}	98.7±0.9 ^{E}	63.8±3.9 ^{F}
Neutralised cell-free supernatant (CFS-N), pH 7.3	C	26.7±31.2	24.3±22.3	6.7±11.5 ^{A}	13.0±18.4
Neutralised non-filtered, heat-inactivated supernatant (NFS-N), pH 7.3	D	42.3±9.4 ^{BG}	44.7±16.1	41.3±15.6	48.3±12.6
MRS + HCl acid, pH 3.8 (Control 1)	E	66.5±21.4 ^{AB}	24.5±33.9 ^{AB}	51.0±23.5 ^{AB}	-31±84.8
MRS + acetic acid, pH 3.8 (Control 2)	F	81.9±6.8 ^{AB}	83.0±7.3 ^{A}	80.0±26.9	87.3±2.9 ^{B}
Neutralised MRS, pH 7.3 (Control 3)	G	2.1±4.6 ^{D}	0.0±0.0	6.7±11.5	25.0±18.5

Values are presented as mean ±SD. Superscript capital letters indicate the supernatants from which the corresponding value differed significantly in predefined pairwise comparisons (Welch's tests with Holm adjustment, adjusted p<0.05). Comparisons were performed separately within each concentration. The predefined comparisons were A vs B, A vs C, B vs D, A vs E, B vs F, C vs G, and D vs G.

The use of neutralised supernatants provided additional information on the contribution of acidity to the observed effects. Previous studies have shown that biofilm-inhibitory activity may persist after neutralisation of LAB-derived cell-free supernatants, indicating, that acidity is not necessarily the sole determinant of this effect (Alhubail et al., 2024).

In the present study, although neutralised CFS (CFS-N) and NFS (NFS-N) did not inhibit the planktonic growth of *S. aureus*, NFS-N at a concentration of 50 % still reduced biofilm formation by 42.3±9.4 %, and this effect was significantly greater than that of the neutralised medium control. Similar levels of inhibition were observed at the lower tested concentrations and did not differ significantly from the control. Direct pairwise comparisons between CFS-N and NFS-N did not reveal statistically significant differences at any tested concentration, indicating that the present data do not demonstrate superior antibiofilm effect of NFS-N over CFS-N. Nevertheless, the retention of biofilm-inhibitory activity after neutralisation suggests that factors other than acidity alone may have contributed to the observed effect.

Because NFS was obtained by centrifugation without subsequent membrane filtration, it may have retained cellular or subcellular material that differed quantitatively or qualitatively from the filtered CFS. However, the presence and contribution of such components were not directly determined in the present study. Comparative studies using cell-free supernatants, inactivated cells and combined preparations further indicate that soluble metabolites and cell-associated components may contribute differently to antimicrobial and biofilm-inhibitory activity (Falqueto et al., 2026). *L. helveticus* has been shown to release membrane vesicles and other high-molecular-weight material into culture supernatants, demonstrating that particulate extracellular components can occur in this species (Bringer et al., 2026).

Overall, both *L. helveticus* preparations exhibited strong concentration-dependent antibacterial and biofilm-inhibitory activity against *P. aeruginosa* and *S. aureus*. At concentrations at or above the MBC, inhibition of biofilm formation largely coincided with near-complete suppression of planktonic growth and therefore most likely reflected, at least in part, the strong antibacterial effect. At the lowest concentration of 6.25 %, substantial inhibition of biofilm formation persisted despite a weaker and more variable effect on

planktonic growth. At this concentration, differences between CFS and NFS became more apparent, particularly against *P. aeruginosa*, whereas such differences were less evident under bactericidal conditions.

Following neutralisation, planktonic growth inhibition was lost, whereas NFS retained a more pronounced biofilm-inhibitory effect against *S. aureus* than CFS-N. These findings suggest that, although acidity and soluble metabolites are major contributors to the activity of both preparations, additional pH-independent factors may contribute to the biofilm-inhibitory effect of the heat-treated, non-filtered supernatant.

The inability to distinguish the individual contributions of heat treatment and membrane filtration to the observed effects represents a limitation of this study, as no separate controls were included to assess the effects of each procedure independently.

Conclusions

1. Both *Lactobacillus helveticus* cell-free supernatant (CFS) and heat-inactivated non-filtered supernatant (NFS) exhibited strong, concentration-dependent antibacterial activity and inhibition of biofilm formation against *Pseudomonas aeruginosa* and *Staphylococcus aureus*.
2. At concentrations of 12.5 % and above, both preparations nearly completely inhibited planktonic bacterial growth and biofilm formation.
3. At 6.25 %, planktonic growth inhibition decreased markedly, whereas biofilm formation remained substantially inhibited.
4. At 6.25 %, CFS retained substantially greater antibacterial activity against planktonic *P. aeruginosa* than NFS, whereas both showed comparable activity against *S. aureus*, indicating that the difference depended on the target microorganism.
5. In the *S. aureus* assays, neutralisation eliminated planktonic growth inhibition, whereas substantial antibiofilm activity was retained across all tested NFS-N concentrations (41.3-48.3 % inhibition). The effect was statistically significant at 50 %, 25 %, and 6.25 % NFS-N, but not at 12.5 %. Direct pairwise comparisons did not demonstrate significant differences between NFS-N and CFS-N.

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THE EFFECT OF FREEZE-DRYING ON THE PHENOLIC AND ANTHOCYANIN CONTENT IN BERRY PRESS RESIDUES

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Abstract
Cranberries, sour cherries and chokeberries are an important source of bioactive compounds and are widely used in the food industry for the production of preserves, jams, juices and other products. These berries are rich in polyphenols, anthocyanins, flavonoids, organic acids and vitamins, which contribute to their antioxidant properties. During berry processing, press residues are produced. The berry press residues contain valuable bioactive compounds and could be used for anthocyanin extraction. The aim of this research was to evaluate the total anthocyanin and phenolic content in the press residues of cranberry, sour cherry and chokeberry in order to determine their potential as raw materials for bio-based indicator production, as well as to assess the effect of freeze-drying duration on the stability of anthocyanin compounds. The results showed that the highest total phenolic (2.06 g GAE 100 g^{-1} dry matter) and anthocyanin (2262.25 mg C3G 100 g^{-1} dry matter) contents were found in chokeberry press residues. The duration of freeze-drying significantly ($p<0.05$) affected the anthocyanin content in sour cherry and chokeberry press residues. The obtained results indicated that berry press residues, especially chokeberry press residues, are a valuable source of bioactive compounds. Overall, the research highlights the potential of berry processing by-products as a sustainable and promising raw material for anthocyanin extraction, as well as their potential application as bio-based indicators in smart packaging systems.
Keywords: chokeberries, sour cherries, cranberries, by-products, bioactive compounds.

Introduction

The food industry, during the food production process, annually produces many by-products, for example, fruit and berry press residues that arise during the production of juices and other products. The press residues can constitute 10–60% of the initial mass of the raw material (Kruszewski & Boselli, 2024). The fruit and berry press residues are often considered as waste; however, they contain valuable bioactive compounds such as polyphenols, anthocyanins, dietary fibre, and other components. Therefore, in recent years, attention to the utilisation of such by-products has increased. The by-products could be used as a source of bioactive compounds in food and pharmaceuticals, and packaging materials (Zhang et al., 2025a).

Berries such as sour cherries, chokeberries, and cranberries are an important source of polyphenols and anthocyanins. Due to the high concentration of polyphenols and anthocyanins in chokeberries (Chamberlin et al., 2024), they have been considered some of the richest berry sources of polyphenols. However, bioactive compounds could also remain in berry press residues after juice extraction. That makes berry press residues a promising and sustainable source of bioactive compounds. As berry press residues contain pigments (anthocyanins), they could be used in the food industry as natural colourants or as functional components (Dias et al., 2020) in various innovative products, including smart packaging, where they could serve as bio-based indicators (Bao et al., 2026).

Cranberries (*Vaccinium macrocarpon* L.) are an important source of bioactive compounds, as they contain polyphenols, carotenoids, vitamins, organic acids, and dietary fibre (Varnaitė et al., 2022). Cranberries are commonly used in the production of jams and juices, which results in by-products such as press residues that are rich in polyphenols, anthocyanins, phenolic acids, and flavanol's (Franco-Londoño et al., 2025; Song et al., 2025).

Similarly, sour cherries (*Prunus cerasus* L.) are rich in antioxidants and polyphenolic compounds (Jawad et al., 2025). The main phenolic compounds found in sour cherries are catechin, epicatechin, quercetin glycosides, and kaempferol derivatives (Oksuz et al., 2019). Sour cherry press residues consist of fruit skins, pits, and pulp, which make up approximately 15–28% of the initial fruit mass (Teslić et al., 2023). Therefore, sour cherry press residues are considered a promising raw material for the development of new food products and a source of bioactive compounds.

Chokeberries (*Aronia melanocarpa*), also known as black chokeberries, are rich in anthocyanins, polyphenols, and flavonoids. Due to chokeberry's bitter and astringent taste, fresh berries are mainly used for juice production, as well as for the preparation of jams and purées (Kim et al., 2024). During juice production, press residues are produced as by-products, which contain anthocyanins and polyphenols in high concentrations. Therefore, chokeberry press residues can be used as a source of natural pigments (reddish-purple colourants) or as bio-based indicators in smart packaging applications (Kim et al., 2024).

Chokeberry press residues mainly consist of the insoluble fraction, including the remaining berry pulp, skins, and seeds (Roda-Serrat et al., 2022).

Anthocyanins are water-soluble flavonoid pigments responsible for red, purple and blue colours (Khoo et al., 2017). These compounds occur in plants, berries and fruits as a glycoside. Cyanidin-3-glucoside is one of the common anthocyanins present in berries and their press residues (Khoo et al., 2017). Anthocyanins also have the ability to change colour depending on the pH of the medium, which makes anthocyanins potential natural indicators in smart food packaging (Bao et al., 2026).

This kind of packaging can indicate a possible food spoilage by responding to pH changes in the product. However, the stability of anthocyanins must also be

ensured, as it is dependent on several factors such as temperature, light, pH, co-pigmentation, oxygen, sulphites, ascorbic acid and enzyme presence and activity (Enaru et al., 2021).

According to Roda-Serrat et al. (2022), the main anthocyanins in chokeberries (*Aronia melanocarpa*) are cyanidin glycoside derivatives: cyanidin-3-O-galactoside, but cyanidin-3-O-xyloside, cyanidin-3-O-gucoside and cyanidin-3-O-arabinoside are present in lower concentrations (Roda-Serrat et al., 2022). Sour cherries also contain various anthocyanin derivatives, such as cyanidin-3-glucoside, cyanidin-3-rutinoside and cyanidin-3-sophoroside (Teleszko & Wojdyło, 2015). In sour cherries, the anthocyanin content ranges from 90 to 1000 mg per 100 g of fruit mass (Wojdyło et al., 2019).

The content of bioactive compounds in berry press residues depends not only on the type of berries but also on the applied processing methods. Freeze-drying is one of the most widely used methods to preserve bioactive compounds (Nawawi et al., 2023). This method effectively reduces the moisture content of the material while preserving thermally sensitive compounds such as anthocyanins and phenolic compounds. Moreover, the freeze-drying process results in a more porous material structure, which might facilitate solvent access to cellular components and consequently improve the extraction efficiency of bioactive compounds (Babaei Rad et al., 2025).

However, the parameters of the freeze-drying process, such as drying time and temperature, might affect the stability and concentration of bioactive compounds. Furthermore, the anthocyanin content in berry press residues might differ between fresh and freeze-dried samples, as removing water from the material can increase the concentration of these compounds on a dry matter basis, while under certain conditions it can also affect their stability (Zhang et al., 2025b). At the same time, it should be taken into account that freeze-drying is an energy and time-consuming process; therefore, its practical applicability should also be evaluated from an economic and technological perspective.

Therefore, it is important to evaluate how freeze-drying conditions, especially drying duration, affect the anthocyanin content in berry press residues in order to assess the potential of these materials for anthocyanin extraction and their further use as bio-based indicators.

The aim of this research was to evaluate the total anthocyanin and phenolic content in the press residues of cranberry, sour cherry and chokeberry in order to determine the potential as raw materials for bio-based indicator production, as well as to assess the effect of freeze-drying duration on the stability of anthocyanin compounds.

Materials and Methods

Cranberry (*Vaccinium macrocarpon cv Stevens)*, chokeberry (*Aronia melanocarpa*), and sour cherry (*Prunus cerasus cv Łutówka)* press residues (Figure 1) were supplied by the company Ltd. ANEVA J. Cranberries were sourced from Latvia, chokeberries and sour cherries – from Poland. The berry press residues were obtained using a hydraulic pack press during juice extraction. After juice pressing, the berry press residues were packed into low-density polyethylene resealable zip-lock bags and frozen.

Cranberry and chokeberry press residues were obtained in November 2025, and sour cherry press residues in December 2025.

The berry press residues were stored in a freezer at -18 ± 2 °C until further analysis. Before the analysis, the frozen berry press residues were thawed at room temperature (18 ± 2 °C) for 12 h.

Figure 1

Berry press residues used in the research (cranberries, sour cherries, and chokeberries)



Freeze-drying of the berry press residues

The thawed berry press residue samples were freeze-dried using a freeze-dryer ALPHA 1-2 LD plus (Martin Christ Gefriertrocknungsanlagen GmbH, Germany). Two freeze-drying settings were applied to evaluate the effect of drying duration on the total polyphenols and anthocyanins content in the obtained freeze-dried berry press residues:

a) the pressure was 0.052 mbar, and the temperature of the ice condenser was set to –54±0.5 °C, the duration of the drying was 7 h 30 min;
b) then pressure was 0.044 mbar, and the temperature of the ice condenser was set to –54±0.5 °C, duration of the drying was 8 h 30 min.

Sample preparation

The 15 g fresh press residues were homogenised in a mortar. The freeze-dried berry press residue samples were ground into powder using a coffee grinder (Stollar, China).

pH

The pH of each fresh berry press residue sample was determined using a pH meter inoLab pH 7110 (WTW, Germany). The analyses were performed in accordance with the ISO 1842:1991 standard *'Fruit and vegetable products — Determination of pH'*, and measurements for each sample were carried out in triplicate.

Moisture content

A Moisture analyser AND MX-50 (A&D Company Ltd., Japan) was used to determine moisture content in the samples. The samples were dried to constant weight using glass fibre filters AND AX-MX-32-2 (diameter 78 mm). Fresh chokeberry and sour cherry press residues were dried at 105 °C cranberry and freeze-dried samples were dried at 85 °C, the drying temperature was reduced to obtain more accurate moisture determination while minimising thermal decomposition of sample components.

The analysis for the samples was repeated three times.

The data was recorded using the software 'WinCT-Moisture'.

Total phenolic content (TPC)

Sample preparation: 40 mL of an ethanol–water solvent (80:20, v/v) was added to 1 g of the berry press residue sample. Phenolic compounds were extracted from the obtained mixture by applying an ultrasound-assisted extraction. The extraction was carried out using an ultrasonic bath Sonorex Digitec DT 100 H (Bandelin electronic GmbH & Co. KG, Germany) for 15 minutes at 30 ± 2 °C. After extraction, the obtained solution was filtered through filter paper (pore diameter 0.45 μm), and the filtrate was diluted to a volume of 50 mL with an ethanol–water mixture (80:20, v/v) (Avena et al., 2025).

Modified Folin–Ciocalteu method based on the methodology described by Vernon L. Singleton and Joseph A. Rossi (1965) was used to determine total phenolic content (TPC) (Paganotti & Barbeira, 2024). 0.5 mL of the berry press residue extract was mixed with 2.5 mL of 10% Folin–Ciocalteu reagent. After 5 minutes, 2 mL of 7.5% Na_2CO_3 solution was added to the mixture. The mixture was incubated in the dark for 2 hours (Paganotti & Barbeira, 2024). After the incubation, the absorbance of the analysed sample was measured at a wavelength of λ = 765 nm using a UV-1900i UV-VIS spectrophotometer (Shimadzu Corporation, Japan). The total phenolic content was expressed as grams of gallic acid equivalents per 100 gram dry matter of sample (g GAE 100 g^{-1}) (Ozola & Kampuse, 2017; Zannou & Koca, 2022).

The total phenolic content analysis for the samples was repeated three times.

Total anthocyanin content (TAC)

Total anthocyanin content (TAC) was determined using a pH differential spectrophotometric method described by Jungmin Lee (Lee et al., 2005). Absorbance measurements were performed at wavelengths λ = 520 nm and λ = 700 nm using a UV-VIS Shimadzu UV-1900i spectrophotometer (Shimadzu Corporation, Japan).

Extract preparation: 30 mL of extraction solvent (85% ethanol and 15% 1.5 mol L^{-1} HCl) (v/v) was added to 1 g of the berry press residue sample. The obtained mixture was stirred for 30 minutes, after which the extract was filtered, and the press residues were additionally rinsed with 10 mL of the extraction solvent. The filtrate was diluted to a volume of 50 mL with the same solvent (Avena et al., 2025).

Total anthocyanin content was expressed as cyanidin-3-O-glucoside equivalents (C3GE) in mg per 100 g dry matter (mg C3GE 100 g^{-1}) (Lee et al., 2005). The analysis for each sample was performed in triplicate.

Statistical analysis

The obtained results were expressed as mean values±standard deviation (SD). One-way analysis of variance (ANOVA) was used to evaluate the statistical significance of the data, assuming a significance level of $p<0.05$. Tukey's post-hoc test (Tukey HSD) was used to determine significant differences among the samples.

Data processing and statistical analysis were performed using Microsoft Excel 2026 (Microsoft Corporation, USA) and GraphPad Prism 10.4.2 (GraphPad Software LLC, USA).

Results and Discussion

pH and moisture content

pH and moisture content are important properties that characterise the chemical stability and microbiological safety, and preservation of bioactive compounds of berry press residues. At low pH, the stability of phenolic compounds can be promoted, but high moisture content can induce some microbiological and enzymatic processes that can lead to the spoilage of valuable bioactive molecules.

In this research, it was determined that the pH values of the berry press residues differed significantly ($p< 0.05$). The lowest pH value was determined in chokeberry press residues (pH=2.52±0.04), whereas the pH values of sour cherry and cranberry press residues were higher, and there was no significant ($p>0.05$) difference determined (Table 1). Chokeberries are rich in organic acids and phenolic compounds, which contribute to the pronounced acidity of the berries and their relatively low pH values (Kulling & Rawel, 2008). In the research by Kusur et al. (2025), who also investigated chokeberry press residues, the pH was reported as 3.65. The difference in results could be related to several factors, such as berry cultivar, geographical and climatic conditions, and the methods used to obtain chokeberry press residues.

The moisture content of berry press residues after juice extraction ranged from 44.14 to 65.45%. Similar results were reported by Blicharz-Kania et al. (2025). In the present research, the highest moisture content was observed in sour cherry press residues, and the lowest was found in chokeberry press residues (Table 1).

Roda-Serrat et al. (2022) reported a moisture content of 65±1% for fresh chokeberry press residues. The moisture content of chokeberry press residues analysed in the present study was lower than the values reported by Roda-Serrat et al. (2022). The moisture content of berry press residues can be affected by many factors, such as berry cultivar, processing technology, and pressing efficiency.

The highest moisture content in this research was determined in sour cherry press residues (65.45±1.81%). The high moisture content in sour cherry press residues is related to the structure of the fruit pulp and the high-water content of the berries. In addition, a higher water-holding capacity of the cell walls and a greater proportion of juice-containing parenchyma tissues may contribute to higher moisture retention in sour cherry press residues after pressing (Schumann et al., 2020).

Ebrahimi et al. (2025) reported that the moisture content of fresh sour cherry press residues was 85.80±0.50% (Ebrahimi et al., 2025).

In the present research, the moisture content of berry press residues were decreased by freeze-drying. The freeze-drying was carried out at two different drying durations. It was found that after 7 h 30 min of freeze-drying, the moisture content decreased from 5.38 to 25.14%. The samples, which were freeze-dried for 8 h

30 min, had the lowest moisture content. The moisture content in the samples, which were freeze-dried for more than 8 h, ranged from 3.80 to 15.1%. The low moisture content in freeze-dried berry press residues improves the stability and makes them more suitable for pigment extraction.

The differences in moisture reduction kinetics between tested berry press residues are related to differences in the microstructure, chemical composition, and water-binding mechanisms within the berry matrix. During the initial stage of freeze-drying, free water is predominantly removed, whereas in further stages of the freeze-drying process bound water is removed from cell structures and polysaccharide matrices (Figura & Teixeira, 2023; Nowak & Jakubczyk, 2020). As sour cherry press residues have a more porous structure (Schumann et al., 2020) and have higher initial moisture content (65.45±1.81%), a rapid initial decrease in moisture content after 7 h 30 min of the freeze-drying process was conducted. The moisture content was reduced by approximately 92% compared to the initial moisture content. Continuing the drying process, the removal of bound water was slower. In contrast, cranberry press residues contain higher levels of pectins, dietary fibre, and other hydrophilic compounds. These compounds have a stronger ability to bind water, resulting in a more gradual and even reduction in moisture content throughout the freeze-drying process (Nowak & Jakubczyk, 2020).

For chokeberry press residues, the initial moisture reduction was lower than observed for sour cherry press residues; however, a rapid decrease in moisture content continued even after 7 h 30 min of freeze-drying. This observation indicates the differences in water-binding mechanisms and internal moisture diffusion within the berry matrix.

Similar observations of various berry matrices during drying processes have also been reported in studies investigating the stability of biologically active compounds during drying (Gricenko et al., 2026).

Table 1

pH and moisture content of berry press residue samples before and after freeze-drying

Sample	pH	Initial moisture, %	7.5 h FD, %	8.5 h FD, %
Sour cherry press residues	3.61±0.06^{a}	65.45±1.81^{a}	5.38±0.13^{c}	3.80±0.78^{b}
Cranberry press residues	2.52±0.04^{b}	58.86±3.45^{ab}	25.14±1.31^{a}	15.1±1.09^{a}
Chokeberry press residues	3.57±0.01^{a}	44.14±1.09^{b}	11.99±0.40^{b}	4.59±0.22^{b}

FD-freeze-drying; initial moisture - moisture content after berry pressing.

Values are expressed as mean±standard deviation (n = 3). Different letters within the same column indicate statistically significant differences ($p < 0.05$).

Total phenolic compound content (TPC)

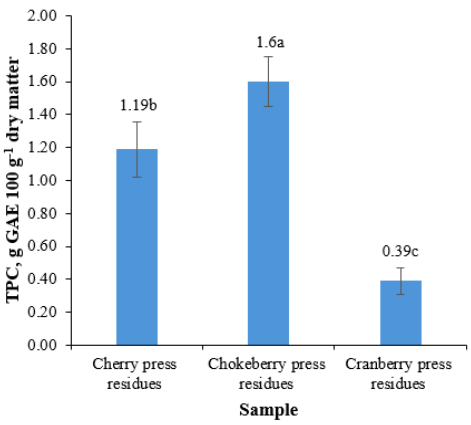
Berries that were used to obtain berry press residues are rich in bioactive compounds. The highest TPC was observed in fresh chokeberry press residues 1.6±0.16 g GAE 100 g^{-1} dry matter, whereas the lowest was found in fresh cranberry press residues 0.39±0.08 g GAE 100 g^{-1} dry matter (Figure 2). These differences in total phenolic content could be explained by the chemical composition of each berry and the distribution of different bioactive compounds within berry tissues.

High TPC in chokeberry press residues was reported by Pădureţ et al. (2024). In their investigation, they found that TPC in chokeberry press residues reached 0.004 g GAE 100 g^{-1} (Pădureţ et al., 2024). In another research conducted by Denev et al. (2012), researchers determined that the total phenolic content of chokeberry berries ranged from 0.00069 to 0.0026 g GAE 100 g^{-1} (Denev et al., 2012). Similar results have also been reported in other studies – Tolic et al. (2015) found that TPC in chokeberry press residues reached 0.0042 g GAE 100 g^{-1} (Pădureţ et al., 2024; Tolic et al., 2015). The determined high TPC in chokeberry press residues can be explained by the fact that chokeberries are considered one of the richest sources of polyphenols among berries (Šimat et al., 2024). The dominant polyphenolic compounds in chokeberries are anthocyanins, proanthocyanidins, phenolic acids and flavonoids.

It is worth noting that the distribution of polyphenols within berries is not uniform; approximately 10% of polyphenols are found in the fruit pulp, 28–35% in the skins, and 60–70% in the seeds (Klavins et al., 2022). It should also be noted that the TPC in chokeberry press residues may vary significantly due to several factors, such as berry cultivar, growing and storage conditions, and pressing technology. Consequently, these factors may substantially affect the extraction and stability of bioactive compounds.

Figure 2

Total phenolic content (TPC) in sour cherry, chokeberry and cranberry press residues



Results are expressed as mean value ± standard deviation (n=3). Different letters indicate statistically significant differences ($p<0.05$).

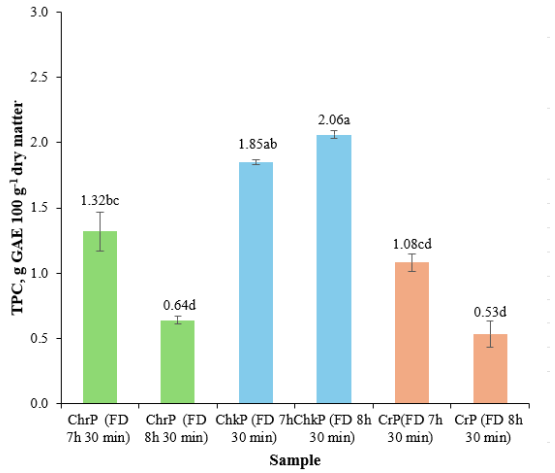
The differences in TPC in the tested berry press residues are related to each berry's phenolic compounds profile. In cranberries, predominant compounds are proanthocyanidins, phenolic acids and flavonoids, which are related to the biological activity and antioxidant properties of the berries (Xu et al., 2025). The low polyphenol content in sour cherry press residues is related to the juice pressing process. During the process, a large portion of polyphenols is extracted in the juice (Repajić et al., 2025).

The total phenolic content (TPC) was also determined in freeze-dried berry press residues (Figure 3). The freeze-drying was carried out using two duration times: a) 7 h 30 min and b) 8 h 30 min. The obtained data showed that the drying duration affects the total phenolic content. After 7 h 30 min of drying, the TPC decreased by 52% in sour cherry press residues and 51% in cranberry press residues. In contrast, chokeberry press residues showed an 11% increase.

The increase in total phenolic content could be related to the stability of phenolic compounds that are present in chokeberries. The berries' skins and seeds contain a lot of phenolic compounds that remain in the press residues after juice processing.

Figure 3

Total phenolic content (TPC) in sour cherry, chokeberry and cranberry press residues after freeze-drying



ChrP – sour cherry press residues; FD-after freeze-drying; ChkP - chokeberry press residues; CrP - Cranberry press residues.

Results are expressed as mean value ± standard deviation (n=3). Different letters indicate statistically significant differences ($p<0.05$).

The decrease in TPC in sour cherry and cranberry press residues after freeze-drying could be related to the lower stability of the phenolic compounds present. For example, sour cherries contain higher levels of anthocyanins. Anthocyanins are more sensitive to light and temperature changes and can be easily oxidized during sample preparation and juice processing. Consequently, a longer freeze-drying duration might promote structural changes and/or oxidation of polyphenols, thereby reducing total phenolic content. It would be necessary to analyse the individual phenolic compound profile of each berry press residue. The analysis could give a better insight into the stability of individual phenolic compounds.

Total anthocyanin content (TAC)

Total anthocyanin content in the samples was determined spectrophotometrically. The highest TAC was determined in fresh chokeberry press residues 723±104 mg C3G 100 g^{-1} dry matter. TAC in sour cherry and cranberry press residues ranged from 190 to 214 mg C3G 100 g^{-1} dry matter (Figure 4).

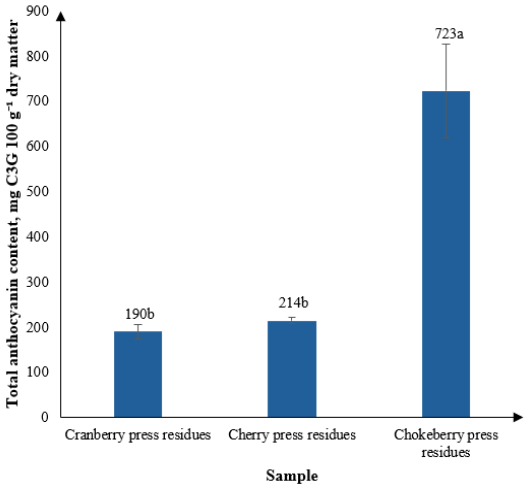
Roda-Serrat et al. had also studied TAC in chokeberry press residues and reported that the content of these compounds ranged from 284 to 686 mg 100 g^{-1} dry matter (Roda-Serrat et al., 2022). In our research, TAC converting to dry matter was 723±104 mg 100 g^{-1} dry matter. Total anthocyanin content can vary with many factors, such as chokeberry cultivar, growing conditions, degree of fruit ripeness, and the pressing method that was used for sample preparation.

The total anthocyanin content is also affected by each berry's tissue structure. Sour cherries and cranberries have a specific distribution of anthocyanins within berry tissues compared to chokeberries. When sour cherries and cranberries are pressed, a high concentration of anthocyanins is transferred into the juice fraction. That explains the lower anthocyanin content in the press residues of sour cherry and cranberry.

Anthocyanins are relatively unstable compounds that can degrade under the influence of oxygen, temperature and light, as well as during storage. During pressing, anthocyanins may undergo oxidation or degradation, reducing the total anthocyanin content in the berry press residues.

Figure 4

Total anthocyanin content (TAC) in fresh sour cherry, chokeberry and cranberry press residues



Results are expressed as mean value±standard deviation (n=3). Different letters indicate statistically significant differences ($p<0.05$).

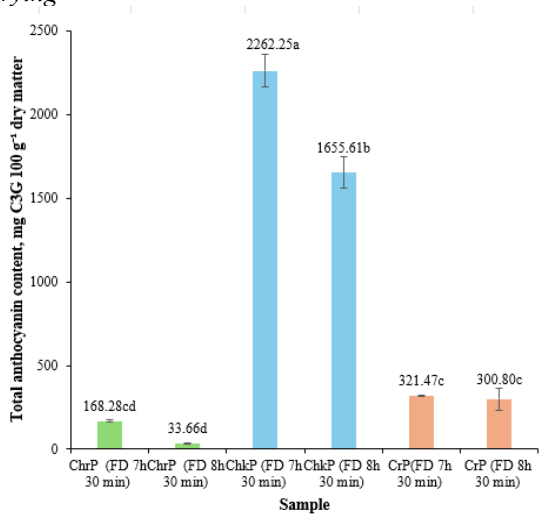
Figure 5 shows the total anthocyanin content (TAC) in freeze-dried berry press residues after 7 h 30 min and 8 h 30 min of drying. As shown in the figure, freeze-drying duration affects total anthocyanin content.

Prolonging the drying process by an hour led to a decrease in anthocyanin content. The TAC in sour cherry press residues decreased by 80%, in chokeberry press residues by 27%, and in cranberry press residues by 7%.

The results of the research indicate that freeze-drying duration can significantly ($p<0.05$) affect the anthocyanin content in berry press residues. An extended freeze-drying duration resulted in a significant ($p<0.05$) decrease in TAC in sour cherry and chokeberry press residues. However, the effect of an additional hour of drying of cranberry press residues was not statistically significant ($p>0.05$). This suggests that anthocyanin stability varies across berry species, and that freeze-drying could promote structural changes or oxidation.

Figure 5

Total anthocyanin content (TAC) in sour cherry, chokeberry and cranberry press residues after freeze-drying



ChrP – sour cherry press residues; FD-after freeze-drying; ChkP - chokeberry press residues; CrP - Cranberry press residues.

Results are expressed as mean value±standard deviation (n=3). Different letters indicate statistically significant differences ($p<0.05$).

At the same time, sample preparation and handling before freeze-drying should also be taken into account. For example, it is important to consider whether press residues are freeze-dried immediately after removal from the freezer or allowed to stand for a period before freeze-drying, as this could also affect anthocyanin stability.

Ross et al. reported that the retention of bioactive compounds in berry press residues is affected by the parameters and duration of the drying process, which could promote the degradation of polyphenols and anthocyanins (Ross et al., 2020).

This tendency partly corresponds with the results obtained in the present research. Furthermore, in the research by Ross et al., the TAC in the analysed cranberry press residues reached 147.22 mg C3G 100 g^{-1} dry matter, which is lower than the TAC determined in cranberry press residues in the present research 300.80 mg C3G 100 g^{-1} dry matter. These differences could be related to the cranberry cultivar and the freeze-drying parameters used.

Conclusions

1. The highest total phenolic and anthocyanin contents were found in fresh and lyophilised chokeberry press residues, indicating that these residues represent a valuable source of bioactive compounds.
2. The duration and parameters of freeze-drying affected the total anthocyanin content in berry press residues, particularly in sour cherry and chokeberry press residue samples.
3. Chokeberry press residues are a potential raw material for anthocyanin extraction and their further application in the development of bio-based indicators for food packaging.
4. The freeze-drying process of berry press residues should be more accurately studied to optimise the drying process. It is necessary to determine the optimal freeze-drying duration to maintain anthocyanin stability.

Acknowledgements

The authors would like to Ltd ʻANEVA J’ for their support in conducting the research and for providing berry press residues for the experiments.

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HIGH-POWER CHARGING SOLUTIONS FOR ELECTRIC TRANSPORT: REVIEW OF EXISTING TECHNOLOGIES AND APPROACHES

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Abstract
High-power charging (HPC) systems are becoming a critical enabling technology for the rapid electrification of heavy-duty, industrial, and mission-critical transport sectors. This review analyses converter topologies, energy-storage-integrated architectures, and microgrid configurations that define the performance, scalability, and stability of next-generation HPC infrastructure standardization (MCS, CCS), IT communication protocols (ISO 15118, OCPP) and microgrid configurations that define the performance, scalability, and stability of next-generation HPC infrastructure. The study shows that advanced AC/DC and DC/DC topologies – such as Vienna rectifiers, three-level NPC converters and modular multilevel converters-support the transition toward Megawatt-level charging systems while maintaining high efficiency and reduced harmonic distortion. Energy storage integration, especially an energy storage system connected to a DC bus, reduces the peak load of the grid by approximately 30-70% and can reduce voltage fluctuations by 4-8%, allowing systems to be integrated in locations where grid reinforcement is limited. Hybrid AC/DC microgrids can increase the flexibility of the power grid, reduce conversion losses by approximately 10-15%, and improve resilience in networks with pronounced demand peaks, such as those in airports, ports, and agricultural infrastructure. Predictive and AI-based charging strategies can further improve grid efficiency by approximately 10-25%, as they optimize charging schedules and electricity distribution in specific situations. The findings highlight that HPC deployment is most successful when based on topological system-level design rather than isolated technological improvements. The paper provides a structured comparative analysis and proposes topology-aware pathways to support scalable, stable, and sector-specific HPC deployment in climate-neutral transport systems.
Keywords: high-power charging, electric vehicles, microgrid, energy storage, smart control.

Introduction

The rapid electrification of transport systems is becoming one of the central pillars of the European Union's climate-neutrality strategy, as outlined in the European Green Deal and national frameworks such as Latvia's updated National Energy and Climate Plan (NECP) (National Energy and Climate Plan 2021-2030). While the electrification of light vehicles is progressing steadily, with charging infrastructure largely relying on the existing energy supply network, sectors such as agriculture, airport ground operations, public transport and port operations show significantly different operational profiles and energy requirements for transport units and notably for charging systems. These sectors are characterised by highly visible working conditions where downtime can significantly impact productivity, making it particularly important to provide them with reliable, high-power (HPC) infrastructure capable of providing 300-2000kW of charging capacity in short periods of time (Tietz et al., 2025; Kumar et al., 2019). This applies to the light and heavy vehicles used there, as well as the related technical equipment.

However, such high-intensity irregular charging events impose sudden and significant load peaks on distribution grids that were not originally designed to support transient megawatt-scale power flows. Observational studies show voltage instability, thermal overloads and reduced power quality when high-power charging stations are operated without solutions that reduce problems, risks or negative impacts (Kapoor et al., 2023; Maghami et al., 2025) Infrastructure upgrades, such as transformer replacement, additional deployment or grid capacity expansion, often involve a complex set of administrative procedures and high capital investments, so these solutions cannot be considered as the only and real solution for large-scale HPC deployment (Schoenberg et al., 2023).

Consequently, research and development is underway on integrated architectures that combine high-efficiency power electronics, local energy storage systems (ESS), renewable energy support and improved microgrid management. Studies show that combining energy storage with charging systems reduces the peak power demand of the grid by 30-70% depending on the configuration and operating models (Karimi et al., 2022; Agajie et al., 2023), while HPC systems connected to microgrids increase overall flexibility and resilience (Paule et al., 2025), in particular, research shows that in sectors such as aviation ground handling and port operations. For example, Zoutendijk & Mitici (2024) research demonstrates how airport ground operations create demand peaks that exceed the current infrastructure capacity, unless local buffering and predictive management solutions are used (Zautendijk & Mitici, 2024). Alfredsson et al. (2024), in their research, similarly conclude that implement fully electrified aviation ground operations services will require entirely new HPC topologies and grid-support structures (Alfedsson et al., 2024) A particularly important challenge that is still underexplored is the topology of HPC systems, combined with standardized communication and charging protocols to create complete infrastructure solutions. HPC implementation involves much more than just power electronics solutions, it is a complex and integrated approach, that includes a megawatt charging system (MCS) for heavy-duty vehicles and complex IT management systems that it combines a coordinated AC/DC conversion stage, DC/DC converters, ESS interfaces, bus voltages and microgrid layer

deployment (Hellgren et al., 2023). Power quality is largely determined by the power converter solution chosen, how efficient, stable, safe and usable the HPC charging system will be, including they determine harmonic spectrum, dynamic response, thermal performance and compatibility with future 800-1500 V electric vehicle platforms. Recent studies highlight that methods such as Vienna rectifiers, three-level neutral-point-clamped (NPC) converters, modular multilevel converters (MMC), dual-active-bridge (DAB) DC/DC converters, and resonant converters (LLC), which is a high-efficiency DC/DC converter topology, are increasingly being used for high-power charging, as they provide higher efficiency and lower total harmonic distortion (THD) (Safayatullah et al., 2023; Mateen et al., 2023; Arena et al., 2024; Atanalian et al., 2023).

Studies on the development of microgrids show that the choice between AC, DC and hybrid AC/DC topological solutions affects the system efficiency, energy storage capacity and also affects the integration of renewable energy resources, their fault tolerance in HPC nodes (Urooj & Nasir, 2024; Modu et al., 2023). The available literature sources are still fragmented and only a few studies review a unified comparative analysis of high-power charging topologies in different transport sectors and network usage conditions.

For this reason, the aim of this review is to review the analysis of high-power charging topologies in different transport sectors and network usage conditions, reviewing existing studies on high-power charging systems, paying special attention to topological architectures, their operation and sector-specific requirements.

The objectives of the article are:

1. To identify and classify the main problems associated with the implementation of high-power charging in agriculture, public transport, aviation and port operations;
2. Describe and compare different types of high-power charging converter topologies (AC/DC and DC/DC), topologies with energy storage system integration, and commonly used microgrid architectures;
3. Evaluate predictive control algorithms and control approaches that improve the performance of high-power charging (HPC) topologies under limited network capacity conditions;
4. Analyze the selection guidelines for existing topologies, taking into account the operating environment and power system constraints;
5. Provide a comprehensive overview and assessment of the development prospects of HPC infrastructure.

Based on previous research findings in power electronics, microgrid engineering, power system modeling, and industry experience, the article provides a technically sound and practically applicable perspective on existing high-power charging architectures, as well as insight into their development trends.

Materials and Methods

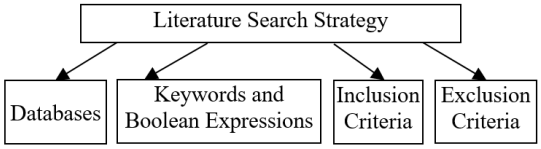
To create this review, a structured and systematic methodology was used to find, classify and evaluate existing research on high-power charging systems, and the associated operational constraints and technical topologies that have affected their implementation. The methodology was designed to ensure transparency, reproducibility and compliance with generally accepted scientific practice in literature reviews.

Literature Search Strategy

The literature search strategy is based on those stages, as shown in Figure 1.

Figure 1

Literature search strategy

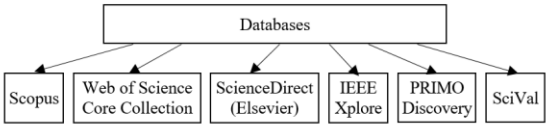


A comprehensive literature search was conducted in several internationally recognized scientific databases. In order to cover the most relevant studies in the field, databases with a high citation count were used, which help identify the most relevant studies, as well as those specializing in specific fields, such as power systems, transportation engineering, power electronics and microgrid design. The availability of full text was also an important factor, so that full articles could be analyzed before being included in the review.

The databases that were used are shown in Figure 2.

Figure 2

Used databases



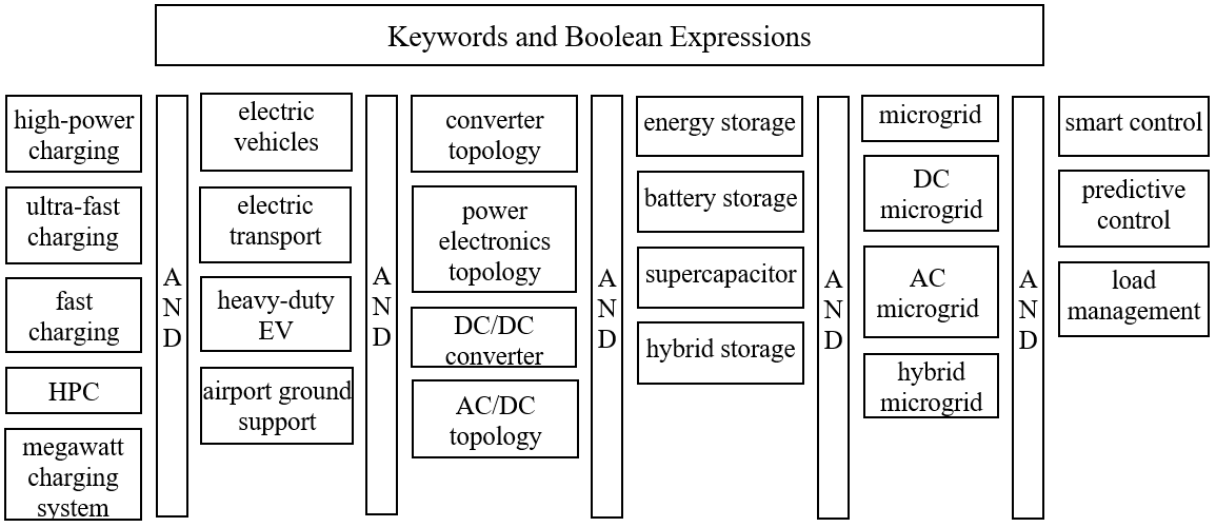
This review covers publications from the last decade (2015 to 2025) in both Latvian and English. Reviewing literature in both languages provided a deeper understanding of the context and effectively captured rapid technological development in high-power fast-charging architectures, power converter topologies, and energy storage integration.

Keywords and Boolean expressions

In creating the index, search queries were focused on keywords, phrases, titles, summaries, keywords. The set of Boolean expressions included the questions that are shown in Figure 3.

The methods given in the scheme ensured the inclusion of studies that are directly related to high-power charging infrastructure, with a special emphasis on topology, as well as network integration and system-level design.

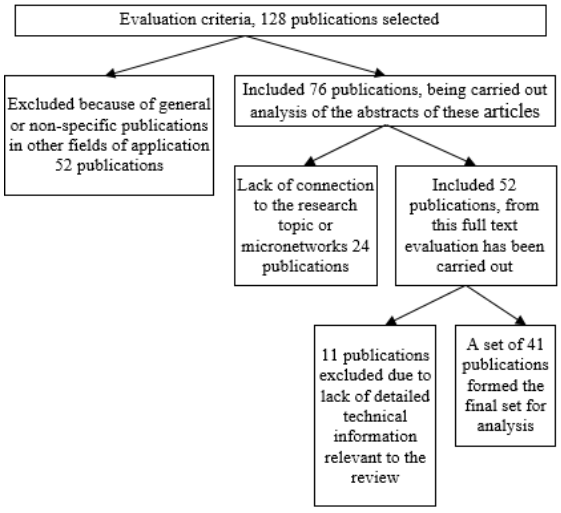
Figure 3
Keywords and Boolean expressions schema for literature search



Inclusion and Exclusion Criteria
These criteria determine which studies or data may be included in the study and which may not.
Inclusion Criteria
Publications were included in the review if they addressed high-power or ultra-fast charging (≥150 kW), network integration, power converters, energy storage systems, or microgrid architectures. These included AC/DC converter topology, DC/DC converter topology, bus configuration or microgrid structure analysis, modeling, or experimental evaluation. For inclusion in the review, methodological features were assessed, and publications that provided empirical data, modeling results, simulations, and prototype testing, as well as publications that discussed formal optimization methods, were included.
Exclusion Criteria
Publications were subject to multiple levels of exclusion criteria. Initially, as shown in the table, a check of titles and keywords was performed, and 52 publications were excluded that had a general or off-topic application. This was followed by an analysis of abstracts from the 76 publications that had passed the previous selection. At this stage, publication abstracts were analyzed, and publications were excluded if their abstracts were not related to the topic of the review study or microgrids. When performing this selection, 52 publications met the criteria, as shown in the table. At the final stage of publication selection, the full texts of the publications were evaluated, and exclusion was performed if the publications focused only on low-power charging, only considered the charging of light electric vehicles, were not scientific, lacked methodology, and did not provide engineering insights. After analyzing the literature, 41 publications were deemed eligible for inclusion in the review, the full process of which is mapped out in Figure 4.

Thematic Categorization of Publications
To ensure a transparent analysis of the research, all included studies were categorized into thematic groups, each of which covers a part of the topic under consideration. The following groups were distinguished: articles on network load and stability analysis, articles on high-performance charging demand modeling for heavy-duty electric vehicles, publications on energy storage integration and hybridization, as well as power grid topologies, microgrid architectures, and control algorithms; and specific articles related to agricultural, airport, port, and public transport research relevant to the topic of the article.

Figure 4
Evaluation criteria



This classification supports a structured comparison across different technological dimensions. These categories allowed for a comparative analysis of the

latest high-power charging infrastructures, which formed the basis for the 'Results' and 'Discussion' sections.

Methodological Limitations

Limitations of the review:

- The rapid pace of development of high-power charging stations and new topologies after 2025 is not yet widely documented, and information on the established charging infrastructures is not published.
- Lack of real-world case studies for 1-2 MW industrial high-power systems.
- Limited public data on the charging architectures used.

However, the methodological framework provides a comprehensive and replicable basis for a review of the topologies of existing high-power charging systems and their associated impact on the power system.

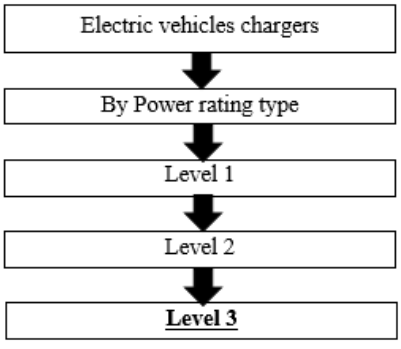
Results and Discussion

Overview of High-Power Charging System Topologies

Fast charging of electric vehicles can be performed with alternating current or direct current. The main difference in these charging methods is that in alternating current charging, the current is converted to direct current inside the electric vehicle; therefore, for fast charging, direct current is used, bypassing the converter built into the electric vehicle and its associated limitations (Ivarsøy, 2020). Modern electric vehicle charging infrastructures can be divided into several levels according to their capacity, as shown in Figure 5, dividing chargers according to their capacity. The solutions reviewed in the review are from level 3 and higher.

Figure 5

Types of electric charging according to their power ration type



Fast charging is defined with a capacity starting from 50 kW and a charging time of less than 30 minutes, while ultra-fast charging is defined with a capacity above 400 kW, which allows charging the vehicle's battery in less than 10 minutes (Zeb et al., 2025). With the development of heavy electric transport (electric tractors, trucks, ships, and aviation), the Megawatt charging system standard is being introduced, which aims to achieve up to 3.75 MW of power (1250 V/ 3000 A) (Alfedsson et al., 2024; Hellgren et al., 2024). Fast charging is a key prerequisite for reducing vehicle downtime and making electric vehicles more competitive in terms of performance with internal combustion engines (Zeb et al., 2025). Fast charging is essential for sectors such as agriculture, heavy transport, maritime shipping and aviation. Implementing fast charging during short operational breaks minimizes vehicle downtime, making it increasingly viable for these high-demand industries (Tietz et al., 2025; Ramberg & Levin, 2024).

Insights from the German truck infrastructure modeling by Tietz et al. (2025) suggest the need for high-power charging (HPC) in combination with night-time charging in logistics parks study concluded that this approach gives the best results (Tietz et al., 2025). Swedish action research on the feasibility of implementing charging infrastructure for heavy-duty electric vehicles operating in the construction sector shows that low-power night-time charging creates less grid load than high-power daytime charging, which takes place during the day, also because more HDEVs are charged at night (Ramberg & Levin, 2024). Most Norwegian research on the planning of fast charging stations (FCS) is focused on optimizing the location and layout of stations to reduce network losses and increase social benefits (Kapoor et al., 2023).

Main challenges in implementing high-power charging

In a study on truck charging and the creation of a fast charging network to decarbonize long-distance cargo transport, Tietz et al. (2025) focus on Germany while citing examples from Sweden. There, high-power mobile charging stations with buffer batteries have been studied to reduce the load on existing electricity grids. The authors emphasize the need for a minimum charging capacity of at least 720 kW, which poses a significant challenge for existing electricity networks (Tietz et al., 2025; Ramberg & Levin, 2024).

The next sector examined in the review is public transport, and the study by Prussi et al. (2024) examines solutions where trams in urban environments are equipped with fast-charging batteries or supercapacitors that are charged at stops, allowing trams to travel even in sections where there is no wired electrical network. The biggest challenges in this sector are peak load management and integration with existing infrastructure, such as the existing tram DC network described. Coordination of the movement schedule should also be mentioned as a challenge, as traffic is often unpredictable and optimization algorithms are complex (Zautendijk & Mitici, 2024).

In studies on ship and port infrastructures, a fast charging system is used that is supplied from the grid, but is also supported by shore-side batteries (OSB). Focusing on shore-to-ship power to provide zero-emission ferry traffic, the study examines shipping in the Baltic Sea and Norwegian fjords. The study compares three general S2SC solution power system architectures in terms of energy efficiency for AC, DC and inductive charging. Fast charging ports can charge

ships within 2 hours using charging connections on shore (Karimi et al., 2022; Kumar et al., 2019). It is concluded that problems can arise if there is a lower ratio of direct grid power to the total charging capacity, due to a lower energy efficiency of the system. This is due to energy losses that occur during the charging and discharging process of shore-side batteries. Problems also arise due to the lack of space on shore and the need for galvanic isolation for safety reasons (Kumar et al., 2019).

In aviation, business continuity and tight schedules – along with the short time aircraft spend on the ground between flights - make fast charging crucial. Consequently, studies in this sector examine megawatt charging systems capable of delivering up to 3000 A current and megawatt-level power (Alfedsson et al., 2024). The main challenges are related to the critical load that these charging stations place on airport networks, as well as the strict safety requirements such as fire hazard, electromagnetic interference (Alfedsson et al., 2024). Studies show that hybrid AC/DC microgrids in combination with DC coupler energy storage (ESS) at airports provide the most robust energy storage configuration, especially in the case of peak demand of 1 MW for a few minutes (Berdahl et al., 2020; Ahmad et al., 2025).

In the agricultural sector, studies describe challenges regarding charging infrastructure, noting that this sector predominantly uses private charging stations rather than public charging networks (Riedner et al., 2018). There is a strong interest in the use of renewable resources, mainly solar panels. Studies show that farms with their own energy storage infrastructure are more motivated to introduce electric vehicles on their farms. However, there is often a lack of grid capacity, high-power charging, especially in rural areas, so several studies are being conducted in this sector that could increase the number of mobile charging stations with energy storage systems that may not have an independent grid connection to ensure their operation, for example, in the field (Ramberg & Levin, 2024). Similar to other sectors, the main obstacle to introducing electric vehicles in agriculture is the long charging time. Furthermore, because heavy battery infrastructure can account for approximately 40% of a tractor's weight, it significantly increases the risk of soil compaction. Finally, research highlights logistical hurdles, such as the need for specialized rental agreements (Ramberg & Levin, 2024; Riedner et al., 2018; Lagnelöv et al., 2021).

Research conducted in Latvia is focused on ensuring the current stability of the grid and increasing energy efficiency in these sectors. For example, studies by Rubenis et al. (2025) focus on bidirectional energy transmission (V2G). This allows vehicles to become an active part of the grid, adjusting charging depending on the grid load and price, this approach reduces the peak load on the grid. Studies show that energy efficiency improves by 20-30% compared to unmanaged charging strategies. Researchers at Riga Technical University have studied an integrated multi-energy community hub for several houses, which can be installed with rooftop solar panel systems with a total capacity of 51 kW, such a solution increases self-consumption and creates greater grid flexibility (Paule et al., 2025). By the end of 2023, more than 20,000 small energy producers with a capacity of over 560 MW were connected to the grid in Latvia, the majority of which are solar energy systems, but there has been an increased interest in energy storage solutions, which are a crucial factor for fast charging capacity in regions where grid energy consumption is limited (Zemite et al., 2024).

Charging Standards and IT Infrastructure

To improve the applicability of the system, which covers electric vehicles from different manufacturers, charging stations, energy storage systems and power grids, it is imperative to introduce international standards. Research indicates that a standardized megawatt charging system (MCS) for heavy vehicles is being developed, designed to support charging power up to 3.75 MW (1250 V / 3000 A), which is very important for trucks and electric aviation (Hellgren et al., 2023). While the combined charging system (CCS) supports up to 400 kW, the MCS provides the necessary scalability for large batteries (Hellgren et al., 2023). The IT infrastructure and communication protocols are the 'brains' of HPC solutions. ISO 15118 (specifically ISO 15118-20) defines the communication between the vehicle and the charger, enabling 'Plug & Charge' and 'Vehicle-to-Grid' (V2G) capabilities. At the same time, the Open Charging Point Protocol (OCPP 2.0.1) facilitates communication between the charging station and the management system (CSMS), enabling real-time load balancing and smart charging management (Hellgren et al., 2023).

High-power charging converter topologies

In high-power charging stations AC/DC architectures:

- AC-DC rectifiers, often using a Wien rectifier to provide a high power factor, are widely used due to their high efficiency, low total harmonic distortion (THD), and unidirectional power density (Zeb et al., 2025; Bharaneedharan et al., 2024).
- NPC (Neutral Point Clamped) converters provide a bipolar DC bus and bidirectional power flow but are more expensive, and their control is more complex. Neutral point clamps (NPCs) are widely used in 350-600 kW chargers due to their high voltage capability and reduced semiconductor voltage (Zeb et al., 2025).
- T-shaped and active neutral point clamp (ANPC) converters, which support improved harmonic suppression and flexible modulation schemes (Sadeghi et al., 2022).
- Modular multilevel converters (MMCs), are becoming the preferred architecture, especially for megawatt charging systems with a capacity of 1-2 MW, due to their scalability, fault tolerance and excellent waveform quality (Barresi et al., 2022; Rodriguez et al., 2022).

In high-power charging stations DC/DC architectures:

- Non-isolated (interleaved buck) has a modular design and low current ripple but lacks galvanic isolation, which is a safety risk (Zeb et al., 2025).
- Isolated (Phase-Shifted Full-Bridge (PSFB) and LLC) are popular due to their high power density. LLC
- resonant converters provide ‘soft’ switching and low EMI. These resonant converters provide high efficiency in the 20-200 kW range, but their design is difficult due to the nonlinear charging profile (Zeb et al., 2025; Peng et al., 2025).
- The Dual Active Bridge (DAB) is recommended for bidirectional power flow from vehicle to grid (V2G) with built-in soft-switching capability, where transistors switch when the voltage is very low or the current is very low, and modular scalability that can gradually increase the system according to the required power, electric vehicles not only consume energy, but can also return it to the grid (Zeb et al., 2025; Chaudhury & Kastha, 2025).
- Research shows that interconnected buck and multi-port converters appear in modular charging solutions that provide flexible power sharing across multiple charging outputs (Elkeiy et al., 2023).

Studies consistently emphasize that DC microgrids offer the highest efficiency for multi-MW charging infrastructure, while hybrid architectures offer the best compromise between efficiency and compatibility with existing infrastructure (Azeem et al., 2021; Feng & Chi, 2021).

Microgrid architectures:

- AC microgrids are becoming less widely used because their use requires a higher number of conversion stages; for example, solar panels produce DC, which is converted to AC with the help of an inverter. If this energy needs to be stored, then the energy is stored in batteries, and this energy must be converted back to DC.
- DC microgrids are becoming a priority because they reduce the number of energy conversion stages, for example, from solar panels and batteries directly to electric vehicles, thus reducing losses (Berdahl et al., 2020).
- Microgrid Architectures and Efficiency AC and DC microgrids are core components of HPC hubs. While AC networks remain the standard for low-power applications, DC microgrids are becoming a priority for high-power installations (Berdahl et al., 2020). This shift is technically justified because DC distribution reduces the number of energy conversion stages; for instance, PV panels, batteries (BESS), and electric vehicle batteries all operate natively on DC (Berdahl et al., 2020). By eliminating redundant AC - DC and DC-AC conversions, DC microgrids can reduce energy losses by 10-15% and significantly improve overall system efficiency. This configuration also simplifies the control structure and allows for higher current capacity in localized energy hubs (Berdahl et al., 2020).

Predictive Control Algorithms and Approaches

Under capacity constraints, studies have shown that Model Predictive Control (MPC) and its corresponding network regulation power and thermal constraints can be improved by optimizing charging in real time. Smart charging algorithms, such as those based on the ISO 15118 standard for dynamically adjusted charging and load-dependent charging, provide dynamic charging capacity adjustment depending on the network load and the price of each exchange and peak demand, thus reducing electricity costs by 20-30% (Rubenis et al., 2025). Quadratic Programming (QP) is an optimization method where the objective function is quadratic, but the constraints are usually linear. In the case of airports, real-time QP algorithms allow prioritizing aircraft charging, largely attacking flight time and available power (Alfedsson et al., 2024). Heuristic algorithms (ALNS, PSO) and loss methods that search for a good (not always perfectly optimal) solution to complex problems, where classical network methods as well as investment optimization methods (e.g., QP) become too slow or unusable due to costs (Zautendijk & Mitici, 2024).

Future research focuses on the use of artificial intelligence (AI) in battery management systems to more accurately predict SoC (State of Charge) and SoH (State of Health), thereby extending battery life under aggressive, high-power charging cycles (Devi et al., 2026).

Guidelines for choosing topologies

Topologies of systems depend on the operating environment and constraints, e.g., AC-coupled BESS (T1 topology) are simpler and with higher technology readiness (TRL), but DC bus topologies (T2/T3) offer better scalability for the creation of future energy hubs (Alfredsson et al., 2024). If any spatial constraints are defined, such as urban environments and airports, then the choice of topologies should be given preference to ground installations, or mechanized solutions to save space, as integrated (Alfedsson et al., 2024). In terms of mobility, it is described in places where the use of stationary infrastructure is not economically advisable, such as fields and construction sites (buffer batteries) (Ramberg & Levin, 2024).

HPC infrastructure development prospects

The future of HPC infrastructure is moving towards integrated and decentralized energy management. How it should be developed is the transition to new materials, such as the use of silicon carbide (SiC) and gallium nitride (GaN) in converters, they reduce the size and heat loss by more than 70% (Zeb et al., 2025). Smart microgrids with individual charging stations will evolve into multi-energy community hubs that combine RES generation, BESS, and V2G service network stability, as already available studies show (Paule et al., 2025). The introduction of megawatt charging systems is essential; the introduction of such a standard electrical system will allow for MW-level charging capacities to be achieved, making electric vehicles competitive with internal combustion engine

vehicles (Ramberg & Levin, 2024). The use of AI and digital twins is increasingly important; specifically, the integrating artificial intelligence into battery management systems allows for more accurate SoC prediction, thereby extending the service life of battery packs (Rahman et al., 2025; Kurkin et al., 2025).

Table 1

Comparative Analysis of HPC-Related Topologies

Topology Type	Specific Topology	Power Range	Efficiency	Harmonics / PQ	Scalability	Dynamic Response	Strengths (Applications)	Limitations
AC/DC Converter Topologies	Vienna Rectifier	150-600 kW	96-98%	Low THD (2-5%)	Medium	Medium	High-efficiency front end for bus depots, logistics chargers; compact size	Unidirectional power flow; not ideal for V2G or hybrid ESS
	3-Level NPC Converter	150-800 kW	96-98%	Low THD (3-7%)	High	High	Stable high-power charging; compatible with 800-1000 V platforms	More complex control; increased component count
	Active NPC / T-Type Converter	150-750 kW	97-98%	Very low THD	Medium-High	High	Lower switching losses; good harmonic suppression for aviation GSE chargers	Thermal balancing challenges
	Modular Multilevel Converter (MMC)	500 kW-2 MW	97-99%	Excellent PQ	Very High	High	Best option for mega-watt charging (airports, ports); high voltage capability	Complex control; higher cost
DC/DC Converter Topologies	Dual Active Bridge (DAB)	50 kW-1 MW	96-98%	N/A	High	Very high (sub-ms)	Bidirectional charging, ESS integration; excellent for depots and airports	Requires precise control; EMI considerations
	LLC Resonant Converter	20-300 kW	95-97%	N/A	Medium	High	High-frequency operation, compact form; good for modular chargers	Limited scalability to MW-class
	Interleaved Buck / Multiport	20-800 kW	94-97%	N/A	High	Fast	Flexible output distribution; good for multi-user charging hubs	Lower efficiency at very high power
ESS Coupling Topologies	AC-Coupled Battery ESS	100 kW-5 MW	92-96% system	Supports grid THD reduction	Medium	Medium	Easiest retrofit; grid-side buffering for depots and ports	Two conversion stages → higher losses
	DC-Bus-Coupled ESS	100 kW-2 MW	95-98% system	Direct support to charger	High	Very High	Reduces peak loads by 30-70%; ideal for airports, agricultural hubs, high peaks	Requires aligned DC bus voltages
	Hybrid ESS (Battery + Supercapacitor)	50 kW-2 MW	95-98%	Excellent smoothing	High	Extremely high	Reduces transient stress 15-30%; stabilizes pulsed loads	Higher initial CAPEX
System-Level / Microgrid Topologies	AC Microgrid	100 kW-10 MW	Moderate	Grid-dependent	Medium	Medium	Compatibility with existing infrastructure; suitable for public transport	Higher conversion losses (5-8% more than DC MG)
	DC Microgrid	100 kW-10 MW	High (loss reduction 10-15%)	Very stable	High	High	Efficient multi-charger clusters; avoids multiple conversions; ports & bus depots	Requires harmonized converter interfaces
	Hybrid AC/DC Microgrid	100 kW-20 MW	High	High	Very High	High	Best flexibility; integrates renewables, ESS, HPC under constraints; optimal for airports	Higher control complexity; coordination layers needed

To better understand high-power charging topologies, they are summarized in Table 1. The summary demonstrates that no topology is universal and optimal for every situation, the choice depends on the requirements of the specific application.

Comparative Analysis of HPC-Related Topologies

A critical conclusion derived from current research is the necessity of ‘peak shaving’ to protect the utility grid from high-power demand spikes (Hellgren et al., 2023; Kapoor et al., 2023). Peak shaving is achieved by integrating Battery Energy Storage Systems (BESS) that act as an ‘energy buffer’ (Karimi et al., 2022).

Battery Energy Storage Systems (BESS) can be charged from the grid during periods of low demand, such as at night when electricity consumption is lower. These systems can return the stored electricity during high-power charging, effectively helping to reduce the peak power consumed from the public grid (Hellgren et al., 2023). Studies show that the peak grid load can be reduced by 30-70%, avoiding expensive grid reconstructions and the need for larger transformers. To improve the use of BESS, it is possible to use dynamic charging capacity limitation, where the charger adjusts its capacity based on real-time grid constraints, which further helps to reduce the grid load (Ramberg & Levin, 2024; Kapoor et al., 2023).

Conclusions

1. In high-power charging stations, the most efficient AC/DC conversion efficiency is provided by Vienna

rectifiers, which guarantee high efficiency and low total harmonic distortion (THD). In DC/DC transmission, priority is given to isolated topologies (such as PSFB and LLC resonant converters), which provide galvanic isolation, that is, there is no direct electrical connection between the two electrical circuits, and thus ensure user safety.

2. Successful implementation of high-performance high power charging (HPC) is not limited to the choice of power electronics, it is a complex and comprehensive approach, requiring full integration with international standards, such as the Megawatt Charging System (MCS). The MCS is designed to provide charging capacity up to 3.75 MW (1250 V / 3000 A) for the heavy transport and aviation sectors. Such standardization is crucial to ensure infrastructure interoperability and scalability across different transport sectors.

3. Smart control algorithms (MPC, QP) combined with standardized IT communication protocols that ensure data exchange and interoperability between charging system components, such as ISO 15118-20 and OCPP 2.0.1, serve as the 'brain' of the system. These algorithms enable real-time power distribution, Vehicle-to-Grid (V2G) functionality, and grid load balancing, which are essential for managing large-scale charging hubs.

4. The integration of stationary Battery Energy Storage Systems (BESS) is a technically and economically justified solution for 'peak shaving'. It can reduce peak loads on the electrical grid by 30-70%. This system and approach is an indispensable tool for avoiding expensive investments in grid expansion and the installation of high-capacity transformers in areas with limited grid capacity.

5. In high-power charging stations, direct current (DC) microgrids are touted as a more efficient solution compared to alternating current (AC) microgrids, as they significantly reduce the number of energy conversion stages. Since photovoltaic panels, battery-powered energy storage systems (BESS), and electric vehicle batteries are inherently DC voltage environments, a local DC architecture can reduce the overall system energy losses by 10-15%, thereby improving the cost-effectiveness of the infrastructure.

6. This review, based on a broad analysis of international literature (including HPC network modeling in Germany, fast-charging station planning in Norway, and simulations from the Swedish construction industry), provides a comprehensive insight into integrated HPC infrastructure solutions, identifying that the success of HPC implementation depends on topological system-level design rather than isolated technological improvements.

7. In the future high-power charging infrastructures will transition toward integrated 'Smart Energy Hubs' that harmonize local renewable generation, energy storage, and V2X capabilities. This evolution is driven by three key trends: the adoption of SiC/GaN semiconductors to maximize efficiency and power density, the application of AI and Digital Twins for predictive battery health and grid management, and the global standardization of Megawatt Charging Systems (MCS). These innovations in HPC technology are essential for achieving full competitiveness for heavy-duty electric transport, aviation, and maritime sectors against traditional fossil fuels.

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A LINEAR PROGRAMMING APPROACH TO LAND AND IRRIGATION WATER ALLOCATION FOR PRIORITY CROPS IN RWANDA

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Abstract
Efficient irrigation-water allocation remains a critical pillar of climate-resilient agricultural development, particularly in Rwanda, where more than two-thirds of the population depends on rain-fed production. To advance national targets outlined in the Irrigation Master Plan (2020) and the Rwanda Water Resources Board Strategy (2022–2027), this study developed a multi-constraint linear optimization model to allocate irrigation water among eleven major crops, utilizing five years of agricultural data (2019–2024). The model incorporated three water-availability scenarios (100%, 80%, and 60%), ecological flow requirements, FAO-56 yield response factors (Ky), and minimum area thresholds for staple crops. The study employed a rigorous statistical assessment of Linear Programming (LP) with coefficients of determination (R^2) ranging from 0.69 to 0.94, and Principal Component Analysis (PCA), which explained 77.5% of the total variance in the first two principal components. Ky ($\beta = +0.74$) most strongly explained variation in deficit-irrigation levels. At 100% and 80% national water availability, the model maximizes profits to 490.2 million USD and 376.2 million USD, using 1.84 and 1.46 billion m^3 of water, respectively. The study concluded that a linear optimization model provides a transparent and quantitatively robust decision-support tool for achieving the targets set in irrigation planning in Rwanda.
Keywords: Rwanda, irrigation, linear programming, biophysical determinants, major crops.

Introduction

Agriculture remains the backbone of Rwanda's economy (Nzeyimana et al., 2024), employing 70 percent of the workforce and contributing 33 percent to GDP (Sunday et al., 2024). Despite its significance, the sector faces challenges, including dependence on rainfall, fragmented landholdings, steep terrain, and climate variability. About water resources in Rwanda, with only 9 km^3 of renewable freshwater available annually (Nibagwire & Drouiche, 2017), and increasing competition from urban and industrial sectors, irrigation has become essential for sustainable agricultural intensification (MINAGRI, 2020). Consequently, government agencies are prioritizing the expansion and optimization of irrigation systems to enhance resilience and productivity (Chandra et al., 2023). In Rwanda, freshwater ecosystems cover about 15% of the country (Nzarora et al., 2024) with uneven distribution of water regarding space, time, and quality (Kifle Arsiso et al., 2017).

Water allocation based on historical cropping patterns or political considerations often results in inefficiencies (Ryan & Sudarshan, 2022; Browne & Ji, 2023). UN-Water (2024) defines water allocation as who receives water, when, and under what conditions. Water reallocation during shortages is essential for enhancing resilience in drought-prone basins (Alfredo & Russo, 2017). Allocation systems distribute permits or property rights that determine access, withdrawal, and use of water (Wang et al., 2018). In the case of Rwanda, to support basic natural resource and ecological functioning, water must be allocated efficiently across competing uses (RWFA, 2019).

Linear programming (LP) offers a rational and transparent framework for optimizing scarce resources (Hillier & Lieberman, 1995). In irrigation planning, LP is used to determine cropping patterns that maximize total profit and minimize water use, subject to constraints on land, labour, and water availability (Mizyed, 2025; Sadati et al., 2014), for countries like Rwanda, which aim to expand irrigated land to over 100,000 hectares by 2030 (RWB, 2020). LP models simplify computation and enable scalable analysis (Park et al., 2017). When decisions involve discrete choices—such as whether to irrigate a field—mixed-integer linear programming (MILP) is employed (Gong et al., 2020). Linear programming has been applied to optimize irrigation water allocation and reduce energy consumption, as demonstrated by Zhang et al. (2022). First application of LP to irrigation water allocation, demonstrated a 27% increase in profit through optimal redistribution of limited water among crops (Frizzone et al., 1997). Since then, LP applications have expanded to multi-crop systems, basin-level management, and irrigation scheduling under uncertainty (Gong et al., 2020). Researchers used LP in Ethiopia to allocate cropland for smallholder households (Mellaku et al., 2018). LP counted 10–30% of evapotranspiration (ET) deficits to enhance water productivity in Ethiopia (Simegn, 2019). Different studies reported that crops responded uniquely to irrigation deficit, including tomato (Boari et al., 2016), wheat (Bayisa et al., 2024), cotton (Xu et al., 2024), rice (Sedighkia & Datta, 2025), maize (Zou et al., 2021), potato (Niu et al., 2024). Optimizing irrigation in multi-crop systems requires precise modelling of crop coefficients (Kc), crop evapotranspiration (ETc), and yield response factors (Ky), as outlined in FAO-56 guidelines (Allen et al., 1998). In regions lacking local evapotranspiration (ET) data, the water footprint (WF) approach offers global coefficients for blue and green water use per unit of

crop yield (Mekonnen & Hoekstra, 2011).

LP is integrated with modern computational tools such as LINGO (Afshar et al., 2007), GAMS (Silori & Khanam, 2018), MATLAB (Fei et al., 2022) and Python's PuLP (Vinten et al., 2017) to enhance the applicability. Multivariate techniques such as scatterplots, correlation matrices, and principal component analysis (PCA) reveal structural relationships within agronomic datasets that influence optimal land and water allocation (Abdelghany et al., 2025).

Previous studies in Rwanda have focused on single crops or localized irrigation schemes. Consequently, a comprehensive national optimization covering all major crops has not yet been published. This research aims to compile a unified dataset for Rwanda's eleven key crops, apply a linear profit-maximization model under three water-availability scenarios, and analyse how crop area, water use, and national profit respond to scarcity. This study also has significant implications for the agriculture domain, where agriculture is both a cause and a victim of water scarcity. The results may serve as a resource for sectoral water allocation plans to ensure equitable sharing of water resources at the regional scale. It will also provide a policy-ready, quantitative basis for irrigation planning.

Materials and Methods

Detailed Description of the Study Area

This study was conducted in Rwanda, which lies between latitudes 1° and 3° S and longitudes 29° and 31° E. Rwanda covered 26,338 km² and ranged in elevation from 900 m in the east to more than 2,500 m in the northwest highlands. The major crops in Rwanda are beans, bananas, maize, cassava, sweet potatoes, Irish potatoes, sorghum, soybeans, vegetables, paddy rice, groundnuts, peas, fruits, and wheat crop, cultivated in seasons A (September-February) and season B (March-June). Beans are the first crop cultivated on a large scale, with 342,418.3 ha, with corresponding production of 234,027 tons. During 2024, agriculture contributes to climate resilience interventions by farming practices of 142,318.7 ha and 1031,282.8 ha of radical and progressive terraces (MINAGRI, 2024). Irrigation is leading in consumptive water use in Rwanda. The country's irrigation potential area is 600,000 ha (Mabhaudhi et al., 2025). Out of this area, 13.8% (or 72,913 ha) is already developed, including 37,273 ha for marshland, 9,439 ha for hillside irrigation, and 26,201 ha for small-scale irrigation technology (SSIT).

Rwanda has a bimodal rainfall pattern, with rainfall ranging from 1,000 to 1,600 mm, falling between September-January and February-June. Renewable water resources are about 6.80 billion m^3 per year. However, Rwanda has 670 m^3 per capita (Hakiruwizera et al., 2022), which means not rich in renewable water resources compared to the water threshold value of 1,700 m^3 per inhabitant per year (Zhong et al., 2023). Rwanda accounts for forty lakes with an estimated storage capacity of 225.2 billion m^3. Lake Kivu is the largest, with 222.33 billion m^3, and about 1000 km^2 (42%) belongs to Rwanda (RWB, 2020). Besides that, a total of 250 islands representing 315 km^2 are present in Kivu Lake. However, the previous studies indicated that the Kivu Lake zone has lost over 346,000 ha of forest cover during the period of 13 years from 1988 to 2011, due to farming activities and animal rearing (Uwamahoro et al., 2024). Rwanda accounts for fifty water storage dams with a total storage capacity of 72563,300 m^3, including 45 dams used for irrigation, 2 dams for hydropower, 2 dams for water supply, and one is used for both irrigation and water supply. Table 1 provides a summary of the key characteristics of the top ten irrigation dams (RWB, 2023). Domestic water use is the second-highest water consumption, with 38.61% (234.8 million m^3 per year). Followed by mining, industries, fishponds, and coffee washing stations with 0.79%, 0.53%, 0.17%, and 0.4%, respectively (Hakiruwizera et al., 2022).

Table 1

Classification of dams by type, height, storage capacity, and their uses in Rwanda

Name	Location	Dam type	Height, m	Storage, m^3
Rwinkwavu	Kayonza	Earth fill	9.5	4200,000
Rwangingo	Gatsibo	Earth fill	10	3750,000
Gacaca	Kayonza	Earth fill	9.5	2500,000
Muyanza	Rulindo	Earth fill	26	2300,000
Nyanza 23	Nyanza	Earth fill	19	1820,000
Kayonza-4	Kayonza	Earth fill	9.5	1600,000
Gatinga	Kayonza	Earth fill	-	1500,000
Rugende	Rwamagana- Gasabo	Earth fill	13.5	1350,000
Rwamagana-34	Rwamagana	Earth fill	14	1000,000
Cyili	Huye	Earth fill	9.5	950,000

Source: (RWB, 2023).

Data sources and parameter compilation

This study uses multi-crop optimization in Rwanda because of its varied agro-ecological zones, which support perennial crops, cereals, legumes, and roots. To allow reallocation among 11 major crops, including maize, sorghum, rice, wheat, cassava, Irish potatoes,

bananas, dry beans, peas, groundnuts, and soybeans, the study's scope includes all the country's irrigated land. Ecological flow (m³) was designed for scenarios where environmental protections are guided by nationally documented policies, such as the Irrigation Master Plan. Cultivated area and yields data were derived from the agricultural seasonal survey of seasons A (September-February) and B (March-June), which was compiled by the National Institute of Statistics of Rwanda (NISR, 2022). Water footprint, WF (m³ kg⁻¹), refers to the blue-green water footprint per crop from 1996-2005. Water per hectare (m³ ha⁻¹) collected by following the methodology of Allen et al. (1998) and calculated as yield × 1000 × WF. Producer prices (USD t⁻¹) were adapted from the farm-gate price built by the FAOSTAT producer domain (Vos et al., 2023). Water availability (m³) was referred to the national annual envelope of irrigation water at 100%; scenarios scale this by 80% and 60% to represent drought stress (RAB, 2010). In addition, yield-response factors (Ky) follow FAO-56 guidelines. Seasonal yield-response factors, Ky, represent the linear effect of deficit irrigation (Allen et al., 1998).

Model Optimization

The study developed a linear programming model that includes four constraints and uses McCormick linearization to maintain linearity (Leyffer & Manns, 2025), while enabling continuous deficit irrigation decisions for each crop (Table 2). The study used Python's PuLP algorithm to enhance the applicability of LP models. Multivariate techniques, including scatterplots, correlation matrices, and principal component analysis (PCA), were used to validate the structural relationships within agronomic datasets that influence optimal land and water allocation.

Table 2

Set and definitions of variables

Variables	Definition of variables
$\mathcal{C}$	Crops (11), including maize, sorghum, rice, wheat, cassava, Irish potatoes, bananas, dry beans, peas, groundnuts, and soybeans
A_c	Irrigated area of the crop c (ha), noted by Area_cap_ha, and it should be positive
x_c	Deficit level (fraction of full irrigation), applied to the crop c, nd varies between $[0,1]$
Z_c	Linearization of water and yield variables($A_c x_c$). It should be positive
$Y_c(x_c)$	Yield and revenue under deficit linear terms ($Y_c(x_c)$, using FAO-56 $K_y$response, the per-hectare yield under deficit
$K_{y,c}$	Yield response factor for 11 crops
Y_c^{pot}	Five years Average of yields 11 crops at full irrigation (t ha⁻¹).
W_c^{full}	Linearization of water accounting with full-irrigation water requirement per hectare (m³ ha⁻¹),
$x_c W_c^{full}$	Under deficit x_c, water per hectare, (m³ ha⁻¹)
P_c	Producer price revenue (USD t⁻¹).
C_c	Per-hectare cost (USD ha⁻¹).)
s	Water availability scenarios (100%, 80%, and 60%)

Objective functions

Application of a linear profit-maximization model for water-availability scenarios has aimed to analyze how crop area, water use, and national profit respond to scarcity as in Equation 1.

$$\text{Max} \sum_{c \in \mathcal{C}} [\underbrace{\left(P_c Y_c^{\text{pot}} - C_c - P_c Y_c^{\text{pot}} K_{y,c}\right)}_{\text{coefficient of } A_c} A_c + \underbrace{\left(P_c Y_c^{\text{pot}} K_{y,c}\right)}_{\text{coefficient of } Z_c} Z_c] \quad (1)$$

Formulation of the Constraints

Equation 2 illustrates water availability with ecological reservation.

$$\sum_c Z_c W_c^{\text{full}} \leq s \cdot W^{total} - \text{Eco Flow} \quad (2)$$

Under scenarios, total water use should not exceed the amount of water available (by scenario $s \in \{1.0,0.8,0.6\}$).

Equation 3 indicates the cultivated area limitations.

$$\sum_{c \in C} A_c \leq A^{total} \quad (3)$$

The total adjacent area should not exceed the usable agricultural land limit.

Minimum cultivated area constraints for staple crops under the food safety policy (Equation 4).

$$A_c \geq \bar{A}_c \text{ for } c \in \{\text{maize,beans,cassava}\} \quad (4)$$

All constraints should be positive as McCormick envelopes (Equations 5-8).

$$Z_c \leq A_c, \quad (5)$$

$$Z_c \leq \bar{A}_c \, x_c \quad (6)$$

$$Z_c \geq A_c - \bar{A}_c(1 - x_c) \quad (7)$$

$$Z_c \geq 0. \quad (8)$$

These four linear inequalities exactly bound the bilinear term on the $[0, \bar{A}_c] \times [0,1]$ rectangle and deficit feasibility boundaries $[0 \leq x_c \leq 1, 0 \leq A_c \leq \bar{A}_c]$.

Statistical Analysis

A statistical methodology deployed to assess if the linear optimization model is internally consistent and has implications in real field agronomy. Both the Standardized regression (β) analysis, the regression model of determination of coefficient (R^2), and the correlation matrix were analysed. A principal component analysis (PCA) was also used in the exploration of the data. Scatterplots were useful for observing linear and non-linear relationships, with evident crop groups such as cereals, legumes, and tubers.

Results and Discussion

Under full irrigation (100% water availability), the optimization model allocates land to maximize national profit, which reaches $490.2 million, using 1.84 billion m³ of water. When water availability drops to 80%, national profit declines to 376.2 million USD, and total water use falls to 1.46 billion m³, prompting a more conservative allocation. Under severe scarcity (60% availability), the system undergoes a dramatic restructuring, with national profit dropping to $262.6.0 million USD and water use decreasing to 1.13 billion m³ (Table 3). Cassava stands out for its drought tolerance and high caloric output, while potato provides stable yields on volcanic high plateaus; these findings are consistent with studies in SSA and East Africa (Nweke, 2004). In contrast, rice and beans have a high-water footprint, with optimization studies emphasizing their opportunity costs (Bouman & Tuong, 2001). Cassava dominates due to its low Ky value and high caloric output, while potato benefits from favourable physiology and high farm-gate prices (Kiziloglu et al., 2006; Badr et al., 2022). Rice and beans, however, show limited growth due to their high-water footprint and stress sensitivity, consistent with findings in the optimization literature (Bakhsh et al., 2024; Rathore & Pandey, 2023). Under moderate scarcity, cassava, potato, and banana maintain dominance, whereas rice and beans contract sharply (Zwart & Bastiaanssen, 2004). Under extreme scarcity, the model prioritizes drought-tolerant crops to ensure optimal water resource utilization.

Table 3

LP model for crop area allocation under water availability scenario and profitability

Crop	Allocate area (ha) by water availability scenario			Profit (USD Million) by scenario		
	100%	80%	60%	100%	80%	60%
Cassava	180,000	165,000	150,000	112.4	89.7	64.5
Irish Potato	165,000	150,000	124,000	154.9	113.2	79.8
Banana	140,000	126,000	110,000	97.5	82.5	63.2
Soybean	75,000	60,000	42,000	33.6	24.8	15.6
Groundnut	62,000	48,000	32,000	27.4	19.3	11
Maize	50,000	50,000	50,000	21.5	18.4	13.5
Beans	60,000	60,000	60,000	15.9	11.1	6.2
Peas	25,000	18,000	11,000	8.7	5.2	2.8
Sorghum	18,000	14,000	10,000	6.3	4.7	2.4
Wheat	15,000	11,000	8,000	7.8	5.4	3.1
Rice	8,500	4,200	1,200	4.2	1.9	0.5
Total	798,500.0	706,200.0	598,200.0	490.20	376.20	262.60

The integrated analysis of Rwanda's LP-optimized irrigation model, using averaged national data from 2019–2024, reveals a clear biophysical and economic logic behind crop prioritization across 11 major crops. The model processed a total feasible irrigable base of 798,500 ha, with yields ranging from 1.1 t ha^{-1} (beans) to 18.5 t ha^{-1} (Irish potato) and water requirements from 2,900 m³ ha^{-1} (cassava) to 14,200 m³ ha^{-1} (rice).

LP model allocated area, profitability, water-use efficiency, deficit irrigation resilience, and performance stability by ranking as 1st Irish potato, 2nd Cassava, 3rd Banana, 4th Soybean, 5th Groundnut, 6th Maize, 7th Beans, 8th Peas, 9th Sorghum, 10th Wheat, and 11th Rice.

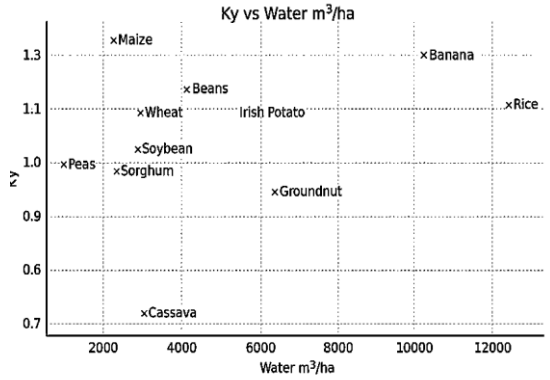
Irish potato leads due to its high yield (18.5 t ha^{-1}), strong market value, and moderate water needs, contributing $97.5–154.9 million annually with a Ky of ~1.1. Irish potatoes have shown resilience even at 60% water availability. Cassava follows, valued for its drought tolerance, low water footprint (3300 m³ ha^{-1}), and stable profits ($64.5–112.4 million), supported by its low Ky (~0.7). The model considers bananas as a fixed crop due to its perennial nature and profits between $63.2–97.5 million per season, despite a higher water footprint. Peas, sorghum, and wheat offer niche returns, while rice ranks last due to its high-water footprint (12,750 m³ ha^{-1}), cost, and Ky sensitivity, contributing only $0.5–4.2 million. This ranking was

validated statistically via PCA and regression diagnostics, confirming that Rwanda's LP-optimized crop prioritization is grounded in biophysical and economic realities.

Figure 1 illustrates the water use by crop response factor (Ky), crops like cassava, banana, and Irish potato tolerate moderate to high deficits with minimal yield loss due to their low Ky value, consistent with FAO-56 findings that lower Ky correlates with reduced sensitivity to water stress (Allen et al., 2004). This enables the model to apply strategic water-saving measures while maintaining profitability, especially for resilient, high-efficiency crops. In contrast, maize and beans exhibit high sensitivity to deficit irrigation, with elevated Ky values causing steep yield declines even under slight water reductions (Ma et al., 2023). Consequently, the model reduces the area allocated to these crops rather than subjecting them to high deficits, like optimization studies from India (Srilatha et al., 2022), Indonesia (Hidayat et al., 2023). The LP model revealed that when water availability drops to 80% and 60%, agricultural water use also decreases, but not linearly, indicating a strategic shift toward high water-productivity crops like cassava, Irish potato, and banana.

Figure 1

Allocation of water use by crop response factors



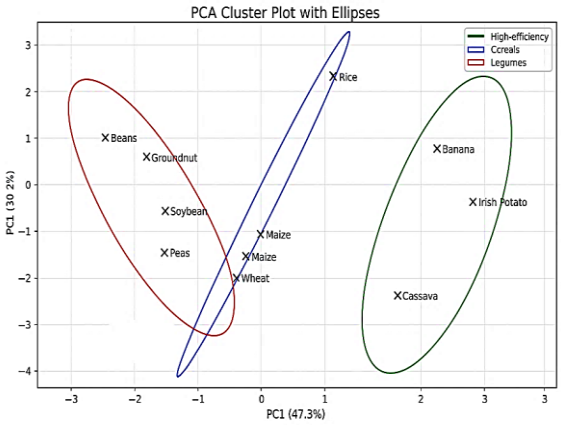
Standardized regression (β) analysis confirms three LP outcomes of optimized area, profit, and deficit response as follows: yield is the strongest positive predictor of land allocation (β = 0.71), while water footprint is the strongest negative (β = –0.64). Profit is the strongest predictor of price and yields, with β of 0.82 and β = 0.55, respectively, as key drivers. While water footprint again reduces profitability (β = –0.47). Ky factor (β = 0.74) is the dominant predictor of deficit-irrigation response, validating the model's sensitivity to crop stress tolerance. These findings collectively reinforce the LP model's structural logic, showing that multi-dimensional biophysical and economic traits are essential for sustainable irrigation planning in Rwanda.

Figure 2 illustrates the Principal Component Analysis (PCA) scatter plot, which explains 77.5% of the total variance across the first two principal components (PC1 and PC2). PC1 visualized crop clustering with 47.3% variance. This PC1 separates crops by yield and water footprint. It places cassava, Irish potato, and banana in a high-efficiency cluster. In contrast, PC1 places rice, beans, and groundnuts into a low-efficiency group. PC2 of 30.2% variance visualizes economic traits. PC2 indicated that rice has a high-price/high-cost extreme. However, cassava is at the low-cost/high-yield end. PCA indicates that cereals such as maize, wheat, and sorghum cluster near the origin, reflecting moderate biophysical traits and sensitivity to water constraints.

Standardized regression (β) analysis confirms three LP outcomes of optimized area, profit, and deficit response as follows: yield is the strongest positive predictor of land allocation (β = 0.71), while water footprint is the strongest negative (β = –0.64). Profit is the strongest predictor of price and yields, with β of 0.82 and β = 0.55, respectively, as key drivers. While water footprint again reduces profitability (β = –0.47). Ky factor (β = 0.74) is the dominant predictor of deficit-irrigation response, validating the model's sensitivity to crop stress tolerance. These findings collectively reinforce the LP model's structural logic, showing that multi-dimensional biophysical and economic traits are essential for sustainable irrigation planning in Rwanda.

Figure 2

Principal Component Analysis scatters plot of major crops

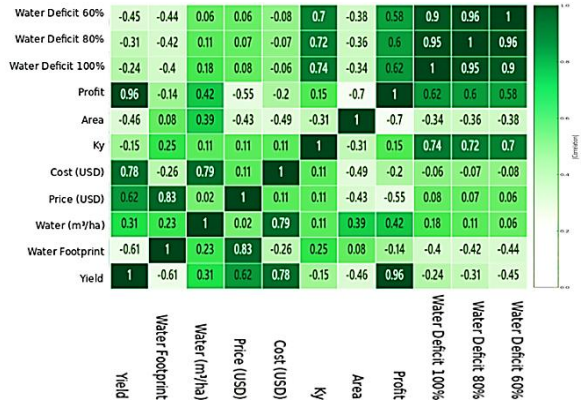


The coefficient (R^2) results provided robust evidence that the linear programming (LP) model behaves realistically. Predicted values for profit, land allocation, and deficit-irrigation responses closely matched the observed patterns. Economic variables, especially yield and market price, played the largest role, accounting for about (R^2 = 84%) of the variation in optimized profit and 78% of the variation in how land was allocated. In contrast, water footprint consistently reduced both profit and the area assigned to each crop. The response to deficit irrigation showed more biological complexity but remained predictable; the yield response factor (Ky) emerged as the strongest single driver (R^2 = 0.74), and when combined with

water footprint and price, explained (R^2 = 70%) of the overall variation. Altogether, these findings show that LP optimization is realistic in agronomic and economic relationships. Figure 3 highlights relationships among the key variables by correlation matrix analysis. Yield shows a strong negative correlation with water footprint (r = –0.61), reinforcing the idea that higher-yielding crops typically use water more efficiently. Water footprint, however, is strongly and positively correlated with price (r = +0.83), suggesting that crops requiring more water are often high value but less practical when water is limited.

Figure 3

Correlation matrix analysis



Land allocation also follows a logical pattern: it increases with yield (r = 0.84–0.86) and decreases as water footprint rises (r = –0.45 to –0.46). Deficit levels are negatively related to both profit and cultivated area, particularly in the 60% water-availability scenario, where correlations reach r = –0.62 to –0.64 for profit and r = –0.59 to –0.70 for area.

Across all scenarios, profit maintains strong correlations with both yield and optimized land area (r > 0.90), reflecting consistent crop performance within the optimization framework.

Conclusions

1. The findings indicate that the LP model serves as an analytical decision-support tool that informs decision-makers on optimal irrigation water allocation across eleven major crops in Rwanda.
2. Study found that crops like cassava, Irish potato, and banana perform best under full irrigation, while water-demanding crops lose land.
3. When water is scarce, the system shifts toward drought-tolerant crops and uses deficit irrigation to stay efficient.
4. Good water management needs strong coordination across environmental, agricultural, and water-related sectors.
5. Future research should explore digital storage, groundwater recharge, and reservoir strategies to improve sustainable and fair water allocation.

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BELL PEPPER RESPONSE TO MULCH TYPES UNDER DIFFERENT IRRIGATION STRATEGIES

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Abstract
Water shortages and competition for irrigation water demand strong measures to cope with the needs in an efficient manner. Therefore, this work investigated the impact of plastic mulching and organic mulching on bell pepper production under both deficit- and full-irrigation regimes, particularly in the Southern Province of Rwanda. The field experiment was designed as a split-plot combined with a Randomized Complete Block Design (RCBD). The study set the main plots as irrigation levels (100% and 50% of crop evapotranspiration), while subplots represented mulching types (organic and plastic), with three replications. The soil moisture sensors with profile probes were installed in the experimental field to monitor the daily depletion of soil moisture. Results showed that the total water requirements for organic mulch (OI_{100}) and plastic mulch with full irrigation (P_{I100}) were 420.4 mm and 390 mm, respectively. In OI_{100}, the treatment with organic mulch yielded the highest fresh fruit yield at 58.5 t ha^{-1}, while the highest dry matter yields were reached with organic mulch and 50% deficit irrigation (OI_{50}), at 765.4 kg ha^{-1}. Organic mulching with full irrigation produced the best yield, surpassing plastic mulch with full irrigation. Compared to organic grass-clipping mulch, plastic mulch maintained 6% to 24% higher soil moisture content. Consequently, it saved between 7.8% and 18% of irrigation water under full and deficit irrigation conditions, respectively. Building on previous research, both plastic and organic mulches provide various benefits to the soil and bell pepper crops.
Keywords: crop water requirement, deficit irrigation, organic mulch, plastic mulch.

Introduction

Water scarcity and increasing competition for irrigation resources demand effective strategies to improve water-use efficiency. The widely adopted irrigation strategy used to minimize irrigation water use is deficit irrigation without compromising crop yields, thereby improving water use efficiency (Demo & Tsehai, 2024). This method enhances water productivity without inducing water stress or drought conditions (Mardani et al., 2017). Bell pepper is recognized as a high-value crop with significant income both locally and on a global scale. It is consumed fresh or cooked in a variety of dishes (Truong et al., 2025). Rich in nutritional compounds of vitamins A, C, and E, phenolics, as well as capsaicinoids, bell pepper offers notable antioxidant and health benefits (Alonso-Villegas et al., 2023). Despite progress in breeding and genomic research aimed at improving traits like fruit development and capsaicin production, the phylogenetic relationships within *C. annuum* remain underexplored. Originating from Mesoamerica, particularly Mexico - *C. annuum* exhibits broad environmental adaptability (De la Cruz-Ricardez et al., 2024). Bell pepper presents promising opportunities for small-scale farmers and food innovation (Van Zonneveld et al., 2015). Environmental and developmental factors also influence the synthesis of bioactive compounds in bell pepper, affecting its nutritional quality. However, bell pepper production is often limited by suboptimal temperature conditions. Agronomic practices such as polyhouse cultivation, black plastic mulching, and adjusted planting dates have been shown to improve early and total yields in regions with unfavorable temperatures (Dhaliwal et al., 2017). As one of the top contributors to the horticultural economy (Carvalho et al., 2023), bell pepper cultivation benefits significantly from water-saving practices. Previous studies reported that mulching techniques improve soil moisture holding capacity and reduce erosion, as well as regulate soil temperature in drought-prone areas (Ramakrishna et al., 2006). Research confirms that mulching enhances plant growth and yield due to its capture of soil loss and water use efficiency (Bijalwan et al., 2022). Nevertheless, the combined application of irrigation and mulching remains underrepresented in scientific literature. Plastic mulching is widely used for soil warming, weed suppression, and yield quality improvement. However, concerns persist regarding the environmental impact of non-biodegradable plastics (Guerra et al., 2024).

Colak (2021) announced that bell pepper requires intensive monitoring of water management to reduce the drop in yields. The study proposed drip irrigation as a technique to optimize water use and enhance crop productivity. Both excessive and insufficient water stress can significantly affect plant growth and yield (Menezes et al., 2024).

Therefore, this study aims to evaluate in the field the effect of different irrigation strategies combined with mulching practices on the response of bell pepper, with a focus on optimizing water use and improving irrigation scheduling. It seeks to monitor soil moisture dynamics for precise irrigation planning, determine crop water requirements, and estimate seasonal evapotranspiration. This case study was conducted in Huye District, Rwanda, where dry season conditions limit pepper production, and water deficiency adversely affects flowering and yield.

Materials and Methods

The field experiment was conducted at the Rwanda Polytechnic Huye College research center, located in Huye District (2°36'37" S, 29°43'59" E). Huye district

has an average altitude of 1,700 m, a mean annual temperature of 20 °C, and an annual rainfall of 1,150 mm (Dahlin et al., 2021). The climate is sub-equatorial temperate, and agriculture is traditional with limited mechanization. At the national level, irrigated land in the district includes 1,740 ha of marshland and 81 ha of hillside irrigation (Hakiruwizera et al., 2024).

Variety California Wonder-PP2285-05B, sourced from Holland, was used. Plants were spaced 40 cm apart with 50 cm between rows, resulting in a population density of 50,000 plants per hectare. Nursery planting began on April 26, 2024, with transplanting performed one month after each nursery establishment. The maximum root depth ranges from 0.3 to 0.6 m (Waller & Yitayew, 2016). Sweet peppers have an allowable soil moisture depletion (p) of 0.30 (Bozkurt Çolak et al., 2023). Bell peppers grow optimally at temperatures between 21 and 24 degrees Celsius. However, it tolerates a temperature of less than 18 °C and a maximum of 26 °C. Fertilization at planting included 600 kg ha^{-1} of 2:3:4 NPK.

Bulk density for 30 cm soil depth was 1.49 g cm^{-3} and 1.51 g cm^{-3} at 60 cm soil depth. Field capacity was 22.2%, permanent wilting point 14%, and soil texture was sandy loam. Saturation content was 43.3%, hydraulic conductivity 22 mm h^{-1}, and organic matter content 3.3% at 30 cm depth and 2.4% at 60 cm.

A drip irrigation system is used to supply water to the plots. Pressurized water was pumped into a 10 m^3 storage tank elevated 3 m above the field, then distributed by gravity through a 32 mm main pipe and four 25 mm submains. Each submain supplied three 16 mm driplines, totaling 36 driplines with emitters discharging 2 L h^{-1}. Screen filters ensure water quality. Each treatment plot measured 1.4 m × 10 m with 1 m spacing. The experimental area covered 308 m^2. Soil moisture was monitored with eight profile probe sensors. The experiment used a split-plot design within a randomized complete block design. Irrigation levels were the main plots, and mulching types were subplots with three replications. Irrigation treatments were full irrigation at 100% field capacity and deficit irrigation set at 50% field capacity. Mulching treatments included a black polyethylene sheet and organic grass clippings. Treatments: OI_{100} (organic mulch + full irrigation), PI_{100} (plastic mulch + full irrigation), OI_{50} (organic mulch + deficit irrigation), PI_{50} (plastic mulch + deficit irrigation). No stress was imposed during germination. The study adapted the soil-water balance approach to monitor the frequency of irrigation scheduling.

Soil water depletion (Dc) was calculated daily using the method (Allen et al., 1998). During the experiment, soil moisture content was measured using a hand-held moisture meter (HH2) connected to profile probe sensors (PR2), with data recorded in Excel (Marković et al., 2024). The irrigation threshold was 30% water depletion. The difference between field capacity and the current soil water level determines net irrigation. Seasonal irrigation requirements were obtained as the sum of all irrigation events. Crop evapotranspiration was calculated as Allen et al. (1998), ETc = ETo × Kc × Ks, where ETo stands for reference evapotranspiration, Kc for the crop coefficient, and Ks for the water stress coefficient (1 for full irrigation, less 1 under deficit irrigation).

Yield and yield parameters were monitored during the season. Plant height was observed weekly from three weeks after transplanting on five plants per plot. Nodes were counted at harvest. Yield was measured from a 1 m^2 area, weighing marketable and non-marketable fruits. Pericarp thickness was measured on vine-ripened fruits with a vernier caliper. Fruits' dry matter was determined after drying at a temperature of 65 °C. Fruit number per plant and fruit length were measured on four plants/fruits per plot. ANOVA was performed using Minitab 17. LSD Fisher test with $p = 0.05$ compared treatment means for yield parameters, and OriginPro software is used to generate graphs.

Results and Discussion

Black plastic-mulch maintained soil moisture between 6% and 24% under full and deficit irrigation, respectively. Plastic mulch delayed moisture depletion and reduced irrigation frequency, consistent with El-Beltagi et al. (2022). These results confirm plastic mulch as a promising practice for deficit irrigation management. The crop season lasted 121 days. Effective rainfall contributed only 13.6 mm. Net irrigation under full irrigation was 376.4 mm (plastic mulch) and 406.8 mm (organic mulch). Under deficit irrigation, 262 mm and 313.3 mm were applied, respectively. Seasonal crop water requirements were 390 mm and 420.4 mm under full irrigation and 275.6 mm and 326.9 mm under deficit irrigation (plastic and organic mulch, respectively) (Figure 1). Plastic mulch saved 7.8%–18% irrigation water compared to organic mulch. Different irrigation regimes, mulching type, and interactions were significantly different and affected yield parameters ($p < 0.05$), except for nodes per plant. Fresh weight ranged from 12.2 t ha^{-1} (PI_{50}) to 58.5 t ha^{-1} (OI_{100}). Dry yield ranged from 0.35 t ha^{-1} (PI_{100}) to 0.76 t ha^{-1} (OI_{50}). Fruit numbers ranged from 5.5 per plant (PI_{50}) to 8.8 per plant (OI_{100}). Fruit length ranged from 4.4 cm (PI_{50}) to 7.5 cm (OI_{100}), as illustrated in Table 1. Organic mulch with full irrigation achieved the highest yield performance, while plastic mulch under deficit irrigation performed the poorest (Figure 2). The results observed were aligned, as reported by (Rocha et al., 2025) and (Asif et al., 2016). The study observed that plastic mulch conserves water but may reduce yield potential under stress, whereas organic mulch maximizes yield under optimal irrigation. Higher dry matter yield under OI_{50} suggests moderate stress enhances fruit solids, beneficial for processing (Candido et al., 2009). Rocha et al. (2018) demonstrated that drip irrigation at 50% of ETc combined with mulching produced 42.15 t ha^{-1} and the highest water use efficiency (148.99 kg ha^{-1}

mm^{-1}). Similarly, our results under OI_{50} showed improved dry matter content, suggesting that controlled deficit irrigation with mulching can optimize quality traits even under reduced water supply.

Figure 1

Seasonal irrigation requirements under different mulch and irrigation treatments

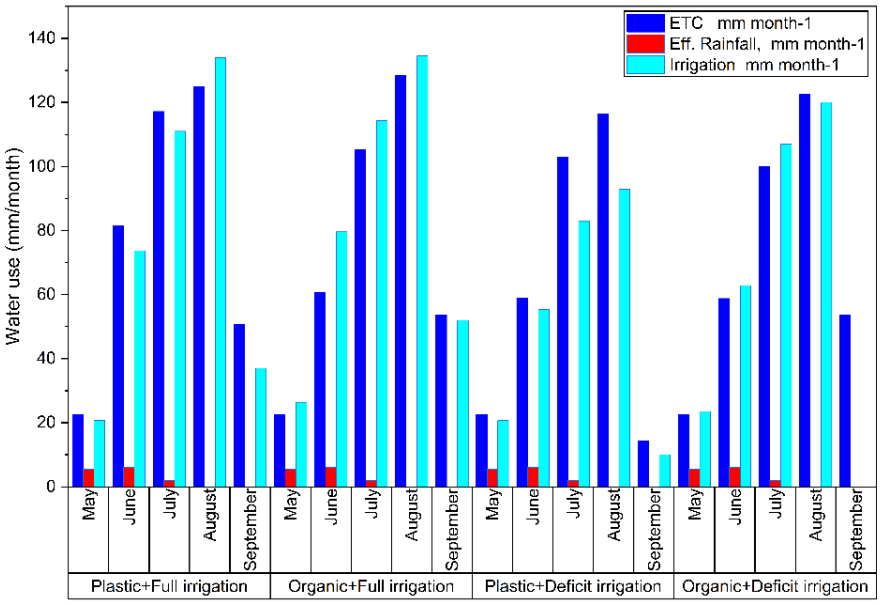


Table 1

ANOVA results and treatment mean for the yield components of bell pepper for two seasons

Treatments	Fresh weight t ha^{-1}	Dry matter yield t ha^{-1}	Number of fruit $plants^{-1}$	Fruit length, cm	Number of nodes $plant^{-1}$
Effect of main plots: Irrigation					
I100	45.5 ± 2a	0.4 ± 0.03b	7.96 ± 0.3a	6.89 ± 0.3a	6.20 ± 0.2
I50	16.1 ± 1.9b	0.7 ± 0.02a	5.93 ± 0.3b	5.24 ± 0.2b	6.17 ± 0.2
Effect of sub-plot: Mulching type					
O	39.3 ± 2a	0.6 ± 0.03a	7.56 ± 0.33a	6.78 ± 0.3a	6.35 ± 0.2
P	22.4 ± 1.9b	0.5 ± 0.02b	6.33 ± 0.3b	5.34 ± 0.2b	6.03 ± 0.2
Interactions: Irrigation x mulching					
OI100	58.5 ± 4.2a	0.48 ± 0.04b	8.80 ± 0.4a	7.55 ± 0.3a	6.27 ± 0.2
PI100	32.6 ± 1.8b	0.35 ± 0.00	7.13 ± 0.5	6.22 ± 0.3	6.42 ± 0.4
OI50	20.0 ± 2.7	0.76 ± 0.05	6.33 ± 0.5	6.03 ± 0.3	6.07 ± 0.3
PI50	12.2 ± 1.4	0.61 ± 0.04	5.53 ± 0.4	4.47 ± 0.4c	6.00 ± 0.2

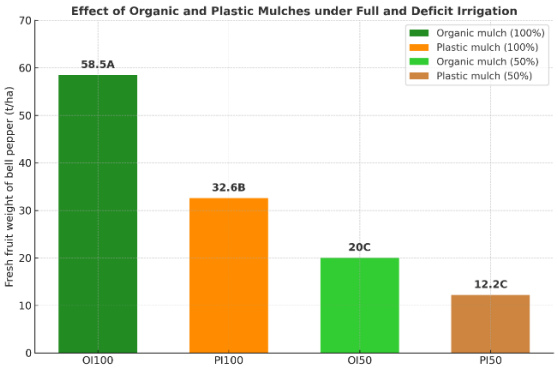
Different lowercase letters (a, b, c) show statistically significant differences ($p < 0.05$).

Mateille et al. (2020) further highlighted the disease suppression benefits of mulching when combined with tobacco waste, while Bijalwan et al. (2022) reported that combining mulch with growth regulators (NAA) boosted yield to 38.5 t ha^{-1}. Our study complements these by showing that organic mulch with full irrigation not only enhances yield but may also improve crop health through soil fertility benefits.

Varietal responses under mulching emphasize that mulching benefits extend across genetic lines, which aligns with the robust performance of organic mulch treatments in our trial (Valšíková-Frey et al., 2022). Likewise, Candido et al. (2009) confirmed that full irrigation (100% ETc) combined with balanced nitrogen fertilization produced the maximum yield (72 t ha^{-1}), whereas late-season stress reduced yields by 44%. This parallels our observation that deficit irrigation under PI50 was severely limited despite water savings.

Figure 2

Effect of organic and plastic mulches under full and deficit irrigation



Note: Different letters (A, B) show statistically significant differences ($p < 0.05$), while the C letter is not significantly different. I100: Full irrigation, I50: Deficit irrigation, O: Organic mulch, P: Plastic mulch.

Other studies confirm the broader environmental benefits of mulching. Neto et al. (2020) demonstrated effective weed suppression with polyethylene and biodegradable mulches, while Hernández-Aranda et al. (2021) reported that crop-residue mulch improved biomass by 84% under limited irrigation. These findings are consistent with the water-conservation benefits we observed with plastic mulch. Bozkurt Çolak et al. (2023) suggested that integrating mulching with modern irrigation technologies can further enhance water productivity and yield resilience. Together, these comparative insights reinforce the dual role of mulching for maximizing yield in water-abundant contexts (organic mulch with full irrigation) and saving water in water-limited environments (plastic mulch with deficit irrigation).

Conclusions

1. The study demonstrated that mulch type and irrigation strategy significantly influence bell pepper productivity and improve water use efficiency. Organic mulch with full irrigation produced high yield (58.5 t ha^{-1}), whereas plastic mulch achieved greater water savings (7.8%–18%) under both irrigation regimes.
2. Both Organic and plastic mulch are important in deficit irrigation and water management of bell pepper crops.
3. In the context of practical implications, plastic mulch should be prioritized in water-limited environments, while organic mulch should be adopted when maximizing yield and soil health is the goal.
4. In Huye's ecological settings, the mulching techniques take significant steps to enhance water scarcity, competition for irrigation demand, and water usage efficiency.
5. Future studies should assess the economic feasibility and environmental sustainability of these practices, particularly regarding non-biodegradable plastics.

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THE POTENTIAL OF ROBOTISATION FOR STRAWBERRY CULTIVATION IN OPEN FIELDS: A REVIEW

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Abstract
Strawberry cultivation is one of the most labour-intensive areas of horticulture, relying heavily on manual labour. In fruit production, these costs can reach up to 60% of total production expenses. At the same time, demand for fresh, locally grown strawberries is relatively high throughout the world. There are various robotic solutions for both the establishment and maintenance of strawberry fields. Most of these solutions are designed as tractor-pulled units, but the biggest challenge is mechanized harvesting. In recent years, thanks to advances in technology and artificial intelligence, the mechanization and automation of strawberry picking has also been developing rapidly. The aim of this study is to review the development and application of robotic and automated technologies in strawberry cultivation, analyse their use across different cultivation processes, and identify future directions for robotisation in open-field systems. The study is based on an analysis of recent scientific publications in the relevant field. The results of the study identify the most important stages in the strawberry growing process where robotisation can be introduced and where additional investment in development is needed. The results indicate that several strawberry cultivation processes, particularly transplanting, irrigation management and monitoring, show strong potential for automation due to their structured and repeatable nature. More complex operations such as pruning and harvesting remain technically challenging and require further development of perception systems, manipulators and end-effectors.
Keywords: strawberry, robot, cultivation, automation, horticulture.

Introduction

The strawberry (*Fragaria × ananassa Duch*.) is one of the most widely cultivated and economically important berry crops worldwide. It is characterised by high market demand and intensive production practices. In open-field production, a significant proportion of total production costs is related to manual labour, particularly for activities such as crop monitoring, weed control, harvesting and post-harvest handling. According to Defterli et al. (2016), labour-related expenses account for a large share of overall production costs, particularly in specialty crops that require frequent and delicate manual operations. Studies suggest that labour costs can reach up to 60% of total production costs in labour-intensive agricultural sectors such as fruit production (Baraldi et al., 2007). Strawberry cultivation involves low-growing plants and a production cycle that requires frequent close-range interventions in the field throughout the growing season. As a result, many critical operations must be carried out repeatedly and with high precision, making strawberry cultivation a labour-intensive and operationally complex production system (Hancock, 2020). In addition to high manpower costs, the production of strawberries is increasingly affected by a shortage of agricultural workers, driven by factors such as urbanisation, an ageing rural workforce, and the seasonal nature of agricultural employment. These labour shortages have become a key motivator for adopting robotic and automated solutions in agriculture, particularly in work-intensive crop production systems (Anastasiou et al., 2025).

Wider reviews of the automation of agricultural machinery emphasize that the level of automation achieved varies substantially between different processes and systems in agriculture and crop production. This reflects differences in task complexity, environmental variability, and economic feasibility (Jiang et al., 2025). Consequently, despite rapid technological development, the adoption of robotic and automated solutions remains uneven across the full range of agricultural operations, highlighting the need to evaluate the technological maturity of each process specifically.

Technological progress in agricultural robotics, including autonomous ground vehicles, sensor-based systems and machine vision technologies, has enabled the automation of various field operations such as monitoring, weeding and harvesting. Further advances in sensing technologies, machine vision, and autonomous navigation have facilitated the development of robotic platforms that can operate in outdoor agricultural environments. These platforms support data-driven decision-making and reduce dependence on manual manpower in crop production. At the same time, despite significant technological progress, the maturity and adoption levels of robotic solutions vary considerably between different agricultural operations and crop types. There is a persistent gap between technological development and practical, farm-level requirements (Fontani et al., 2025). Several review studies on precision agriculture indicate that robots are most frequently used for repetitive, structured operations such as crop monitoring, weed control, planting activities and harvesting, where tasks can be clearly defined and executed with high repeatability (Comparetti et al., 2025). Such applications are commonly implemented using ground-based robotic platforms or unmanned aerial vehicles (UAVs) equipped with cameras, proximity sensors, and navigation systems, allowing continuous field operation and spatially explicit data collection. The suitability of these operations for automation has led to faster technological progress in monitoring and weed management than in other cultivation tasks.

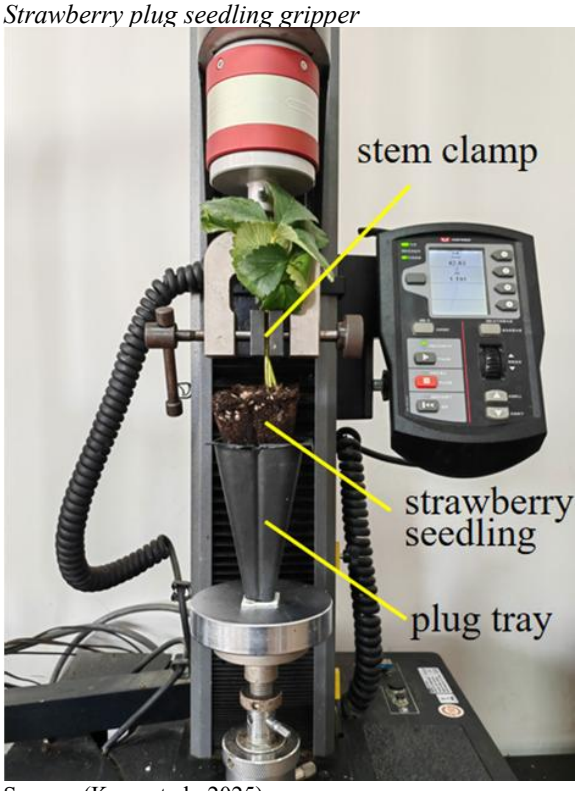
In contrast, operations requiring high selectivity, delicate manipulation, or close interaction with the crop canopy are considerably more challenging to automate. This is particularly true in unstructured open fields, where there is variable lighting, plant morphology, and environmental disturbances (Spagnuolo et al., 2025). Therefore, many robotic systems targeting such tasks remain in the prototype or experimental stage and have not yet been widely adopted commercially.
The aim of this study is to review the development and application of robotic and automated technologies in strawberry cultivation, analyse their use across different cultivation processes, and identify future directions for robotisation in open-field systems.

Materials and Methods
A literature search was conducted across multiple scientific databases, including Scopus, Web of Science, and ScienceDirect. The search and screening procedure was performed independently within each database. The initial search results were screened based on titles and abstracts, and approximately 20 articles were considered for each of the seven crop management processes. From these, up to five of the most relevant studies were selected for detailed analysis based on their focus on the development and practical implementation robotic solutions, with the most promising among them included in the study. Additional scientific publications not indexed in the aforementioned databases were also considered. The selected publications mainly included peer-reviewed journal articles and conference proceedings related to automation and robotics in strawberry cultivation.
Keywords such as ‘strawberry’, ‘automation’, ‘robot’, and ‘robotics’ were used together with terms describing specific cultivation processes. Studies where robotic solutions were tested under open-field conditions were prioritised. If such studies were not available for a particular cultivation process, research from greenhouse or indoor environments was also considered. In some cases, studies describing promising individual automation components were also included. Review articles were mainly used to provide contextual understanding and identify broader technological trends. The selected studies were analysed in terms of their practical applicability, technological maturity and potential to reduce manual labour. In instances where such data were documented, comparisons were drawn with conventional human-performed operations. The analysed publications were further grouped according to the main cultivation processes in strawberry production, including transplanting, irrigation, monitoring, mulching, weeding, pruning and harvesting.

Results and Discussion
This section presents an analysis of robotic applications across the main stages of strawberry cultivation, with technologies discussed according to individual crop management processes.

Seedling transplanting
In intensive production systems, strawberry seedlings, unlike many other crops, are grown as plug plants in specially designed trays. The seedlings have a relatively large root ball, and during transplanting it is essential to preserve its integrity. Strawberry planting is a precise but repeatable process. The work includes sequential steps such as removing the seedling from the tray, transferring it to the planting location, inserting it into the soil, and compacting the soil around the root ball. Strawberry plugs are characterized by a relatively dense and large root ball, which facilitates mechanical gripping but increases the need for precisely controlled planting depth. Transplanting is one of the processes most suitable for robotisation, as it consists of structured and repeatable stages – gripping, transferring, and precise placement. Kang et al. (2025) presented a recently developed new gripping mechanism for extracting strawberry seedlings from trays.

Figure 1
Strawberry plug seedling gripper



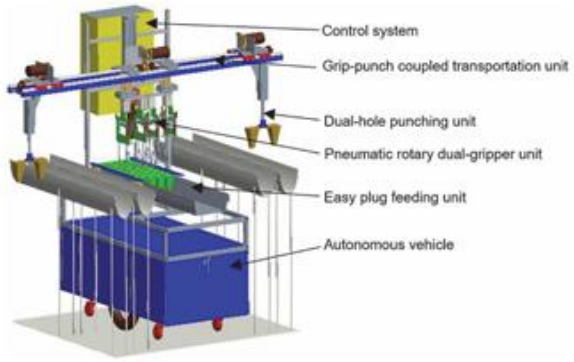
Source: (Kang et al., 2025).

The aim of their work was to design and optimise a strawberry seedling pick-up mechanism to preserve plug integrity. Coupled EDEM-RecurDyn simulations were performed, and three main adjustable parameters were identified – picking acceleration, needle spacing, and insertion depth – which, when modified, can improve the results. After determining the optimal parameters, field tests were carried out, and the gripping mechanism was able to ensure a high level of plug seedling integrity after extraction from the tray – 93.23%. The field test results were very close to the

simulation results, with only a 4.29% relative error between the predicted and the actual seedling integrity ratio. Kang et al. (2025) acknowledge that further research under different conditions is needed in the future, and that the developed solution should be integrated into a complete transplanter system and evaluated according to overall performance indicators. Figure 1 shows the developed gripper during testing.

A complete and autonomous transplanting system was developed and tested in elevated beds by Liu et al. (2019). The developers focused on the specific characteristics of strawberry seedlings – their increased size and the requirement for proper orientation of the plant curvature during transplanting. The developed model includes photoelectric sensor-based navigation, a rotating dual-gripper, a dual-hole punching mechanism, as well as a transport unit synchronized with both the gripper and the punching mechanism. Figure 2 shows the 3D model of the developed autonomous strawberry plug seeding transplanter. In greenhouse field tests, the robot demonstrated successful performance, transplanting 95.3% of seedlings and achieving a working speed of 1047.8 plants per hour. The authors emphasize that working speed is closely related to operational reliability. Excessively fast gripping, rotation, or transport movements may cause seedling damage or dropping. In the future, it is necessary to optimise motion coordination between the different units. Liu et al. (2019) predict that the developed system has the potential to replace manual labour in strawberry transplanting within elevated cultivation systems.

Figure 2
3D model of strawberry seedling transplanter



Source: (Liu et al., 2019).

Data on similar studies involving comparable crops can also be found in research databases. Khadatkar (2023) developed a robotic transplanter equipped with an XY manipulator and a servomotor-driven jaw-type gripper. In tests conducted with 30-day-old chili plug seedlings, the transplanter achieved a 90.3% rate of successfully transplanted seedlings. Magar et al. (2025) developed and tested a seedling extraction mechanism that uses needle-type grippers and applies a closed-loop indexing system. The experiments demonstrated a 96.05% successful extraction rate without damaging the root ball. The device achieved a working speed of 34–38 extracted seedlings per minute. Cabbage and tomato plug seedlings were used in the tests.

Irrigation systems

Strawberry irrigation plays an important role in maintaining plant health and achieving stable yields. Because strawberries have a shallow root system, they respond quickly to changes in soil moisture. Over-irrigation may cause nutrients to leach from the soil and results in unnecessary water use, while insufficient watering can reduce fruit quality and overall productivity. The use of soil moisture sensors, evapotranspiration estimates, and local weather data helps growers better understand soil conditions and decide when irrigation is actually needed. By applying these technologies, it is possible to manage water more efficiently without compromising strawberry yield.

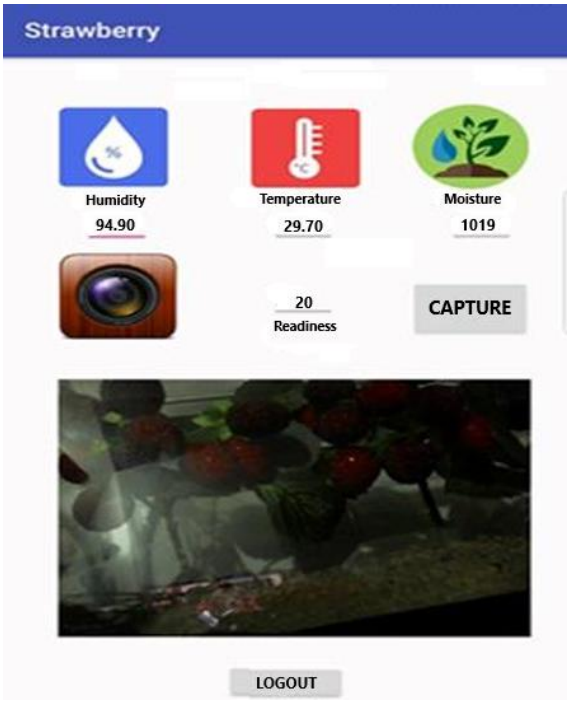
In the context of irrigation control systems, Vega Caicedo & Barco Jiménez (2018) developed a system aimed at maintaining soil moisture within an optimal range while also focusing on water and energy consumption. The control system was based on a Constrained Matricial Model Predictive Control (CMMPC) approach and a dynamic soil water balance equation, in which moisture changes depend on irrigation dose and evapotranspiration. Input data were collected over a three-year period. Compared with a Proportional–Integral–Derivative (PID) controller, the CMMPC reduced control signal energy consumption by approximately 33% under sunny and cold scenarios. In the rainy scenario, the energy reduction reached approximately 95%. Water savings achieved with the developed system were 2.07–2.30 L/h under typical conditions and 35.67 L/h in the rainy scenario. St Fort et al. (2025) conducted a study on the use of micro-irrigation systems as an alternative to traditional high-volume impact sprinklers in strawberry production in Florida. The research was carried out on a commercial farm. A micro-irrigation system such as Mini Revolver reduced water use by approximately 58% during the transplant establishment period and by 63% during freeze protection. Importantly, no significant differences were observed in transplant survival or yield compared to traditional irrigation systems.

In the sensor-based control study, Guéry et al. (2018) analysed an automated soil moisture management strategy on a commercial strawberry farm in Spain. The existing pulse irrigation method was compared with a sensor-based control system, where irrigation decisions were made based on soil volumetric water content measurements. The objective was to maintain soil moisture within an optimal range and reduce unnecessary water use. The sensor-controlled system reduced seasonal water consumption by approximately 21%, while no significant differences in total yield were observed between the two irrigation systems.

A similar study using soil moisture measurements was carried out by Belayneh & Lea-Cox, (2017) on a commercial strawberry farm in Maryland, USA. In this case, a wireless sensor network was set up with sensors placed at different soil depths so irrigation could be adjusted according to actual moisture levels in the field. The sensor-based approach was compared with the farm's usual irrigation practice, which followed a fixed schedule based mainly on experience. Depending on the field and season, water use was reduced by 17–29% when the sensor system was applied. At the same time, there were no noticeable differences in plant condition or total yield compared to the traditional method.

A more comprehensive solution was developed by Leonen & Teleron, (2022). An automated open-field irrigation system for strawberries was created. It included soil moisture sensors, air humidity and temperature measurements, a microcontroller, and automated valve control. The data were transmitted to the controller and were accessible to the user. In Figure 3, it can be seen how the user can monitor field measurements through the Android application. Irrigation was activated automatically when the soil moisture dropped below the predefined minimum threshold. Under real field conditions, the system prototype achieved 58.8% water savings compared to the grower's previous irrigation schedule, and no negative effect on root zone moisture maintenance was observed.

Figure 3
Soil monitoring through application



Source: Leonen & Teleron, 2022.

Crop monitoring

Strawberry monitoring is essential for detecting and evaluating plant health in a timely manner, as well as identifying diseases. Manual inspection is a time-consuming and subjective process. Automated solutions that use computer vision, sensors, image processing, and deep learning algorithms enable continuous monitoring of plant health, early disease detection, and a reduction in labour intensity.

In the context of monitoring data processing, Khan et al. (2026) conducted research on early disease diagnosis. A Strawberry Leaf Disease Inspection (SLDI) system was developed based on a YOLO-NAS deep learning model and demonstrated early disease detection during testing. A manipulator moved a RealSense camera between strawberry plants in a controlled greenhouse simulation environment, and the model detected diseases with 91.1% precision.

Li et al. (2025) conducted research with the aim of improving image processing quality by using the enhanced CAFM-Enhanced YOLOv8 detection model, which was designed to perform better under complex conditions such as occlusions, plant damage, and noisy backgrounds. The YOLOv8 model was optimised by adding an additional ultra-small detection head for capturing very small lesions and by introducing the Convolution and Attention Fusion Module (CAFM), which helps the model focus on relevant features. In addition, a PyQt5-based interactive real-time visualization system was developed. These improvements increased the mAP@50 (mean detection accuracy at a 50% overlap threshold) from 94% to 96%.

With the aim of developing a practical and economically accessible solution, Khosro-anjom et al. (2015) developed a low-cost real-time strawberry leaf disease diagnosis system. The device consists of an RGB camera, an embedded computing platform, a convolutional neural network, and software modules for image preprocessing and result output. The system was mounted on a simple push-type wheeled platform and moved through strawberry fields under outdoor conditions. Images were captured and analysed, achieving disease classification accuracy of over 90%.

An integrated monitoring and control platform was developed by Mirbod & Pritts, (2025).

Figure 4
Monitoring platform in field test



Source: Mirbod & Pritts, 2025.

The aim of the solution was to provide continuous monitoring of microclimate conditions and plant status

while reducing the need for constant human supervision. The system integrated air temperature, relative humidity, and soil moisture sensors, data acquisition nodes, and wireless transmission to a central platform. The platform was tested under real field conditions beneath a low tunnel cover, moving along a cable-based system, and ensured stable data collection throughout the testing period. Figure 4 shows the platform test under field conditions. The device was powered through a cable-based power supply system. The authors indicate that the platform has potential for further development through the integration of additional sensors and monitoring devices.

Mulching

Mulching is a process that can be used in strawberry plant management. It helps control soil moisture and temperature, as well as limit weed growth. In practice, both organic mulch made from plant residues and synthetic materials, such as plastic film, can be used. Nowadays, mulching is largely mechanized—various implements have been developed that are pulled by a tractor and ensure the application of mulch. Sensor-based systems are also being developed to help control the amount of material applied and improve the quality of work.

In their study, Amin et al. (2022) developed a tractor-drawn plastic mulch laying machine. The objective was to design and test equipment that would reduce the amount of manual labour required for mulching under field conditions. The machine includes bed forming units, a mulch film feeding mechanism, and soil pressing discs. During the development stage, attention was given to ensuring continuous operation and reducing the risk of film damage. The machine was tested in field conditions, and operating parameters such as forward speed, bed width, and hole spacing were adjusted and optimised. According to the reported results, compared with manual mulching, the developed machine reduced labour input by 97% and operational costs by 75%.

Chaudhari et al. (2024) developed an IoT-based crop residue mulching machine, intended for the mechanical application of organic mulch. The aim of the research was to create a system that would reduce manual labour requirements while ensuring controlled and uniform mulch distribution. The authors designed a tractor-driven crop residue shredding and spreading mechanism with Internet of Things (IoT) integration, including sensors (a load cell, a soil moisture sensor, and proximity sensors) for data transmission and real-time process monitoring. In Figure 5, the developed model of the device is shown. The performance of the system was evaluated through comparative analysis with manual mulching in terms of labour requirement, cost, efficiency, and mulch uniformity. Compared to manual mulching, the mechanized system reduces labour requirements by 70–90% and operating costs by approximately 70%.

Figure 5

Mulching machine



Source: Chaudhari et al., 2024.

Weed control

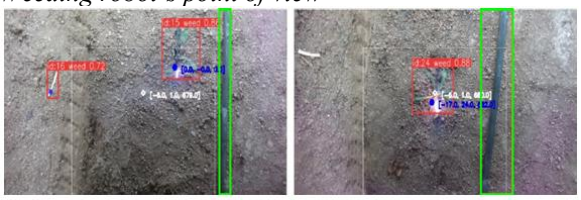
Weeding in crop production is labour-intensive and is mostly done by manual work, and it is an important part of plant protection. In strawberries, weeding is more difficult because the plants are low, the planting is dense, and the foliage is thick. With the development of precision agriculture and robotics, computer vision and deep learning technologies are being used to separate weeds from crops in real time. Robots with laser or spraying systems are being developed and have the potential to reduce human involvement in weeding processes.

With the aim of developing a system capable of distinguishing weeds from crops in real time and performing targeted herbicide spraying, Liu et al. (2021) developed a mobile sprayer prototype equipped with cameras, solenoid valves, and microprocessor-based control. Three convolutional neural network models—AlexNet, GoogleNet, and VGG-16—were used for system control and weed classification. Experiments were conducted both under laboratory conditions and in the field. The highest weed recognition performance was achieved using the VGG-16 model. In field tests, the percentage of completely sprayed weeds reached 93%. It should be noted that the system performance decreased when the platform travel speed exceeded 3 $km \cdot h^{-1}$. The study indicates that the system has the potential to reduce herbicide usage in the weeding process and is suitable for weed control in strawberry cultivation.

Zhao et al. (2025) developed an autonomous laser weeding robot for strawberry fields based on the DIN-LW-YOLO vision model. The purpose of the study was to design a system that can detect strawberry plants, weeds, drip irrigation pipes and weed growth points in real time, and then direct a laser beam precisely to the weed. A mobile robot with an adjustable crawler chassis, a camera-based detection system and a laser unit was built. The control system relies on a deep learning model for navigation and target positioning. The experiments included building

a dataset from both greenhouse and open-field conditions under different lighting and growth stages. In total, 2,153 images were used for training and validation. The model achieved a mean average precision of 88.5% for region detection and 85.0% for growth point detection. In field tests, the weed control rate reached 92.6%, while the crop injury rate was 1.2%. The results indicate that the developed system can be applied for autonomous weed control in strawberry production. In Figure 6, laser weeding from the robot's point of view is shown.

Figure 6
Weeding robot's point of view



Source: Zhao et al., 2025.

Truss pruning

Pruning is a regular maintenance task in strawberry cultivation and involves the removal of runners, excess leaves, and flower trusses. The automation of this process is hindered by the structural characteristics of the plant, which include dense foliage, limited visibility, and the requirement for precise mechanical cutting techniques. The automation of this process is facilitated by the integration of computer vision, deep learning segmentation models, RGB/RGB-D sensors, and precise manipulators.

The aim of the study by Fujinaga (2024) was to develop a multifunctional agricultural robot capable of performing both strawberry harvesting and truss pruning in a small-scale greenhouse. The researchers developed a system consisting of a crawler-type mobile platform, a 6-degree-of-freedom manipulator, a scissor-type cutting and gripping mechanism, and an RGB-D camera. Deep learning-based semantic segmentation (DeepLabV3+) was used to detect the cutting points. Pruning experiments were carried out in a greenhouse under semi-automatic operation. Out of 10 targeted trusses, 8 were successfully cut, resulting in an 80% success rate. The average pruning time was 23 s per truss. The results show that the system is able to perform pruning under real greenhouse conditions, although the success rate is influenced by gripping accuracy and the surrounding plant structure.

Vargas et al. (2025) developed a mobile robot system for strawberry pruning in polytunnel conditions. The system consists of the Thorvald mobile platform, two modified 5-degree-of-freedom manipulators, and several sensors, including RGB and RGB-D cameras, an IMU, and proximity sensors. A simulation environment with virtual strawberry plant models was also created to test perception and motion planning before real experiments. The paper mainly describes the system setup and experimental configuration. It does not report specific pruning success rates or operation times. The results show that the platform and simulation tools can support the development of autonomous pruning, but the system is still under further improvement. Figure 7 shows a visualization of the prototype under greenhouse conditions.

Figure 7
Visualisation of robot prototype



Source: Vargas et al., 2025.

Berry harvesting

Strawberry harvesting is a labour-intensive task that has traditionally been performed by humans. Fruits must be harvested selectively according to their ripeness and handled carefully to avoid damage. Strawberries are sensitive to compression, and the harvesting process must be carried out precisely by cutting or picking at the stem, avoiding direct contact with the fruit itself. Computer vision, deep learning methods, and carefully designed manipulation systems make it possible to develop specialized strawberry harvesting robots. These robots are equipped with visual perception systems, multi-degree-of-freedom manipulators, and end-effectors.

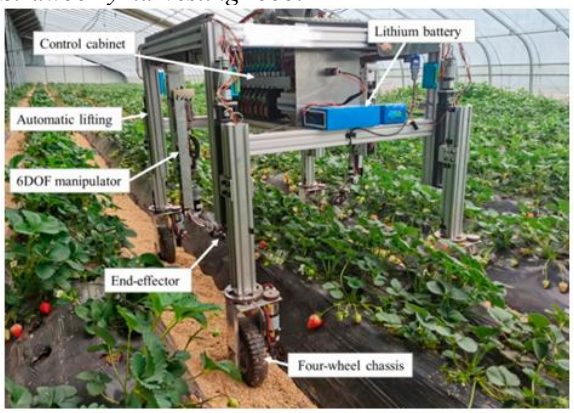
With the aim of developing a cost-effective solution for open-field strawberry harvesting, Ochoa & Mo (2025) developed a pneumatically driven end-effector mounted on a Delta X parallel robot. The study focused on improving the design, so that the stem could be gripped and cut accurately without damaging the fruit or nearby leaves. The end-effector was manufactured using 3D printing. The mechanism combines a pneumatic cutter and a single gripping finger, allowing the stem to be held and cut at the same time. The system was evaluated through simulation and field tests at Farias Farms. In simulation, a harvesting success rate of 94.74% was achieved at a 90° rotation configuration. During field tests, the optimised setup reached a 100% success rate (32 out of 32 fruits). When operating at 0.7 m/s with an acceleration of 8 m/s², the average harvesting time was 2.80 ± 0.08 s, while at 4 m/s² it was 3.78 ± 0.08 s. These results show that the developed end-effector is capable of harvesting strawberries quickly and without visible damage under open-field conditions.

Chang (2024) developed a cable-driven, multi-joint robotic arm intended for use in a hydroponic greenhouse for the purpose of harvesting strawberries.

The system incorporates a cutting and gripping mechanism that cuts the stem and holds the fruit, thereby reducing direct pressure on the berry. A deep learning model has been integrated into the vision system to detect the position of strawberries in real time, determine the optimal picking point and estimate the contour of the fruit while the platform is in motion. Field trials were conducted within a greenhouse environment to assess fruit detection performance, harvesting success, and the time required to pick each fruit. The detection accuracy was 90%, while 82% of the harvesting attempts were successful. The mean duration of one strawberry selection was found to be 6.5 seconds, which decreased to 5 seconds when the arm return movement was excluded from the calculation.

Yu et al. (2024) developed a strawberry harvesting robot that can work in an unstructured greenhouse environment. The robot is intended for ridge-planting systems and operates with a double-arm cooperative mechanism. It includes two self-developed manipulators, a non-destructive stem-cutting end-effector, a lightweight Mask R-CNN-based vision system, and a CAN bus control system. The robot can detect ripe strawberries, determine the picking point, and coordinate both arms while moving along the ridge layout.

Figure 8
Strawberry harvesting robot



Source: Yu et al., 2024.

During field tests in a greenhouse under ridge-planting conditions, the harvesting success rate reached 49.30% in trimmed conditions and 30.23% in untrimmed conditions. In harvesting time tests, one arm required 7 seconds per fruit, while two-arm cooperation reduced this to 4 seconds per fruit. The robot performed navigation, fruit detection, stem cutting, and handling without human assistance. These results indicate that the system operates with a high degree of autonomy in real greenhouse conditions. The robot structure is shown in Figure 8.

The reviewed strawberry cultivation processes differ in their suitability for robotisation. Some operations are more structured and consist of repeatable mechanical actions. Transplanting is one of these processes, as it mainly includes seedling extraction from trays, transfer and placement in the soil. Irrigation management can also be automated relatively easily through the use of soil moisture sensors, weather data and automated control systems.

Monitoring and weed control have developed rapidly due to the use of computer vision and image processing technologies. These systems allow the detection of plant conditions, diseases and weeds in field conditions and support more precise crop management.

Other processes are more difficult to automate. Pruning and harvesting require precise interaction with the plant and careful handling of the fruit. Dense foliage and variable fruit position make these tasks technically more challenging. These processes still require further development of perception systems, robotic manipulators, and specialized end-effectors.

Several technologies already show practical performance in strawberry cultivation. In irrigation management, sensor-based control systems allow water supply to be adjusted according to soil moisture and environmental conditions. Field studies report water savings of around 17–29% with soil moisture sensors, while other automated control approaches show even larger reductions in water consumption without affecting yield.

Progress can also be observed in monitoring and weed control technologies. Image-based systems using deep learning models are able to detect plant diseases or weed presence with relatively high accuracy, which allows more targeted field management. In weed management applications, experimental robotic systems using vision models and laser or precision spraying technologies have demonstrated weed control rates above 90% in field tests.

Some progress is also visible in harvesting technologies. Recent robotic end-effector designs combined with machine vision systems are able to detect fruits and perform stem cutting with high success rates in experimental trials. Although these systems are still being improved for reliable operation in open-field conditions, the results indicate that automated harvesting is becoming technically feasible.

An important aspect in evaluating these technologies is their validation under real cultivation conditions. Compared with controlled greenhouse environments, open-field conditions introduce greater variability in lighting, plant structure and weather conditions. In the analysed studies, experimental robotic systems or prototypes were identified for most of the major cultivation processes, including transplanting, irrigation management, monitoring, weed control and harvesting. However, the reported tests were carried out under different conditions, including greenhouse systems, protected cultivation and open-field environments. Mulching represents a slightly different case. Although studies specifically reporting robotic systems tested in strawberry fields were not identified, similar mechanized technologies are widely used in

other horticultural crops. As the mulching process itself does not differ significantly between crops, these technologies can also be considered applicable to strawberry cultivation.

These results indicate that many of the key operations in strawberry cultivation are already technically feasible for automation at the prototype level. However, most of the developed systems are still in the experimental stage and require further improvement in reliability, operational speed and system integration before wider practical adoption. At the same time, a number of studies focus on individual technological components, such as perception systems, gripping mechanisms or navigation solutions, which demonstrate promising results but are not yet integrated into complete robotic platforms. Further development will therefore require the integration of these individual solutions into more comprehensive systems capable of performing multiple operations under practical field conditions.

In addition to the technological operations analysed in this study, a number of other processes are involved in strawberry plantation management that must be applied during certain periods in order to ensure proper maintenance of strawberry plantations. Such processes include field preparation prior to planting, mowing between rows if such a cultivation technology is applied, mowing and removal of strawberry foliage, removal of plastic mulch material after the end of production of perennial plantations, and other processes. In most cases, the implementation of these operations is technologically simple, and traditional solutions for performing them already exist in strawberry cultivation. However, from a future perspective, there is potential to improve these processes, which have so far been performed manually, and transfer them to automated or even fully autonomous robotic operation. This justifies the need for the development and improvement of equipment and technologies used in strawberry plantation management.

Conclusions

1. All analysed strawberry cultivation processes show high automation potential, and several robotic prototypes already demonstrate technical feasibility.
2. Many studies focus on individual technological solutions; further work should integrate these components into complete robotic systems.
3. Machine vision, sensors and intelligent control are key technologies for automating more complex strawberry cultivation processes.
4. Further research should improve system intelligence and adapt robotic technologies for reliable operation in open-field conditions.

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DIVERSIFYING ENERGY FLOWS IN THE EU: STRUCTURAL CONSTRAINTS AND THE LATVIAN CASE

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Abstract
Diversification of energy flows is the main objective of the European Union's energy and climate policy. It is aimed at enhancing security of supply, reducing greenhouse gas emissions, and increasing system resilience. Despite common targets, EU member states demonstrate markedly different pathways and solutions in energy diversification. Often those strategies reflect constraints related to resource availability, legacy infrastructure, energy policy design, and socio–economic conditions. This study analyzes how select European Union member states are transitioning their energy sectors to align with overarching EU targets. It then considers the implications for Latvia's energy system. Using a comparative review methodology, the research evaluates national practices across electricity generation, heating, and combined heat and power production. Specifically, it assesses how these energy strategies align with local natural resource availability, energy import dependencies, and the technologal efficiencies of energy conversion. Latvia represents a distinct case study due to its high reliance on biomass, extensive district heating infrastructure, and limited domestic fossil fuel reserves. These structural conditions present both opportunities and challenges for Latvia's energy transition. By conducting a comparative analysis of EU member states practices, this study seeks to explain variations in energy transition progress and pinpoint the principal structural barriers facing Latvia's policy implementation. Ultimately, the study's findings will provide foundation for future research on energy system optimization, emphasizing the need to account for country-specific constraints and structural limitations.
Keywords: energy source, renewable energy, energy supply sustainability.

Introduction

The European Union has been working hard to change its energy policy. It wants to use more renewable energy, be more energy efficient, and get its energy from different sources. This is especially true after the EU adopted some big plans like the Energy Union Strategy, the European Green Deal, and the REPowerEU plan. These plans aim to reduce the EU's reliance on fossil fuels from other countries, make more renewable energy at home, and be better prepared for problems that might come from other countries or the market (Ah-Voun et al., 2024; European Comission, 2022).

Stable policies, support programs, investor trust, administrative processes, grid access, and sustained government commitment are all crucial for the targets set. Stronger and more consistent growth in renewable energy was demonstrated by nations like Germany that had robust and predictable support systems. On the other hand, nations with abrupt policy shifts, retroactive subsidy reductions, or difficult approval processes saw stagnation or decline (Shivakumar et al., 2019).

This review examines the mechanisms employed by selected EU countries to diversify energy flows and evaluates their alignment with EU strategic objectives. Some countries rely heavily on expanding variable energy sources such as wind and solar, while others prioritize the development of biomass – based energy systems, nuclear power, or energy efficiency improvements within existing infrastructure. Consequently, the effectiveness and pace of diversification differ substantially between member states. Comparative perspective is particularly important because EU member states exhibit representative but highly differentiated energy transition pathways shaped by their national circumstances.

Understanding how structural conditions influence diversification strategies is particularly important for countries with constrained resource bases or historically embedded energy infrastructures. Latvia represents a notable example within the EU energy landscape. The country is characterized by a relatively high share of renewable energy, largely driven by biomass and hydropower, as well as an extensive district heating sector that plays a central role in heat supply. At the same time, Latvia faces structural limitations related to limited domestic fossil fuel resources, a relatively small energy market, and historical dependence on imported energy carriers.

Given the differences across the EU, comparative analysis of national experiences can provide valuable insights into the mechanisms that enable or hinder diversification. Looking at how different countries in the EU deal with the challenges they face, use the resources they have, and match their plans with the EU's goals can help find common patterns that can be useful for countries with similar characteristics. By understanding how the availability of resources, technological development, and policy tools are connected, we can create strategies that are tailored to the specific needs of each country, which can help them diversify and grow in a way that makes sense for their unique situation.

Using a comparative qualitative review of literature and energy system analyses, the study examines the diversification strategies of several EU countries representing different energy system structures. The findings are then discussed in relation to the Latvian energy system to identify key structural constraints and opportunities relevant to further diversification of

energy flows. The findings provide a foundation for further analytical, engineering, and environmental studies focused on optimizing energy systems under national constraints.

Materials and Methods

In this study, diversification of energy flows is understood as the expansion and balancing of multiple energy sources, supply pathways, and conversion technologies within an energy system. The aim of this process is to reduce dependence on a limited number of fuels or suppliers and to improve system resilience. Diversification may occur across several dimensions of the energy system. First, diversification of primary energy sources involves increasing the variety of fuels and renewable resources used in electricity and heat generation (biomass, wind, solar, hydropower, nuclear energy, and fossil fuels with different supply origins). Second, diversification can occur through supply structures, including the balance between domestic energy production and imported energy carriers, as well as the use of alternative supply routes. Third, diversification may involve conversion and generation pathways, including different technological solutions such as combined heat and power (CHP), district heating systems, decentralized generation, and renewable–based electricity production. Finally, diversification can be associated with increased system flexibility, including energy storage, sector coupling, and the integration of variable renewable energy sources.

In this article, diversification is therefore examined as a multidimensional characteristic of national energy systems, reflecting both resource availability and structural conditions that influence the range of feasible technological and policy pathways. The review covers studies from the past decade - a period when EU energy policy focused on cutting carbon emissions, enhancing energy security, and strengthening grid resilience. To ensure a consistent analysis, we need to evaluate how different countries are diversifying their energy sources. The dimensional comparison framework is presented in Table 1.

Table 1

Dimensions and indicators used to evaluate energy flow diversification

Dimension of diversification	Indicators examined
Energy sources	Share of renewables, fossil fuels, nuclear
Supply structure	Import dependence, domestic production
Conversion technologies	CHP, district heating, renewable generation
System flexibility	Storage, sector coupling

The framework examines multiple dimensions of the energy system, including primary energy sources, supply chains, energy conversion efficiency, and system flexibility. This enables an equitable comparative analysis, taking into account national differences in resource endowments, infrastructure, and regulatory policy. Applying this framework provides deeper insight into national energy diversification strategies and highlights optimal approaches across diverse contexts.

Six national energy systems are considered in the analysis. Latvia is examined as the central case study, while five additional EU member states are selected to represent contrasting structural characteristics within the European energy landscape. The selected countries illustrate different combinations of resource endowments, technological pathways, and historical energy system development. In particular, the analysis includes countries with strong biomass – based energy systems, high penetration of variable renewable energy sources, nuclear–dominated electricity generation, and fossil fuel–dependent energy structures. By comparing energy system configurations, this study aims to identify emerging patterns in how European Union member states pursue energy diversification, given their respective structural constraints. The insights derived from this comparative review provide a basis for evaluating the opportunities and limitations associated with further diversification of energy flows in Latvia.

Results and Discussion

Sweden

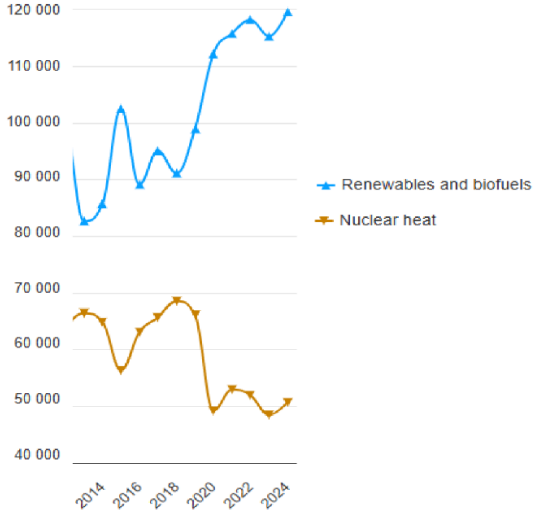
Sweden represents one of the most advanced examples of energy system, characterized by a long– standing transition toward low–carbon energy sources and strong government support for expanding renewables. The Swedish electricity system is largely based on hydropower and nuclear energy, which together provide stable low–carbon baseload generation, complemented by increasing shares of wind power and biomass. In recent years, political discussions have renewed interest in expanding nuclear capacity as part of efforts to meet rising electricity demand associated with electrification and industrial transformation (Morgunova & Linné, 2026).

Another distinctive feature of the Swedish energy system is the extensive use of district heating, which supplies a large share of the national heat demand. Moreover, it enables the integration of multiple energy sources and technologies. District heating systems facilitate sector coupling between electricity and heat sectors through technologies such as CHP plants, heat pumps, and thermal energy storage, thereby improving system flexibility and enabling higher shares of renewable energy (Atabaki et al., 2026).

Swedish citizens generally favor a balanced approach, regarding neither total centralization nor complete decentralization as ideal. Sweden’s experience demonstrates that the best approach combines the two:

the national government should establish goals, provide financing, laws, and oversight, while local governments should modify and carry out policies in accordance with local circumstances (Maliszewska-Nienartowicz & Stefański, 2024).
Figure 1 illustrates the Swedish electricity generation mix from 2014 to 2024.

Figure 1
Gross electricity production in Sweden, GWh (Eurostat, n.d.)



Swedish electricity production is almost entirely fossil–free, with around 96 – 99 % of electricity from renewable or nuclear sources. As of 2025, statistics highlight the dominant sources in Sweden's electricity mix:

- Hydropower: ~39 %
- Nuclear: ~28 %
- Wind: ~23 %
- Biofuels and waste: ~8 %
- Solar: ~2 %

The last decade's trend shows a rapid expansion of renewables as well as a slow decrease in nuclear power. This rapid increase in renewable energy production is mainly connected to increasing wind energy capacities rising from 11235 GWh to 40621 GWh in the depicted time period. Solar generation increased sharply from 47 to 4163 GWh, yet its total volume remains modest in comparison to wind energy. Electricity production from renewables is shown in Figure 2.
However, some perspectives emphasize that maintaining nuclear operations is essential for Sweden to meet rising demand, sustain RES, and preserve grid stability.

Denmark

Denmark is one of the most advanced examples of renewable–based system in the EU with strong policy support for wind energy development. Denmark has pursued a long–term transition away from fossil fuels through a combination of regulatory measures and financial incentives aimed at increasing the share of renewable energy in both electricity and heat production. Early policy frameworks supporting renewable electricity generation, particularly wind energy, created favourable market conditions that allowed Denmark to develop significant technological and industrial leadership in wind power deployment.
Wind energy now plays a central role in the Danish electricity system, supported by extensive onshore and offshore wind capacity in the North Sea. Offshore wind development is expected to continue expanding in the coming decades, supporting both national decarbonization goals and regional electricity supply within the interconnected European energy system (Abid et al., 2026).

Figure 2
Gross electricity production from renewables in Sweden, GWh (Eurostat, n.d.)

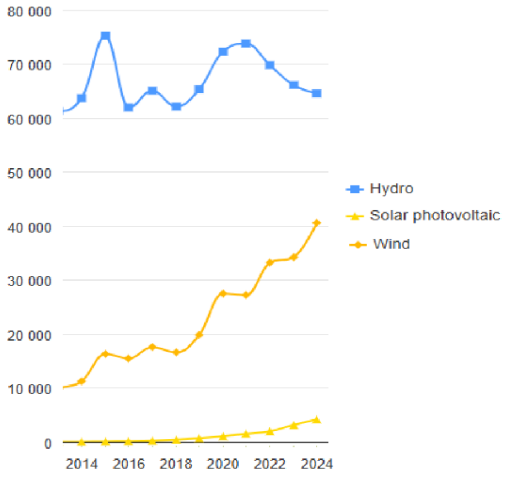
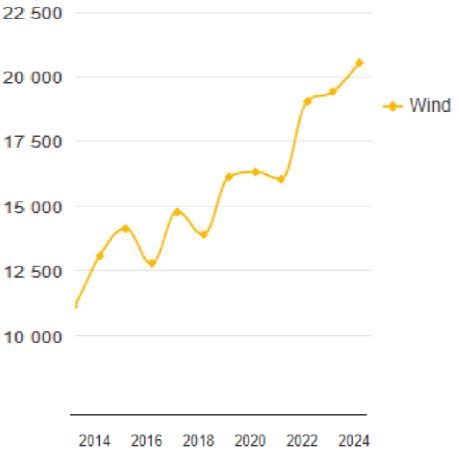


Figure 3 depicts the growth of wind energy capacities in Denmark for the period from 2014 to 2024. In this relatively short timeframe, wind energy production rose form 13000 GWh to 20500 GWh. Wind remains the largest electricity source providing almost 60 % of the whole country's production.

Figure 3
Wind electricity production in Denmark, GWh (Eurostat, n.d.)

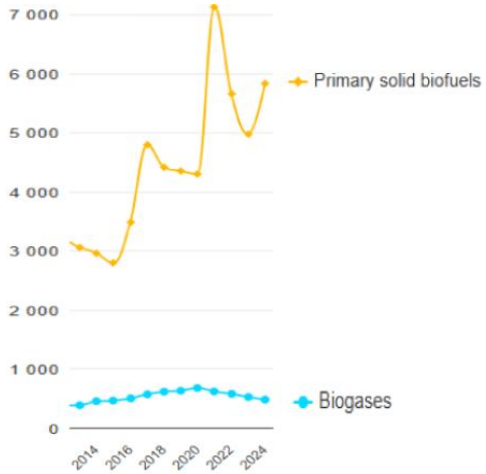


Biomass is the second source of electricity providing almost 20 % of state production capacities. Danish CHP plants supply both electricity and district heating facilitating sector coupling between electricity and heating sectors, allowing surplus renewable electricity and industrial waste heat to be integrated into the heating network. CHP plans improve energy conversion efficiency and system flexibility, supporting the management of variable renewable energy generation (Ono et al., 2026).

Solid biofuel and biogas use in electricity production is shown in Figure 4. In the same timeframe, solid biofuel consumption expanded from 2959 to 5837 GWh; in contrast, biogas consumption experienced minimal growth, moving from 451 to 478 GWh.

Figure 4

Combustible renewables in electricity production in Denmark, GWh (Eurostat, n.d.)



By increasing wind and biofuel capacities, Denmark was able to cut off its solid fossil fuel use from 11064 GWh in 2014 to 1751 GWh in 2024. Natural gas consumption in electricity production also decreased from 2096 to 909 GWh in the depicted time frame. Denmark's electricity production trends are shown in Figure 5.

Denmark's energy transition is therefore often referred to as a 'smart energy system' approach of renewable electricity, district heating, as well as emerging innovations in hydrogen and synthetic fuels. These initiatives support both decarbonization and energy security objectives (Marczinkowski et al., 2022).

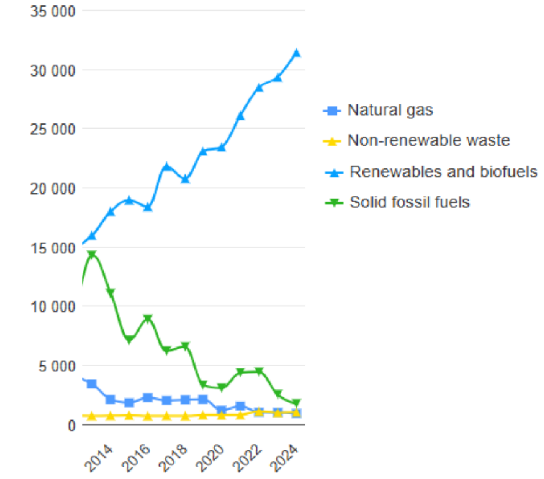
Germany

Germany represents one of the most ambitious energy transition initiatives through its *Energiewende* strategy, which aims to transform the national energy system by expanding renewable energy while phasing out nuclear and coal power.

The German electricity mix has increasingly shifted toward wind and solar generation (Figure 6), supported by strong policy mechanisms such as feed – in tariffs and market incentives for renewable energy investment.

Figure 5

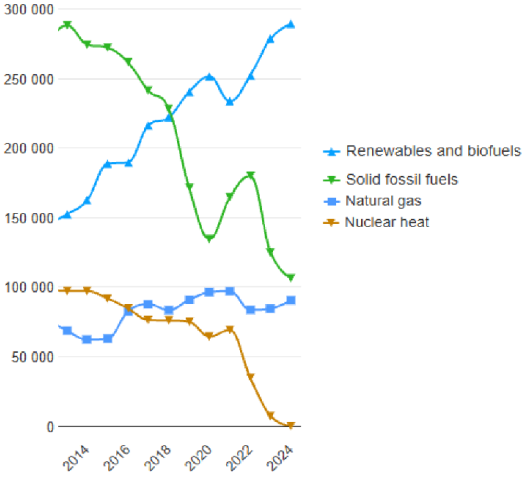
Gross electricity production in Denmark, GWh (Eurostat, n.d.)



Market liberalization and regulatory reforms have also enabled the emergence of new actors and energy technologies within the electricity sector (Pant & Belz, 2026).

Figure 6

Gross electricity production in Germany, GWh (Eurostat, n.d.)



At the same time, Germany faces significant challenges associated with the integration of large shares of intermittent renewable energy. The rapid expansion of wind and solar capacity has led to periods of surplus generation while electricity demand remains concentrated in industrial regions, requiring major investments in grid infrastructure and transmission networks to ensure system stability and efficient electricity distribution. Incentive regulation mechanisms have been implemented to stimulate investment in grid expansion and modernization (Matschoss et al., 2019).

Another key component of Germany's energy transition is the gradual phase-out of coal-fired power plants, which historically played a central role in the country's electricity generation. As the world shifts

towards cleaner energy, climate policies and increasing fuel costs are likely to speed up the end of coal-powered generation. At the same time, renewable energy sources, gas-fired power plants, and new technologies like battery storage are stepping in to replace old fossil fuel capacity. This shift occurs within a broader transitional period and is expected to significantly alter the energy generation landscape. As coal is phased out, these alternative energy sources are becoming critical to meeting growing national demand. According to recent studies, coal is anticipated to lose its central role in electricity generation by 2030. But we will still need some traditional power plants that can adjust to changes in demand. Future reliance on these plants hinges on three main variables: overall electricity demand, the share of renewables in the power mix, and the relative prices of coal and natural gas (Egerer et al., 2025).

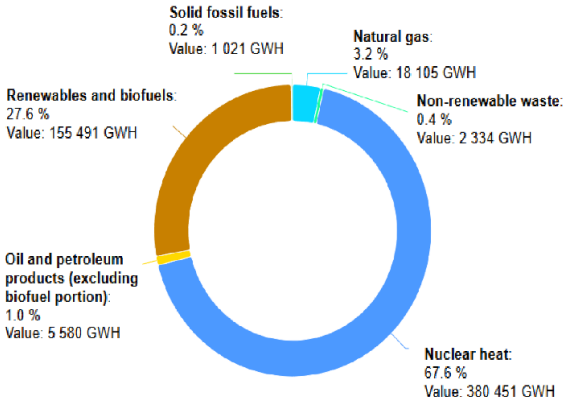
Despite the expansion of renewable energy sources, the German power system still faces economic and technological challenges, such as high electricity prices, infrastructure bottlenecks, and the rising need for critical materials needed for renewable technologies. Such factors indicate the difficulty of achieving large-scale energy diversification in highly industrialised economies. Germany thus exemplifies diversification by large scale renewable deployment, but under large infrastructural and economic constraints (Egerer et al., 2025).

France

France represents a structurally unique case due to its traditional reliance on nuclear power plants as the backbone of its electricity system. Nuclear power has historically produced around 70 % of all electricity generation (Figure 7), enabling France to maintain low greenhouse gas emissions and a comparatively high degree of energy independence. This centralized, large-scale generation model has been a defining feature of French energy policy since the 1970s and continues to shape its diversification pathways.

Figure 7

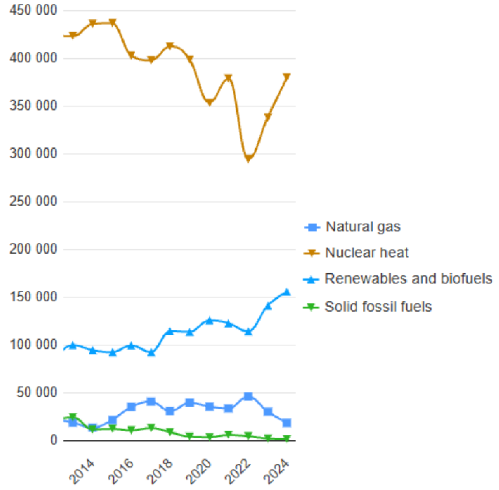
France, gross electricity production in 2024, GWh (Eurostat, n.d.)



In recent decades, however, France has gradually reoriented its energy policy toward alignment with European climate objectives, including increasing the share of renewable energy and reducing fossil fuel consumption. Recent geopolitical tensions and war in Ukraine also forced EU countries to cut their fossil fuel use; therefore, France was forced to increase its nuclear generation (Figure 8). Despite these ambitions, the transition has been non-linear, reflecting both institutional inertia and the complexity of modifying an already low-carbon, highly centralized system (Andriosopoulos & Silvestre, 2017).

Figure 8

France, gross electricity production, GWH (Eurostat, n.d.)



A key structural challenge in the French case lies in balancing the reduction of nuclear dependency with the expansion of renewable energy sources. Policy targets aim to reduce the share of nuclear power to approximately 50% of electricity generation while simultaneously increasing the share of renewables to 32% of final energy consumption by 2030. However, achieving those targets requires significant investments in infrastructure and system flexibility (balancing and accumulating facilities), as well as careful management of supply security and electricity pricing (Andriosopoulos & Silvestre, 2017).

Furthermore, France's energy diversification strategy is constrained by institutional structures built around centralized generation and state-supported energy companies. While renewable energy technologies such as wind and solar are expanding, their integration into the existing system presents technical and economic challenges, particularly in terms of grid adaptation and market design. Thus, France demonstrates a diversification pathway constrained by nuclear generation dependency and centralized system architecture (Xuan, 2025).

Poland

Poland represents a structurally constrained case of energy diversification with strong dependence on coal and a relatively slow transition toward renewable energy. Despite increasing pressure from EU climate

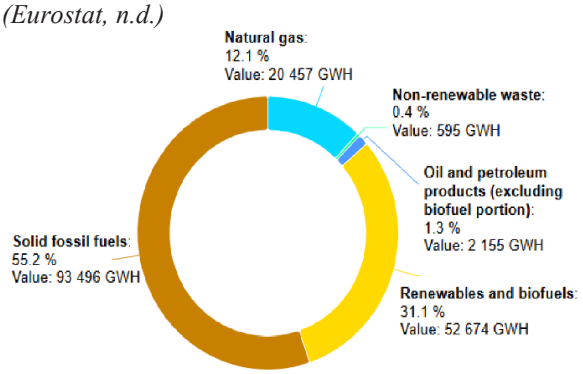
policies, Polish energy system remains dominated by centralized, fossil-based generation (Figure 9).

Recent developments, however, reveal a more complex transition dynamic. Poland has experienced a rapid expansion of distributed renewable energy, particularly in the form of residential photovoltaic installations. This 'prosumer-driven' process has increased public engagement and created a foundation for more decentralized generation models. Nevertheless, this transition remains fragmented and insufficiently integrated into the broader energy system (Xuan, 2025).

Another structural barrier to diversification in Poland is the gap between the lack of government involvement and practical implementation. EU directives promote mechanisms such as renewable energy communities (REC), but their deployment in Poland is still limited. The conditions are largely a combination of political conservatism, regulatory lag and insufficient institutional support, all of which act as a drag on investment (Neska et al., 2025).

Figure 9

Poland, gross electricity production in 2024, GWH (Eurostat, n.d.)



Moreover, the Polish energy system is limited by infrastructural and socio-economic limitations. The continued use of centralised energy management, limited system flexibility and ageing grid infrastructure complicate the integration of RES. Low levels of public trust, limited social capital and a preference for individual rather than collective energy solutions also hinder the development of large-scale renewable energy models (Neska et al., 2025).

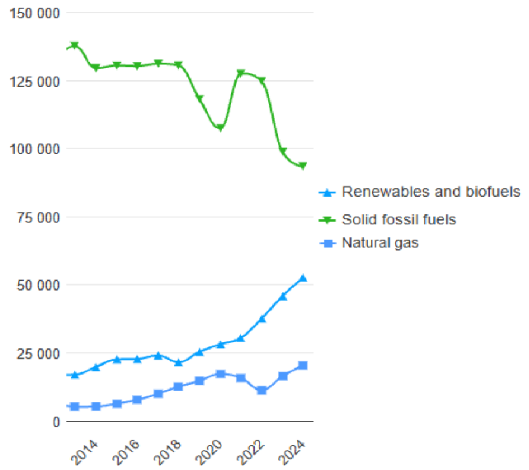
These challenges notwithstanding, the rapid uptake of small-scale renewables signals an increased societal willingness to change. Renewable energy capacities rose from 19 842 to 52 674 GWh (Figure 10).

As such, Poland illustrates both difficulties and opportunities associated with energy transition, highlighting the importance of institutional involvement, regulatory stability, and social engagement in achieving diversification goals.

The European energy systems analysed show substantially different pathways of energy transformation. These are determined by various drivers such as resource availability, infrastructure development and policy priorities.

Figure 10

Poland, gross electricity production, GWH (Eurostat, n.d.)



The comparative analysis of selected European countries shows that energy diversification is not a uniform process but a set of sequential actions driven by resource availability, institutional frameworks and existing energy systems. All the analysed countries operate in a common EU policy framework, but their strategies for diversification differ to a greater or lesser extent, both with respect to strategy and effectiveness. Across all cases, structural constraints emerge as a decisive factor shaping diversification outcomes. These constraints include not only physical infrastructure and resource endowments, but also institutional involvement, market design, and societal factors. The transition dynamics are more complex in countries with higher levels of structural inertia or policy fragmentation (e.g. Poland and, to a lesser extent, Germany) compared to countries with stable policy environment and integrated system planning (e.g. Denmark and Sweden), where diversification is more effective.

From a broader perspective, the comparative analysis indicates that successful energy diversification requires not only technology deployment but also system level integration and institutional engagement. Ultimately, the success of diversification strategies depends on the interplay between the adoption of new energy sources, modernisation of infrastructure, policy frameworks, and societal factors.

These findings provide an important basis for the analysis of the Latvian energy system, which has a peculiar set of challenges and opportunities for energy diversification in the context of the EU.

Latvia

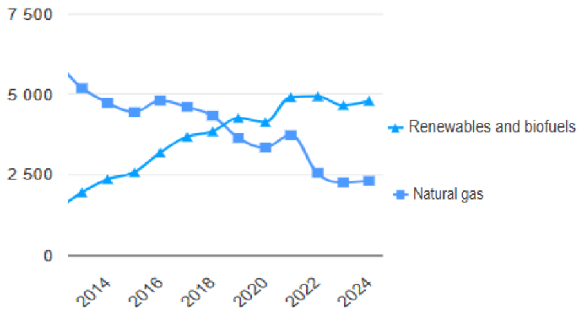
District heating and combined heat and power (CHP) systems are a defining feature of Latvia's energy sector. District heating, especially in urban areas, represents a significant share of the total energy consumption and is characterised by a high level of centralisation that originated from the historical development of the system. Combined heat and power

(CHP) generation is of vital importance, as CHP plants account for approximately 70% of the consumer heat supply. This structure creates both opportunities and constraints for diversification. CHP systems can convert energy very efficiently, but they also create dependence on certain types of fuel, especially natural gas.

The role of renewable energy is increasing, but the energy mix in Latvia is still influenced by natural gas in heat and electricity production. In district heating, natural gas accounts for a substantial share of heat production, with substantial share CHP-generated heat relying on gas. Meanwhile, biomass – primarily wood fuel – plays an increasingly prominent role in smaller boiler houses and decentralized systems, leveraging abundant domestic forestry resources. This dual structure positions Latvia between Sweden's biomass-driven system and Poland's fossil-dependent model. Heat energy produced from natural gas decreased from 4732 GWh in 2014 to 2311 GWH in 2024, renewable and biofuel heat capacities rose from 2365 to 4660 GWh (Figure 11) and are expected to grow even more because of upcoming waste incineration plant installation in Acone. This waste – to – energy CHP plant will strengthen Latvia's energy independence by lowering natural gas consumption.

Figure 11

Latvia, gross heat production, GWH (Eurostat, n.d.)



Another important structural characteristic is the high concentration of energy demand in urban centres, particularly Riga, which accounts for more than half of country population and total heat production. This spatial concentration limits the expansion potential of new district heating infrastructure in other regions and influences the feasibility of large-scale system transformations. At the same time, total heat demand has shown a declining trend in recent years due to efficiency, indicating evolving consumption patterns (Kamenders et al., 2017).

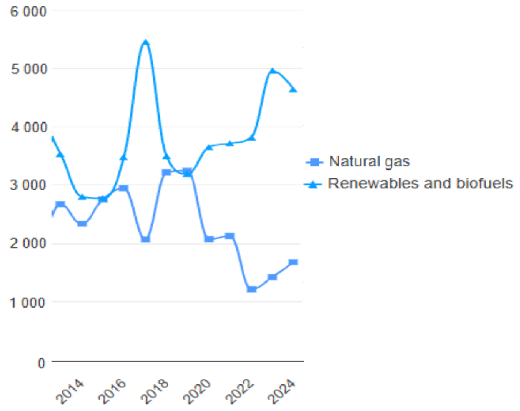
In terms of electricity production Latvia has lowered its natural gas consumption from 2337 GWh in 2014 to 1678 GWh in 2024 as shown in Figure 12.

Intermittency of the renewable energy capacity is referred to hydro power plant yearly output changes since hydro power has the largest share of Latvia's electricity production portfolio.

Hydropower plants remained the main source of electricity generation in Latvia in 2025, generating slightly more than half, or 51%, of the total amount of electricity transmitted to the network, but this figure is decreasing every year (Electricity market overview, 2025).

Figure 12

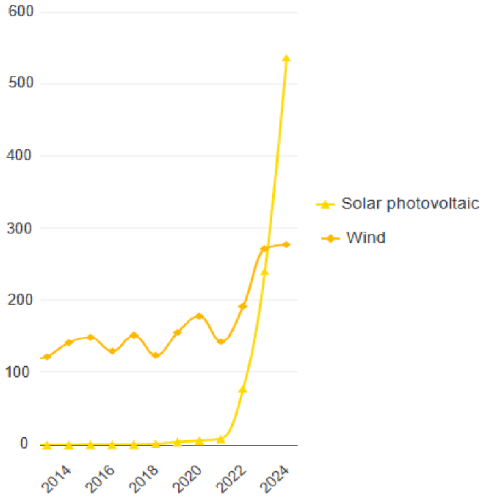
Latvia, gross electricity production, GWH (Eurostat, n.d.)



The primary reason for this shift is gradual increase in wind and solar power generation. In 2024, wind output reached 273 GWh while solar reached 398 GWh; in 2025, these figures shifted to 200 GWh and 678 GWh, respectively (Electricity market overview, 2025) (Figure 13).

Figure 13

Latvia, gross electricity generation from solar and wind resources, GWH (Eurostat, n.d.)



This dataset does not account for the capacity of the new Kauguri wind farm (16 modern turbines with a maximum tip height of 266,5m), which is expected to begin commercial operation this July and produce more than 350 GWh energy per year (Laflora Energy Wind Park, 2026).

This same indicator for biomass and biogas usage for electricity production would be accordingly 286 and 153 GWh in 2024, and 281 and 117 GWh in 2025 (Electricity market overview, 2025).

From a diversification perspective, Latvia demonstrates moderate progress, with decreasing consumption of natural gas, and gradual growth of renewable energy capacities. However, projections indicate that natural gas will remain part of the energy balance, reflecting structural and infrastructural inertia. This highlights a key challenge, also observed in other EU countries: the difficulty of fully transitioning away from established energy carriers within existing system configurations (Kamenders et al., 2017).

Importantly, the Latvian system presents many opportunities for diversification within existing infrastructure, particularly through the modernization of district heating and CHP systems. The widest potential for improving is through low-temperature district heating, heat storage integration, and advanced CHP technologies. These developments directly enable the integration of alternative fuels into biomass-based systems, including co-incineration strategies in fluidised bed technologies.

Latvia in the wider EU context could be described as a structurally adaptable but resource-constrained system. In this context, diversification is less a matter of large-scale capacity expansion, and more of optimisation of existing energy flows. Latvia's path is more infrastructure-driven and incremental, compared to Denmark's highly integrated renewable systems or Germany's large-scale renewable deployment.

Overall, the findings suggest that Latvia's most effective transformation strategy lies in enhancing system flexibility and fuel diversity. While expanding renewable capacity will reduce the country's reliance on natural gas, renewable deployment alone is insufficient. This is particularly evident in the heating sector, which consumes slightly more natural gas than power generation (2311 GWh compared to 1678 GWh in 2024). In this context, a promising pathway involves integrating alternative fuels into biomass cogeneration systems, complementing the construction of a waste-to-energy CHP plant that is already underway. These technologies will improve energy security, reduce fossil fuel dependence, and align with EU climate objectives. Latvia's diversification challenge is therefore not primarily the absence of renewable potential, but also the need to adapt existing heat and cogeneration infrastructure to a more flexible and less fossil-dependent fuel mix.

The general lesson from the Latvian case is that in smaller, infrastructure-limited energy systems, diversification is a slow process of building up system flexibility, renewable expansion and resilience under existing structural conditions.

Conclusions

1. The research indicates that energy diversification within the European Union is driven chiefly by resource endowment, institutional structures, and existing energy system configurations.
2. The comparative analysis identified distinct national approaches to diversification, confirming that successful energy transition strategies depend on system-specific conditions rather than a universal model.
3. Effective energy diversification requires not only the expansion of renewable capacity, but also infrastructure modernisation, market design reform and sector coupling.
4. Latvian energy system can be described as structurally adaptable but constrained by its reliance on natural gas, and limited expansion potential of conventional renewable resources.
5. For Latvia, the most promising path toward diversification lies not in the rapid expansion of renewable capacity, but in enhancing fuel flexibility, expanding CHP output, and modernizing existing district heating and CHP infrastructure.

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IMPACT OF PRATT TRUSS MEMBER SIZING ON OPTIMAL SOLUTIONS

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Abstract
Buckling frequently governs the design of compression members, so optimization approaches that consider only material stress utilization can lead to solutions that are not practically optimal. Efficient designs depend not only on sizing but also on selecting a topology that promotes stable force transfer. This study provides an in-depth investigation of the behaviour of the Pratt truss topology for trusses with varying span, number of panels, and height. Pratt trusses were simulated and optimized (157,212 unique cases) using alternative member-sizing strategies. Results were evaluated using statistical and graphical analyses to compare sizing models. For the Pratt truss topology, consistent response patterns in internal force distribution, stiffness, and optimal height-to-span ratio are observed across the investigated design space, largely independent of the sizing approach. However, a max-utilization sizing rule for members produces substantial dispersion in the result data. Optimal solutions obtained using regression analysis exhibit linear relationships between trusses of different spans with the same number of panels. The optimal height-to-span ratio follows distinct trends for different panel counts. For a fixed panel count, it varies smoothly and correlates strongly with span. Overall, the results indicate a distinct type of behaviour inherent to the Pratt truss topology, suggesting that, when generalized, these trends can support faster pre-design evaluation of near-optimal truss configurations.
Keywords: pratt truss topology, minimum-weight design, iterative finite element analysis, genetic algorithm benchmarking, buckling constraints.

Introduction

Structural efficiency is governed not only by member sizing but also by the chosen load-transfer mechanism, which is primarily determined by shape and topology. Conceptual decisions therefore have a first-order influence on material demand and stiffness, and later sizing adjustments cannot fully compensate for an inefficient structural layout (Baker et al., 2015). For steel roof trusses, this challenge is amplified by the fact that compression design is frequently governed by stability, so the 'best' solution depends on buckling-sensitive member selection rather than on stress utilization alone (Neiburgs & Skadins, 2024). In addition, practical design introduces discrete cross-sections from catalogues, multiple verification rules, and serviceability constraints, all of which tend to make optimization problems computationally demanding and can push many studies toward simplifying assumptions that risk producing solutions requiring substantial post-processing by the engineer (Kripka & Drehmer, 2018). Heuristic global search methods such as genetic algorithms are therefore often used to explore large, discontinuous truss design spaces (including topology/configuration choices) when closed-form or gradient-based optimisation is impractical (Verbeeck et al., 2004). Because of these limitations, several researchers have emphasized the need for conceptual-stage approaches that relate structural performance to a small number of geometric descriptors. One well-established direction is the use of morphology-based indicators (De Wilde et al., 2015), which link slenderness measures such as L/H to volume (strength) and displacement (stiffness) trends and can incorporate buckling effects to guide early decisions (Pyl et al., 2013). At the same time, studies that explicitly include additional phenomena (e.g., buckling and stiffness constraints) demonstrate that fully stressed or 'max utilization' reasoning does not necessarily deliver the lightest structure (Vandenbergh et al., 2006). These observations motivate a more detailed investigation of how practical sizing rules interact with truss topology when discrete catalogues and stability checks are enforced.

Within this context, the present study focuses on the Pratt truss, a widely used topology in building roofs. The research aim is to quantify how alternative member-sizing strategies influence the predicted optimal solutions and the resulting trends in key geometric parameters, with emphasis on the optimal height-to-span ratio and its dependence on span and panel count. The approach is based on a large parametric dataset of simulated and optimized Pratt trusses, followed by statistical post-processing to identify systematic relationships and to distinguish genuine topology-driven trends from sizing-induced dispersion. The study also evaluates whether such trends can support faster pre-design estimation of near-optimal configurations, which is relevant in practice where weight is often directly tied to embodied impacts for single-material structural systems (Ching & Carstensen, 2022).

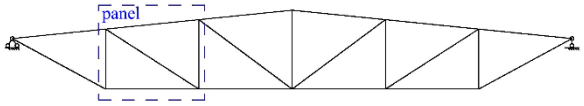
Materials and Methods

This study investigates the structural response of a Pratt truss supported at the top chord ends. The span varies from 12–25 m (1 m steps) and the height from 1.00–3.55 m (0.05 m steps). For all cases, the ridge is 0.5 m above the supports, producing different top-chord slopes while keeping comparable overall heights. The topology is defined by the panel count $n_p \in \{4,6,8,10,16,20\}$ for each span–height pair. One panel is the bay between two adjacent panel points along the span, as illustrated in Figure 1.

The calculations were performed in Rhino 8 using Grasshopper as the computational environment, where custom 2D planar finite element method (FEM) and member-sizing algorithms were developed for this study. A linear-elastic, pin-jointed FEM truss model is

used and self-weight is neglected, consistent with early-stage morphological-indicator comparisons of large candidate sets (French, 1985). One load pattern is applied at two levels (4 and 6 kN/m²) over a 6 m tributary width along the full span; the resulting line load is converted to equivalent nodal loads and applied to upper-chord nodes according to truss geometry. Two boundary-condition variants are analysed: pinned-simple and pinned-pinned. All members are initially assigned a uniform area of either 0.0043 m² or 0.01 m². Each case is solved using an iterative FEM-sizing loop (11 iterations): member forces drive profile updates that are reintroduced into the FEM model. Convergence is monitored via the relative change in total truss weight between iterations (ΔW/W); cases with nonzero last-step change are retained as part of the dispersion.

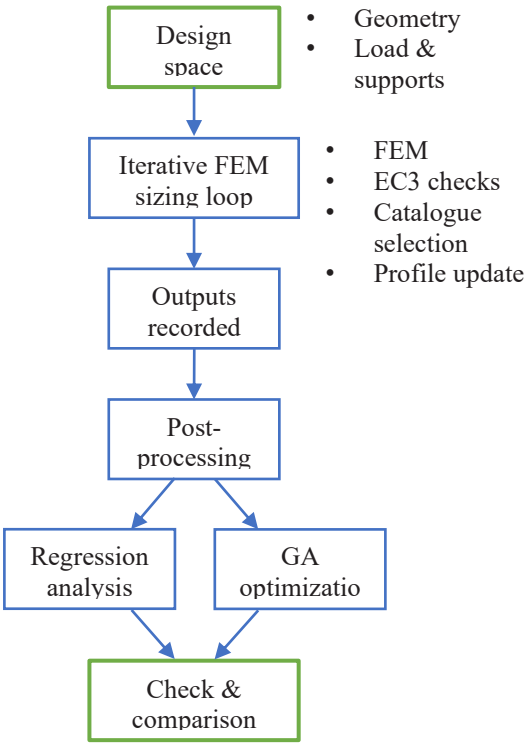
Figure 1
Pratt truss schema



A compact overview of the computational procedure is provided in Figure 2 (workflow schema), summarizing the parametric model, the iterative FEM-sizing loop, response recording, and post-processing. Truss member sizing is treated as the primary modelling variable. Member resistances are verified according to Eurocode 3 (European Committee for Standardization, 2022) for tension and compression prior to profile acceptance; compression stability is checked for pin-ended members with effective length factor k=1.0 (effective length equals the node-to-node length) using the Eurocode 3 (EC3) buckling reduction-factor method with buckling curve b (α=0.34) and utilization $U=N_{Ed}/N_{b,Rd}$; Class 4 profiles are excluded, hence gross section properties are used; nominal loads are used (no action factors) with $\gamma_{M0}=\gamma_{M1}=1.0$, and tension resistance is taken as gross yielding only (no net-section/fracture checks). Profiles are selected from a predefined catalogue using one of two selection rules: maximum utilization or minimum weight among feasible profiles. Here, 'feasible' refers only to member-level Eurocode 3 checks. Joint detailing and cross-section compatibility between connected members are not modelled. For each rule, four sizing approaches are investigated to quantify the influence of sizing assumptions on the resulting optimal solutions. In A1, no catalogue-based sizing is applied, and the initial cross-sections remain unchanged. In A2, profiles are selected from a mixed catalogue including I and U-sections and square/rectangular hollow sections. In A3, profiles are selected from a custom rectangular hollow section catalogue with monotonically increasing dimensions and wall thickness. In A4, the mixed catalogue of A2 is combined with a fabrication constraint: all upper-chord members share one profile, and all lower-chord members share one profile, taken as the largest required along each chord. This improves constructability and reduces variation in connected member sizes. All cases use steel grade S355.

The study includes N_{geom} = 4,367 valid configurations. With three sizing approaches (A2–A4), two sizing strategies, and six load/support cases, the total is: N_{cases} = 4367 · 3 · 2 · 6 = 157,212. A1 is evaluated once as a reference and is not included in N_{cases}.

Figure 2
Iterative FEM-sizing and post-processing workflow



During the iterative procedure, the recorded outputs include geometric descriptors, support reactions, member force measures, selected profiles, total truss mass, and vertical deflections, stored for each iteration together with the corresponding modelling metadata.

The results are analysed using statistical methods and graphical interpretation. Data are grouped by profile selection rule, sizing approach, and support configuration, and subsequently evaluated with respect to panel count and span. To characterize the relationship between truss weight and height for fixed span and panel count, a quadratic regression model of the form Tweight=a+b·Theight+c·Theight² was fitted in R using ordinary least squares, implemented as lm(Tweight ~ poly (Theight, 2, raw = TRUE)). Separate models were fitted for each span–panel subset within each analysed dataset, giving 84 quadratic models in total. Each regression used 52 height values across the investigated range. To estimate the regression-based optimum height, the fitted quadratic curve was evaluated at 1000 equally spaced heights within the analysed range, and the minimum predicted weight

was selected. No explicit outlier removal or influence screening was applied; all available cases were retained. Finally, a genetic algorithm (GA)EC is used to search for minimum-weight solutions and to provide an independent check
for comparison with the regression-derived optima.

Results and Discussion

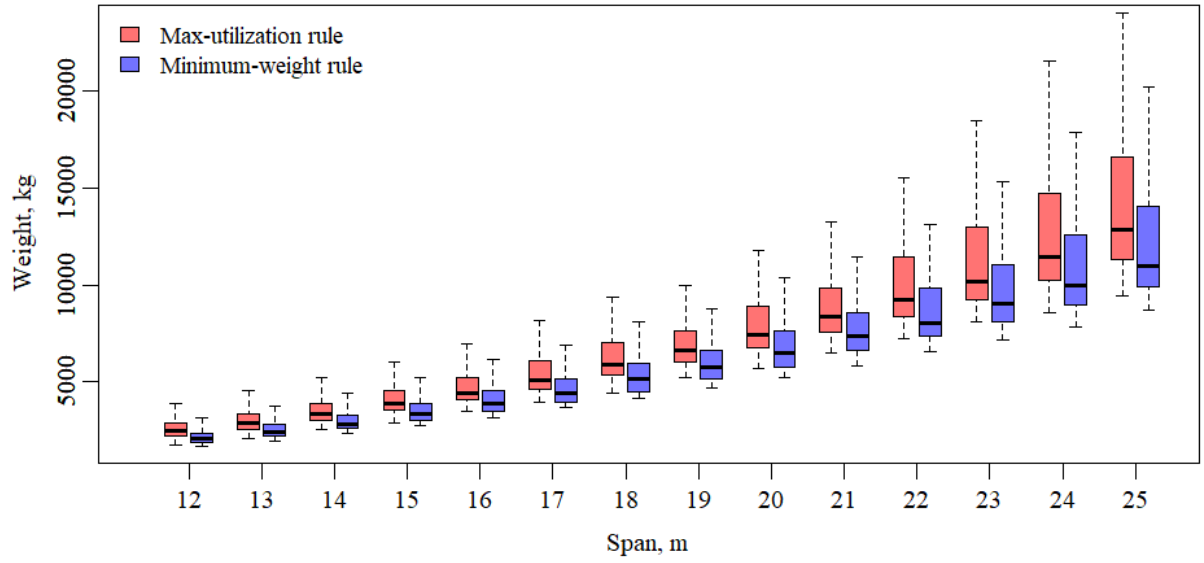
The study generates a large amount of data, the analysis of which requires a systematic approach. To achieve research objectives, data are analysed sequentially using appropriate methods. At first the results of the two sizing algorithms are compared and analysed. Then data are compared by support types, initial cross section and iterations of truss calculations. Following initial data analysis, the sizing approach comparison and regression is performed. Finally, trusses are recalculated at the regression-optimum heights and GA is used to check selected cases.

Sizing algorithm comparison

Visual analysis indicates clear differences between the two catalogue-based sizing rules: maximum utilization and minimum profile weight. For each member, both rules select among profiles that satisfy Eurocode 3 checks. Figure 3 shows that the minimum-weight rule yields lower total truss weight and a smaller spread of results than the maximum-utilization rule for sizing approach A2. The difference is statistically significant (two-sided paired Wilcoxon signed-rank test on matched cases, $p < 0.05$). The weight dispersion increases with span for both sizing rules, reflecting the combined effect of buckling-governed compression design and discrete profile availability in the catalogue.

Figure 3

Truss weight distribution by span for two member-sizing rules

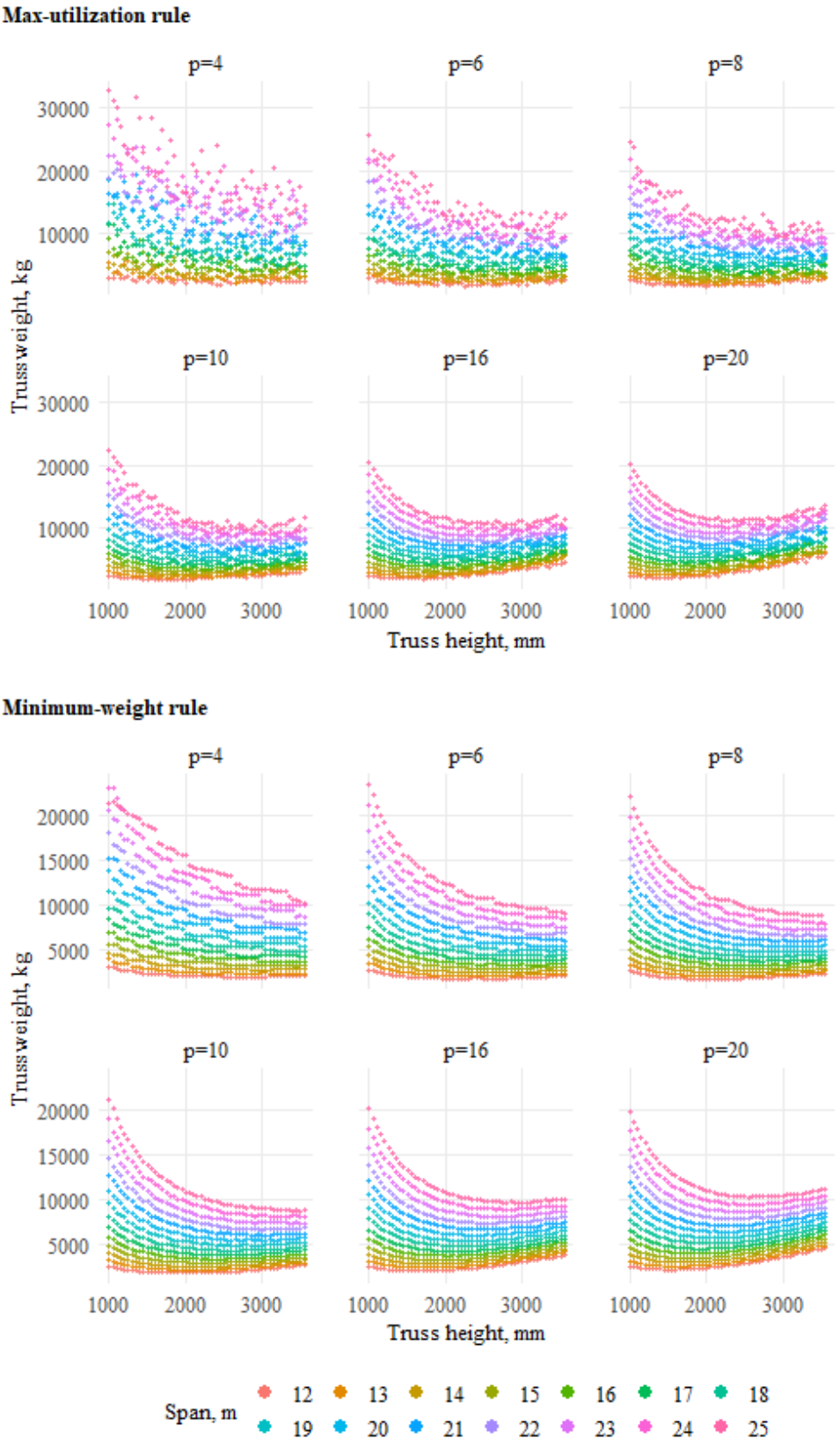


Support sensitivity and iterative coupling

Supports boundary conditions influence the distribution of internal forces and displacements and therefore affect the iterative cross-sectional coupling between FEM analysis and catalogue-based sizing. When one support is modelled as pinned and the other as simple, the coupled analysis-sizing procedure stabilizes rapidly, and the final member set is largely insensitive to the initial cross-sectional area. In contrast, when both supports are pinned, the increased kinematic freedom leads to a stronger redistribution of forces between iterations, and the final outcome becomes more sensitive to the selected sizing rule, sizing approach, and panel count. For pinned–pinned supports, convergence is weaker; using $\Delta W/W$ between the last two stored iterations, an example A3 subset shows ~90% stabilized, while remaining cases exhibit small residual changes ($\leq$ ~0.2%), increasing dispersion.

Figure 4 illustrates this sensitivity by showing how the response changes across panel counts and spans under the alternative sizing rules. In the max-utilization rule, the distribution of results exhibits markedly higher scatter and less stable trends, indicating a more irregular interaction between discrete profile replacement and global stiffness redistribution. The minimum-weight rule produces smoother trends and noticeably reduced dispersion, suggesting more consistent convergence of the coupled procedure. The effect is most pronounced for sizing approaches that enforce stronger catalogue discretization or chord uniformity constraints, where profile 'jumps' introduce larger stiffness changes between iterations. Overall, the support configuration is therefore a key factor in the robustness of optimal-solution identification, and the pinned-pinned case represents the more demanding scenario for sizing-rule comparisons and subsequent regression-based optimum extraction.

Figure 4
Truss weight trends across panel counts and spans for two sizing rules



Regression optimum and comparison by GA

To identify minimum-weight configurations for each truss case, the relationship between total truss weight and truss height is evaluated across the investigated height range. For each fixed combination of span, panel count, support configuration, sizing approach, and sizing rule, a quadratic regression was fitted to the weight-height response, and the minimum of the fitted

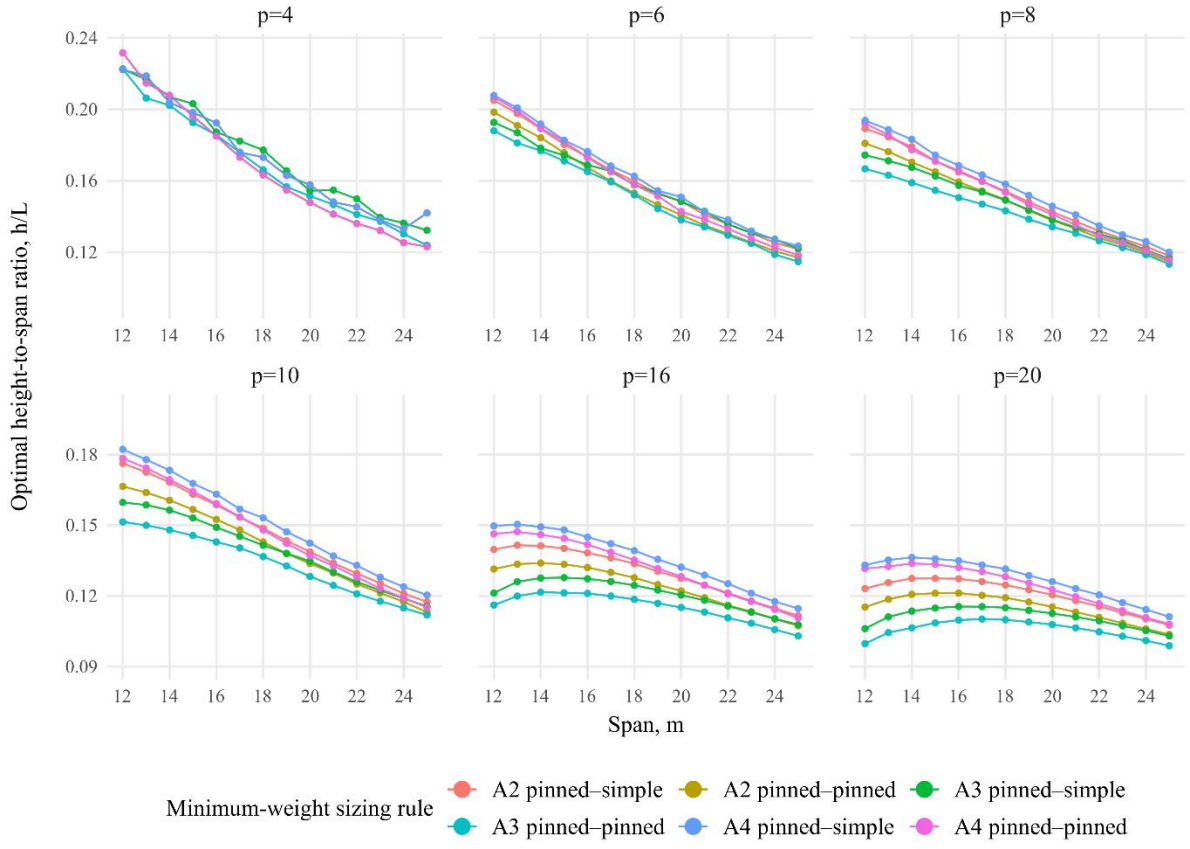
curve is interpreted as the regression-based optimum height. The quality of the fitted optimum depends on the smoothness of the underlying response and thus reflects the stability of the coupled FEM–sizing iterations (final iteration used consistently; non-stabilized cases not excluded). Cases with higher dispersion, most pronounced under the max-utilization sizing rule and more restrictive catalogue settings, yield less reliable minima than cases where weight varies smoothly with height. For the 84 fitted models, the coefficient of determination ranged from R^2=0.3472 to 0.9837, with adjusted R^2 values from 0.3206 to 0.9830 (mean R^2=0.8284; median R^2=0.8697). In all models, the quadratic coefficient was positive and statistically significant (p<0.05), supporting the use of a convex quadratic curve to estimate the minimum weight. Because no explicit outlier removal or influence diagnostics were applied, sensitivity to outliers is reflected indirectly in the lower R^2 values and the wider scatter of the more irregular response cases. For selected cases, GA optimisation is used as a check for the regression-derived optima; however, as a metaheuristic it does not guarantee a global optimum, and systematic deviation statistics over multiple runs are left for future work.

The resulting optimal height-to-span ratios are summarized in Figure 5. The optimal h/L values exhibit distinct trends for different panel counts, while for a fixed panel count the optimal ratio varies smoothly with span. Across the investigated design space, the trends remain consistent between sizing approaches, although the max-utilization rule produces a wider scatter of optimal ratios than the minimum-weight rule.

A complementary interpretation of the optimum is provided by the deflection response shown in Figure 6, where regression-optimum cases are highlighted relative to the full set of evaluated heights. Increasing truss height initially reduces deflections substantially, but beyond a certain range additional height yields diminishing stiffness benefits while the total weight continues to increase. The regression-based optimum is located near this transition, indicating a balance between stiffness gain and added material demand. The clearest span-dependent correlations of near-optimal cases are observed for the minimum-weight sizing rule, whereas max-utilization sizing exhibits higher dispersion and less stable optima, consistent with the previously observed sensitivity of discrete profile selection under buckling-governed compression design.

Figure 5

Optimal height-to-span ratio trends across spans and panel counts



Discussion and implications

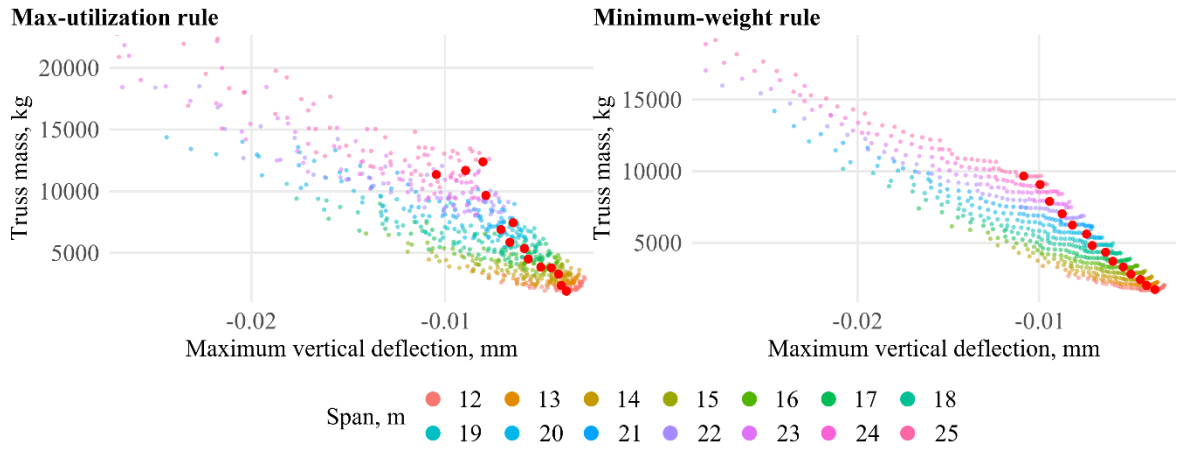
The results confirm that 'optimal' Pratt truss solutions are influenced not only by topology and geometry, but also by sizing mechanics. This is particularly evident in the treatment of buckling in compression members and in the discreteness of catalogue sections. A key finding is the different robustness of trends produced by the two profile-selection rules. Selecting profiles by minimum weight (while satisfying Eurocode 3) yields a smoother weight–height response and more coherent near-optimal solutions across spans and panel counts. This occurs because the minimum-weight rule typically moves between neighbouring sections within the same profile family, leading to smaller stiffness changes between iterations. Consequently, the coupled analysis–sizing loop stabilizes more reliably, which supports regression-based optimum identification.

In contrast, selecting profiles by maximum utilization can produce higher scatter and less stable optima, even though utilization-based selection is widely used in member sizing workflows. The underlying mechanism is most apparent in compression members. For tension members, utilization is closely linked to axial resistance and cross-sectional area, and therefore high utilization typically corresponds to an efficient use of material. For compression members, however, the governing resistance may be controlled by buckling rather than yielding, and buckling resistance depends strongly on section shape through stiffness and radius of gyration. Consequently, a high-utilization compression member may still be relatively heavy because it satisfies buckling through geometry rather than efficient mass distribution. In addition, utilization-based selection can encourage switching between different section families (for example between open and closed sections) because utilization does not inherently penalize mass. Such jumps may cause large changes in stiffness and force redistribution, which amplifies the sensitivity of the coupled iterations and contributes to the observed dispersion. From a methodological perspective, this supports the broader view in buckling-constrained optimization research that compression-member sizing requires dedicated handling, rather than applying the same selection logic used for tension members. In practical terms, weight-optimal sizing workflows should prioritize weight and limit unnecessary cross-family switching for compression-critical members, especially when results are used for regression-based generalization.

The study also demonstrates that the number of panels has a dual role in optimal solution identification: it governs both the absolute weight level and the predictability of response trends. Trusses with a small number of panels exhibit more irregular behaviour, and small geometric changes can lead to disproportionate changes in member angles and load paths. This effect makes low-panel configurations more sensitive to discrete profile updates, which is reflected in larger scatter of the optimal height-to-span ratios derived. As panel count increases, the larger number of members allows greater force redistribution, and the global response varies more smoothly with height and span. This makes the regression-based optimum identification more stable and the dependence of optimal h/L on span more clearly traceable within each panel-count group. This increased predictability comes at the cost of more members and greater total weight, so additional panels represent a trade-off between material demand and design robustness. This trade-off is important for early-stage design decisions, where the ability to predict near-optimal geometry reliably can be as valuable as minimizing mass strictly.

Figure 6

Weight and deflection trends with regression-optimum cases highlighted



Manufacturing-oriented constraints further shape this balance. When chord uniformity is enforced by assigning uniform upper- and lower-chord profiles along the span, the solution space becomes more restricted, and the structure carries larger reserves than the unconstrained optimum. This is reflected in reduced sensitivity and a narrowing of differences between sizing rules, because the uniform-chord

constraint drives the design away from locally efficient member-by-member solutions and reduces the attainable utilization level in parts of the structure. While such constraints increase weight, they also improve constructability and reflect common practice. For applications aimed at industry use, this underlines the importance of reporting not only theoretical optima but also optima under practical fabrication constraints, since these are the configurations that can be implemented without substantial redesign effort.

Several limitations frame the applicability of the presented trends. The analysis considered a single load case and neglected self-weight, which may shift the absolute optimum, especially for longer spans where self-weight makes up a larger share of the total load. Multiple load combinations would also be expected to reduce utilization levels and increase design reserves, which could dampen some of the sharpness of the identified optima and may reduce the contrast between sizing rules. At the same time, the adoption of Eurocode 3 checks and discrete catalogues is a deliberate choice that prioritizes practical relevance over idealized continuous-stress formulations. The design space was limited to common spans and planar configurations; beyond this range, alternative structural forms and spatial systems may become more competitive, especially when dense panel and bracing grids provide stiffness and load distribution with smaller overall depth. Extending the present approach to longer spans and spatial truss systems, testing sensitivity to material grade, and expanding the load cases are natural next steps before generalizing the regression relationships into design charts or predictive models.

From an application standpoint, the present findings provide two immediate implications. First, there is no universal ‘rule-of-thumb’ optimal h/L for all Pratt trusses; the optimum depends systematically on panel count and span, and this dependency remains visible across sizing approaches. Second, robust pre-design guidance is more likely from workflows that prioritize minimum-weight feasible catalogue selection and explicitly include constructability constraints rather than relying only on utilization maximization. With further generalization across load scenarios and material grades, the identified relationships can be converted into practical charts or regression-based equations to guide early-stage selection of near-optimal geometry and narrow the design space before detailed engineering.

Conclusions

1. The results confirm that optimal Pratt truss solutions are strongly influenced by the adopted member-sizing strategy, particularly for buckling-governed compression members. Catalogue selection based on minimum profile weight produces clearer trends and substantially lower scatter than selection based on maximum utilization, indicating that utilization-driven sizing can obscure systematic optimality patterns in discrete, buckling-controlled design.
2. Panel count is a primary factor governing both structural behaviour and the predictability of optimal solutions. The most irregular responses were observed for 4 and 6-panel trusses, while 8-panel trusses showed intermediate behaviour and the trends became clearly smoother from 10 panels onward. This improved predictability comes at the cost of increased member count and total weight.
3. The optimal height-to-span ratio is not a single universal value; within the investigated design space, the optimal h/L was approximately 0.10–0.23. The highest values occurred in short-span trusses with low panel counts, while the lowest values occurred in long-span trusses with high panel counts. Across the investigated sizing approaches, the same overall dependency on panel count and span was preserved, while the sizing approach mainly shifted the absolute level and dispersion of the optimal ratio.
4. Near-optimal cases occur close to a transition in structural response where increasing truss height yields diminishing stiffness benefits while total weight begins to increase due to compression-member sizing requirements. The alignment of optimal cases across spans suggests that, within the investigated design space, the identified relationships can support interpolation-based pre-design estimation of near-optimal Pratt truss geometry and response.

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COMPARISON OF A LATVIAN REGIONAL GNSS-BASED IONOSPHERE TIME SERIES WITH GLOBAL IONOSPHERE MAPS

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Abstract
The aim of this study is to evaluate the agreement and scale-dependent differences between a regional Latvian GNSS-based ionospheric time series and widely used Global Ionosphere Map (GIM) products. The regional model is derived from dual-frequency GPS and Galileo observations collected by a dense national Continuously Operating Reference Station (CORS) network, providing vertical total electron content (VTEC) estimates at ionospheric pierce point locations without spatial smoothing or regional averaging. Slant total electron content (STEC) is computed from carrier-phase geometry-free combinations using standard procedures, and converted to VTEC using a single-layer ionospheric approximation suitable for mid-latitude conditions. Short-term ionospheric variability is additionally characterized using the Rate of TEC Index (ROTI), derived consistently from the same observation set. This approach preserves both the dominant diurnal ionospheric behaviour and finer-scale temporal variability resolved by the dense observation network. An independent comparison is performed using GIM products from CODE, ESA, IGS, and JPL. These models are interpolated to the local ionospheric pierce point geometry, enabling direct comparison without additional calibration. The analysis is based on over one million matched data points and includes root-mean-square error, correlation metrics, and bias evaluation. Results indicate that global models capture the large-scale diurnal evolution of VTEC but significantly smooth short-term and regional variability. While correlations remain moderate to strong, systematic offsets and increased dispersion are observed, particularly during disturbed conditions. The findings highlight the importance of dense regional GNSS networks for capturing ionospheric variability at enhanced temporal and spatial resolution.
Keywords: GNSS observations, ionospheric modelling, TEC, GIM, CORS networks.

Introduction

The terrestrial ionosphere constitutes a variable and frequency-dependent propagation environment for Global Navigation Satellite System (GNSS) signals. Spatial and temporal variations in electron density introduce dispersive signal delays that directly affect GNSS observations and derived products (Hofmann-Wellenhof et al., 2007). Although dual-frequency GNSS techniques allow the dominant first-order ionospheric effect to be removed from positioning solutions, the ionosphere itself remains a highly dynamic geophysical medium whose behaviour cannot be fully described by simplified correction models. Consequently, the representation and interpretation of ionospheric total electron content (TEC) continue to play a key role in both geodetic and ionospheric research.

At the global level, ionospheric conditions are commonly described using Global Ionosphere Maps (GIMs), which provide gridded representations of vertical total electron content (VTEC) over the Earth's surface. These products are routinely generated in the IONEX format by the International GNSS Service (IGS) and its associated analysis centres and serve as a standard reference for a wide range of applications, including long-term climatological studies, model intercomparison, and validation of ionospheric correction approaches (Schaer et al., 1998). By construction, GIM products offer a consistent and globally homogeneous view of the ionosphere.

However, the global nature of GIMs inherently limits their spatial and temporal resolution. The combination of globally distributed input data, regular grid representations, and modelling constraints leads to a smoothed depiction of ionospheric structure (Hernandez-Pajares et al., 1997). While such smoothing is advantageous for capturing large-scale ionospheric behaviour, it may obscure short-term variations and regional-scale features that arise from localized drivers and rapidly evolving ionospheric processes.

This limitation is particularly relevant in mid-latitude regions, where the ionosphere is shaped by a combination of solar radiation, geomagnetic forcing, and thermospheric dynamics. In these regions, the ionospheric response is characterized by pronounced diurnal cycles, seasonal variability, and the occurrence of medium-scale disturbances, such as traveling ionospheric disturbances and localized gradients (Hernandez-Pajares et al., 2006; Emardson et al., 2013). Although such effects are generally less extreme than those observed in equatorial or auroral zones, they can still produce significant regional variability that may not be fully resolved by global models.

Recent advances in GNSS infrastructure have led to the deployment of dense Continuously Operating Reference Station (CORS) networks and to the routine availability of multi-constellation observations. These developments provide the opportunity to investigate ionospheric behaviour at spatial and temporal scales that extend beyond the resolving capability of global ionospheric maps (Otsuka et al., 2002). In particular, the combined use of GPS and Galileo dual-frequency measurements improves observation geometry and enables robust estimation of slant and vertical TEC at the level of

individual signal paths, provided that hardware-dependent biases and inter-system effects are handled consistently.

Within this context, regional GNSS-based ionospheric models offer a valuable complement to global products. Rather than replacing global ionospheric maps, such regional representations allow the examination of how locally derived TEC estimates relate to globally modelled ionospheric fields and to what extent regional observations capture variability that is smoothed in global products. This perspective is especially relevant for regions with dense GNSS coverage, where observation geometry supports high temporal and spatial resolution.

The present study introduces a regional GNSS-based ionospheric representation developed for Latvia and investigates its relationship with established Global Ionosphere Map products. Slant TEC is derived from carrier-phase observations using standard bias handling and phase leveling procedures and is subsequently mapped to vertical TEC using a single-layer ionospheric approximation suitable for mid-latitude conditions. Short-term ionospheric variability is described using the Rate of TEC Index (ROTI), derived consistently from the same observation set.

A systematic comparison is performed using multiple GIM products generated by different IGS analysis centres, including CODE, ESA, IGS, and JPL. Global maps are interpolated in space and time to the ionospheric pierce point geometry of the regional GNSS observations, enabling a direct comparison without calibration or bias alignment. A representative Latvian CORS station is used to illustrate differences in temporal behaviour and variability between regional and global ionospheric representations.

The aim of this study is to evaluate the agreement and scale-dependent differences between a regional Latvian GNSS-based ionospheric time series and widely used Global Ionosphere Map (GIM) products generated by different IGS analysis centres. To achieve this aim, the following tasks were defined: (1) to derive a regional VTEC time series from dual-frequency GPS and Galileo observations collected by the Latvian CORS network; (2) to interpolate selected GIM products (CODE, ESA, IGS and JPL) to the local ionospheric pierce point geometry; (3) to compare regional and global VTEC estimates using statistical indicators including bias, RMSE and correlation; and (4) to assess the ability of global models to represent regional and short-term ionospheric variability.

Materials and Methods

Regional GNSS observation environment

The regional ionospheric model analysed in this study is based on observations from the Latvian national CORS network. The network offers dense and spatially well-distributed GNSS coverage across the territory of Latvia, providing favourable conditions for the investigation of ionospheric variability at regional scales. The typical inter-station spacing is sufficiently small to sample ionospheric conditions with a spatial resolution that exceeds that of global ionospheric products.

GNSS observation data are available in RINEX version 3.04 and include dual-frequency measurements from the GPS and Galileo constellations. The data set comprises carrier-phase and pseudorange observations, together with the auxiliary information required for satellite geometry reconstruction. Observations are sampled at a 1 second interval, allowing the analysis of both longer-term ionospheric evolution and short-term temporal variability. Receiver coordinates are extracted from the RINEX headers and are assumed to remain constant throughout each daily observation session.

The use of a multi-constellation data set enhances ionospheric sampling and reduces dependence on individual satellite geometries. At the same time, it introduces additional complexity related to inter-system biases and constellation-specific characteristics. These aspects are addressed during the modelling procedure and do not affect the definition of the observational environment described here.

Latvia is located in the mid-latitude region of Northern Europe, where ionospheric behaviour is primarily governed by solar radiation, geomagnetic activity, and thermospheric dynamics. Over this region, the ionosphere typically exhibits a pronounced diurnal cycle, clear seasonal variability, and moderate short-term disturbances. Although extreme ionospheric phenomena associated with equatorial or auroral processes are generally absent, mid-latitude structures such as travelling ionospheric disturbances and localized gradients occur regularly (Hernandez-Pajares et al., 2006; Emardson et al., 2013).

From a modelling perspective, the Latvian region represents an intermediate test environment in which global ionospheric models are expected to capture the dominant large-scale behaviour of TEC, while finer-scale and short-term variations may remain unresolved. This makes the region particularly suitable for comparative analysis between global ionospheric maps and regional GNSS-based ionospheric representations.

Representative station selection

To illustrate the characteristics of the regional ionospheric model and to facilitate a transparent comparison with global products, results from the CORS station Aizpute (AIZP) are examined in detail. This station is representative of the Latvian network with respect to data continuity, receiver performance, and geographical setting. Its location sufficiently far from the network boundaries reduces potential edge effects in regional analyses.

Time series derived from AIZP are used as a reference example in the results section to demonstrate the temporal evolution of VTEC, the presence of short-term variability, and systematic differences between locally derived ionospheric estimates and global ionospheric products. While AIZP is employed for illustrative purposes, the regional ionospheric model itself is based on observations from the full CORS network.

TEC estimation methodology

The estimation of ionospheric TEC from GNSS observations exploits the dispersive nature of the ionosphere, whereby signal delays depend on the transmitted frequency. Dual-frequency carrier-phase measurements from GPS and Galileo provide a highly sensitive means of isolating the ionospheric contribution to signal propagation, independent of geometric range and clock effects (Hofmann-Wellenhof et al., 2007).

In this study, ionospheric information is extracted using the geometry-free combination of carrier-phase observables. This combination eliminates non-dispersive terms common to both frequencies and retains the frequency-dependent ionospheric delay, making it well suited for TEC estimation (Ciraolo, 2007). The geometry-free carrier-phase combination is expressed as Equation (1):

$$L_{GF} = \lambda_1 \Phi_1 - \lambda_2 \Phi_2 \qquad (1)$$

where Φ_1 and Φ_2 denote the carrier-phase observations at frequencies f_1 and f_2, respectively, and λ_i are the corresponding signal wavelengths. The resulting observable is directly proportional to the slant total electron content (STEC) along the satellite–receiver line of sight, as given in Equation (2):

$$STEC = \frac{f_1^2 f_2^2}{40.3\left(f_1^2 - f_2^2\right)} L_{GF} \qquad (2)$$

Carrier-phase observations are preferred over code measurements due to their superior precision, which is essential for resolving subtle ionospheric variations at short temporal scales.

Despite their low noise characteristics, carrier-phase measurements are affected by unknown phase ambiguities and hardware-dependent biases. To ensure physically consistent TEC estimates, satellite-specific observable biases are applied prior to TEC computation, and receiver-dependent biases are estimated from the data using robust statistical approaches (Su et al., 2021). To preserve the precision of carrier-phase-derived STEC while maintaining consistency with code-based observables, phase leveling is applied over continuous observation arcs, as described by Equation (3):

$$STEC_{lev} = STEC_{\phi} + \Delta_{bias} \qquad (3)$$

For comparison with global ionospheric products, slant TEC estimates are mapped to vertical TEC using a single-layer ionospheric approximation, as defined in Equation (4), with an effective shell height of 450 km (Li et al., 2020). The elevation-dependent mapping function is given in Equation (5):

$$VTEC = STEC \cdot M^{-1}(e) \qquad (4)$$

$$M(e) = \left(1 - \left(\frac{R_E cose}{R_E + H_{ion}}\right)^2\right)^{-\frac{1}{2}} \qquad (5)$$

Vertical TEC estimates are associated with ionospheric pierce point (IPP) locations. No spatial gridding or averaging is applied, which allows a direct comparison with global ionospheric products after interpolation. Short-term ionospheric variability is characterised using the Rate of TEC Index (ROTI) (Wanninger, 2004; Cherniak et al., 2014).

Validation and comparison framework

Independent validation is performed using GIM products generated by several IGS analysis centers, including CODE, ESA, IGS, and JPL. These products are distributed in the IONEX format and represent global VTEC fields on regular latitude–longitude grids (Schaer et al., 1998; Garcia-Rigo et al., 2011).

GIM-based VTEC values are interpolated spatially and temporally to the IPP locations and observation epochs of the regional GNSS data. Differences between regional and global VTEC estimates are evaluated using standard statistical metrics, including mean bias, root-mean-square error, mean absolute error, and the Pearson correlation coefficient. Aggregation over large data volumes ensures the statistical robustness of the comparison.

Results and Discussion

Temporal behaviour of regional VTEC

The regional GNSS-based ionospheric model yields continuous VTEC time series at ionospheric pierce point (IPP) locations for all stations within the Latvian CORS network. At the individual station level, the derived VTEC values exhibit a well-defined and physically plausible diurnal pattern, characterised by low nighttime levels and a pronounced daytime enhancement associated with solar-driven ionisation processes.

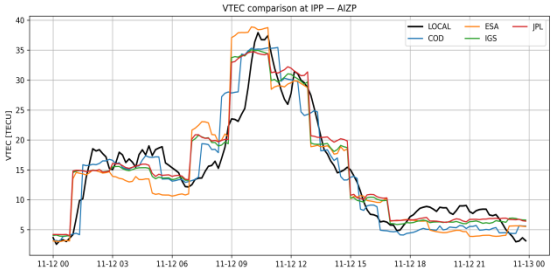
Figure 1 illustrates the temporal evolution of VTEC at the representative station AIZP. The locally derived VTEC time series captures the dominant large-scale diurnal behaviour while simultaneously resolving short-term temporal variations. The absence of discontinuities or step-like features indicates that bias handling and phase-levelling procedures provide a stable and internally consistent reference for absolute TEC estimation over extended observation periods.

Comparison with Global Ionosphere Map products

The regional VTEC estimates are compared with GIM products from CODE, ESA, IGS, and JPL

following spatial and temporal interpolation of the global models to the IPP geometry of the regional observations. All considered global products successfully reproduce the dominant diurnal variation observed in the regional model, demonstrating overall consistency at broad spatial and temporal scales.

Figure 1
Comparison of locally derived VTEC and Global Ionosphere Map products (CODE, ESA, IGS, JPL) at the ionospheric pierce point for CORS station AIZP

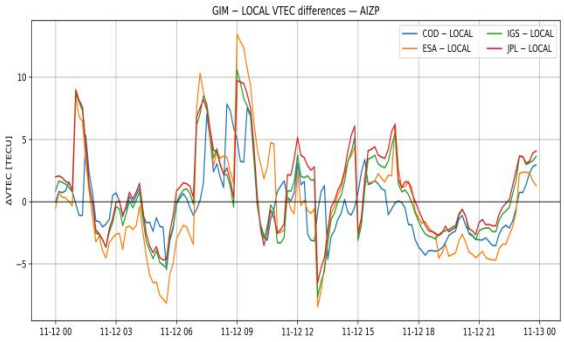


At the same time, systematic differences between the regional and global representations are evident throughout the day. In particular, the GIM-based time series display markedly smoother temporal behaviour, especially during intervals characterised by rapid VTEC changes. This behaviour reflects the coarser spatial resolution and limited temporal sampling inherent to global ionospheric products and contrasts with the higher-frequency variability resolved by the dense regional GNSS network.

VTEC differences and distribution characteristics

Differences between GIM-derived VTEC and locally estimated VTEC are computed at the individual observation level and analysed over the full observation period. Figure 2 illustrates the statistical differences between GIM-derived and locally estimated VTEC at station AIZP. The resulting distributions reveal persistent offsets between the regional model and each global product, together with an increase in dispersion during periods of enhanced ionospheric variability.

Figure 2
Statistical differences between GIM-based and locally derived VTEC for CORS station AIZP



Although the magnitude and sign of the bias differ slightly among the individual GIM products, the overall structure of the differences remains similar. This consistency suggests that the observed discrepancies primarily reflect differences in spatial and temporal resolution rather than shortcomings specific to any single global ionospheric model.

Statistical assessment of model agreement

Quantitative metrics summarising the agreement between the regional VTEC estimates and the four GIM products are presented in Table 1. The table reports the root-mean-square error (RMSE), the Pearson correlation coefficient r, and sample size.

Table 1
Statistical comparison between the regional VTEC model and selected Global Ionosphere Map (GIM) products at station AIZP

Model	RMSE (TECU)	r	N
CODE	12.722	0.570	1096,923
ESA	13.319	0.542	1096,923
IGS	13.109	0.556	1096,923
JPL	13.360	0.555	1096,923

All global products exhibit a negative mean bias with respect to the regional model, indicating systematically lower VTEC values in the GIM solutions. Correlation coefficients exceed 0.54 for all products, pointing to good temporal agreement at large scales. Nevertheless, the RMSE values highlight the magnitude of residual differences associated with ionospheric structures that are not fully resolved by global models.

Resolution-dependent effects

The comparative analysis reveals a clear scale-dependent separation between regional and global ionospheric representations. While global models provide a reliable depiction of the background ionospheric state and its diurnal evolution, the regional GNSS-based model resolves additional variability at shorter temporal and spatial scales.

These results indicate that differences between regional and global VTEC estimates should not be interpreted as modelling errors in a strict sense. Rather, they reflect the inherent trade-off between global coverage and model resolution. Dense regional GNSS observations therefore provide complementary information that is not fully captured by globally smoothed ionospheric products.

Conclusions

1. The aim of the study was achieved through observation-level comparison of a regional Latvian GNSS-derived VTEC time series with four Global Ionosphere Map products and assessment of their statistical agreement and scale-dependent differences.
2. The results show that global ionospheric models reliably reproduce the large-scale diurnal evolution of vertical total electron content, whereas regional GNSS observations capture additional short-term and regional-scale variability.

3. Consistent systematic differences between regional and global VTEC estimates were identified for all analysed GIM products, indicating resolution-dependent smoothing effects rather than deficiencies in individual global models.
4. Statistical evaluation based on more than one million matched observations demonstrated moderate to strong temporal agreement between regional and global ionospheric representations, together with residual differences linked to unresolved regional ionospheric structures.
5. The findings underline the complementary nature of regional GNSS-based ionospheric modelling and global ionospheric products and confirm the importance of dense regional GNSS networks for applications requiring enhanced temporal and spatial resolution of ionospheric behaviour.

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APPLICATION OF THE LBTU METHOD FOR DEFORMATION MONITORING OF A TUNNEL DURING CONSTRUCTION

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Abstract
In modern construction practice, deformation monitoring is applied as a form of quality control for construction works. Such monitoring is important not only after a structure has been commissioned, but also during the actual process of structural erection. One of the methods used for this purpose is the LBTU (laser-based tracking utilisation) method, which is based on distance measurements performed using a laser rangefinder. Depending on the measuring equipment employed, deformations can be recorded with an accuracy of approximately 1–2 mm. During the construction of bridges and tunnels, backfilling operations are almost always required. When soil is compacted, the weight and pressure of the fill material induce stresses within the structural elements of the infrastructure facility. Furthermore, the process of layered soil placement during construction often imposes greater loads on the structure than the static soil pressure acting during the operational phase. Backfilling operations involve the use of heavy machinery, which generates dynamic loads. Water is also applied to increase soil density during compaction, further intensifying these effects. As a result, construction-stage loads frequently exceed those experienced during exploitation. For this reason, deformation monitoring during construction represents an effective quality control strategy and a safety tool for contractors. The application of the LBTU method during tunnel backfilling at a construction site in Riga demonstrated the practicality of the method and the reliability of the obtained data. Such monitoring does not significantly increase construction costs, yet it can improve quality and prevent critical overloads and structural deformations caused by human factor.
Keywords: deformation monitoring, LBTU method, rangefinder, tunnel backfilling.

Introduction

During the construction of infrastructure facilities, monitoring of structural deformations during earthworks represents a critical aspect of ensuring structural safety and performance. One of the most sensitive stages of construction is the backfilling process, during which the structure is subjected to both permanent and temporary loads associated with construction activities. Improper sequencing of operations or localised concentration of loads may lead to undesirable deformations that can affect the structural behaviour and long-term serviceability of the facility.

In recent years, increasing attention within the construction industry has been directed towards operational monitoring techniques capable of detecting geometric changes in structural elements in near real time and enabling the early identification of potentially hazardous deformation trends (Wang et al., 2024). This task becomes particularly relevant in the case of lightweight engineering solutions, such as tunnels incorporating corrugated steel shells, where structural performance is strongly influenced by the interaction between the structure and the surrounding soil during the backfilling process.

One practical approach to addressing this challenge involves the application of simple and cost-effective instrumental monitoring methods capable of providing sufficient measurement accuracy while maintaining low implementation costs. The use of laser distance meters for deformation monitoring represents one such method, allowing efficient and continuous acquisition of geometric data directly on the construction site.

The object of observation is a tunnel constructed from a combination of materials: a reinforced concrete base and walls, together with a corrugated metal roof. The roof has been intentionally designed with a curved profile and stiffening ribs in order to increase its load-bearing capacity while using a minimal amount of material. This engineering solution was selected due to the relatively shallow groundwater conditions at the site. In order to accommodate the tunnel within the limited space between the roadway and the groundwater level, it was necessary to minimise the height of the embankment above the tunnel roof.

A corrugated steel roof effectively distributes loads without significant deformation and allows a reduction in the thickness of the backfill layer beneath the roadway.

In engineering geodetic practice, both classical surveying methods and modern automated monitoring systems are employed for deformation monitoring (Wulf Schubert et al., 2002). The most commonly used approaches include high-precision total station measurements, levelling, GNSS observations, inclinometer monitoring, as well as various sensor-based systems utilised within structural health monitoring frameworks. The selection of an appropriate method depends on the required accuracy, site conditions, the feasibility of measurement automation, and economic considerations. For structures under construction, particular importance is given to methods that can be rapidly deployed, do not require highly specialised personnel, and enable high-frequency data acquisition in near real-time conditions (Ma et al., 2023).

The aim of this study is to analyse the deformation behaviour of a tunnel structure during the backfilling stage and to evaluate the effectiveness of laser-based distance measurements for operational monitoring of geometric changes under construction site conditions.

Materials and Methods

The tunnel backfilling process was carried out in two stages. The first stage proceeded up to the elevation at

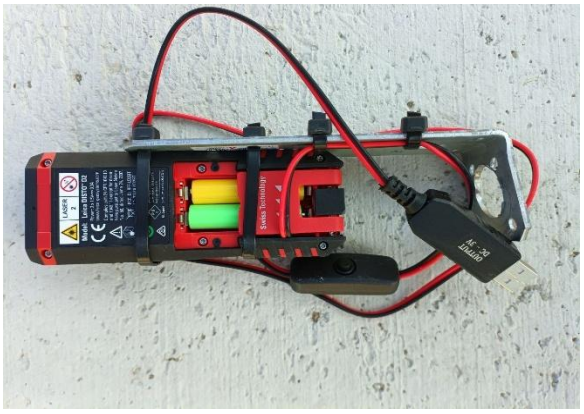
which the reinforced concrete structure terminates and transitions into the steel roof. Consequently, the laser rangefinders were installed at the maximum backfill level corresponding to the completion of the first stage. The second stage of backfilling was scheduled to be undertaken at a later date following the completion of other construction activities. During this stage, the laser sensors are intended to be relocated to the tunnel roof along the tunnel centreline, where the greatest structural deformations are anticipated to occur.
At the time of writing, measurements from the second stage monitoring campaign are not yet available and are therefore excluded from the present analysis. This is justified by the fact that the primary objective of this study is not the assessment of tunnel deformations themselves, but rather the evaluation and demonstration of the Laser-Based Tracking Utilisation (LBTU) methodology as a deformation monitoring technique.

Figure 1
Backfilling of the tunnel



Backfilling of the tunnel must be carried out sequentially. The designer calculated the loads exerted by the soil on the tunnel structure and specified that the backfilling process should be performed in stages, alternately loading one side of the tunnel and then the other. The soil is placed and compacted in layers of approximately 0.5-meter thickness, backfilling process is shown in Figure 1.
Soil represents a static load exerting continuous pressure on the structure, whereas construction equipment used by the contractor such as excavators, rollers, and compactors constitutes a dynamic load (Singh & Mandal, 2019). As this machinery moves across the site, it may create localised concentrations of force that can affect the structural behaviour of the tunnel. Additional loading is introduced by water used during soil compaction. Although this load is temporary and will disappear after construction works are completed, it represents a significant additional factor influencing structural deformation during the construction phase.
In order to record and monitor structural deformations of the tunnel, the LBTU method was selected due to its simplicity of use and low implementation cost. The method is based on distance measurements obtained using a laser rangefinder. Such instruments are widely known and readily available to construction professionals worldwide. More advanced models provide wireless connectivity to a computer and programmable settings that allow the instrument to operate in an automated measurement mode.
The laser distance meter Leica DISTO D2 was employed as the primary measurement instrument, with technical characteristics suitable for monitoring small-scale deformations in construction applications. According to the manufacturer's specifications, the device provides a measurement accuracy of ±1.5 mm and an operating range of up to 100 m, and supports data transmission via bluetooth, enabling its integration into an automated data acquisition system (Product Data Sheet Leica DISTOTM D2, n.d.)

Figure 2
Laser rangefinder equipped with an alternative power supply system



In the present study of tunnel deformation monitoring, two identical laser distance meters were used. This model is well suited for automated monitoring and large-volume data acquisition due to the possibility of connecting the device to a laptop computer and collecting measurements continuously throughout the working day. Figure 2 shows how each distance meter was modified to operate from an external power supply in order to enable extended autonomous operation and was equipped with a mounting system.
One of the principal limitations of the proposed monitoring system is associated with the current capabilities of the manufacturer software. At present, the software does not support the simultaneous connection of multiple laser rangefinders to a single computer, nor does it provide integration with a central communication hub capable of transmitting measurement data to a remote server via the internet.
As a consequence, two separate laptop computers equipped with independent bluetooth communication modules were required to operate the two laser rangefinders used in this study. Under the current system architecture, scaling the monitoring network to

ten sensors would necessitate the use of ten individual computers, which would be both impractical and economically inefficient.

Future software development could substantially improve the scalability of the method. In particular, the ability to connect multiple laser rangefinders to a single computer or to a dedicated data acquisition hub would significantly simplify system deployment and operation. Such an enhancement would enable the method to be readily applied to larger monitoring networks and would broaden its potential application to large-scale civil engineering and infrastructure projects.

Figure 3

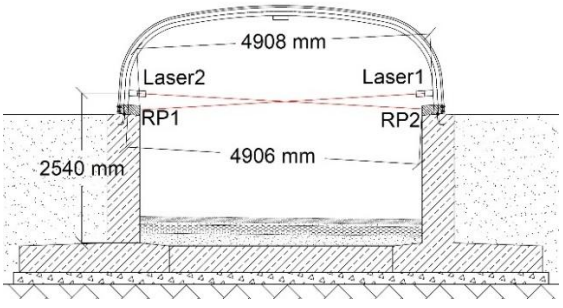
Rangefinder installed on the tunnel and modified for external power supply



Using a bolted mounting assembly, the laser rangefinder was securely installed on the tunnel structure, as shown in Figure 3. A schematic representation of the laser sensor arrangement is provided in Figure 4, illustrating the locations of the monitoring instruments within the tunnel structure.

Figure 4

Layout of the control points and laser distance meters



The laser rangefinders were calibrated and certified by an accredited metrological laboratory prior to their deployment in the monitoring programme. This procedure was undertaken to ensure the reliability and traceability of the measurements, as well as to verify that the measurement uncertainty specified by the manufacturer corresponded to the actual performance characteristics of the instruments.

To establish the initial reference point for deformation monitoring, baseline measurements from the distance meters were recorded under static conditions prior to the commencement of backfilling works. As the intensity of construction activity was relatively low, the automatic measurement interval was set to one measurement per minute.

During the tunnel backfilling operations, continuous monitoring of structural deformations was carried out using two laser distance meters installed in accordance with the arrangement shown in Figure 5. Measurements were performed automatically at one-minute intervals throughout the entire duration of the backfilling works.

Initial distance values were recorded prior to the commencement of backfilling, when the structure was in a stable, unloaded condition. The average baseline distance was 4,909 meters for measurement point RP1 and 4,908 meters for measurement point RP2.

Results and Discussion

The proposed method combines the principles of conventional deformation monitoring techniques, such as tape-based distance measurements and precise levelling, with automated surveying technologies, including electronic total stations and robotic total stations (Ma et al., 2023; Wang et al., 2024). This integration enables continuous or semi-continuous monitoring while reducing the amount of on-site time required from surveyors and engineering personnel.

According to the manufacturer technical documentation, the steel roof structure of the tunnel is permitted to undergo a maximum vertical settlement of up to 30 mm. In contrast, the reinforced concrete structure is designed, in accordance with the project specifications, to experience a maximum horizontal displacement not exceeding 10 mm.

The deformations recorded in this study represent changes in the distance between the two opposing walls of the tunnel. Consequently, the maximum measured deformation corresponds to the combined displacement of both walls. In order to determine the individual contribution of each wall to the observed deformation, independent reference points would be required. Such reference points should be established on stable surfaces that are not mechanically connected to the monitored structure, for example, separately installed reinforcement-bar benchmarks driven into the surrounding ground or other stable reference objects located in the vicinity of the tunnel.

In the present case, the installation of independent reference points was not considered necessary, as the total measured deformation remained within the permissible design limits.

During the backfilling process, gradual changes in the measured distances were observed, indicating deformation of the structure under the increasing load imposed by the surrounding soil. The maximum change in distance recorded during the monitoring period was 8 mm, corresponding to compression of the

structure under soil pressure. This value was consistent with the design calculations and did not raise structural safety concerns. The maximum deformation was registered at the moment when the backfill height reached the transition zone between the concrete structure and the corrugated steel roof. This location is marked in red in Figure 5.

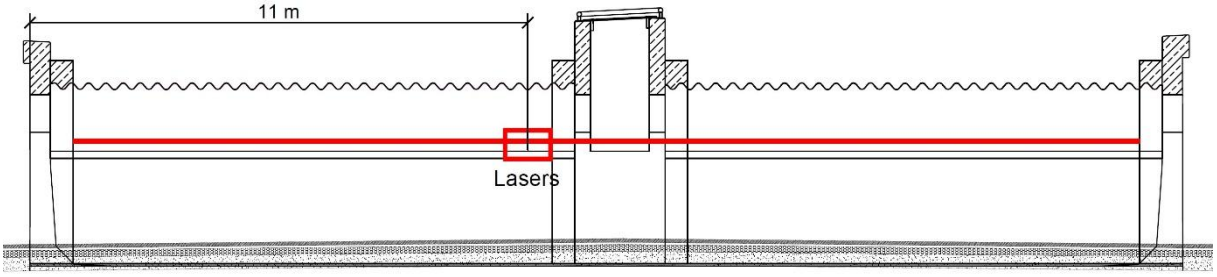
Figure 6 presents the time-dependent variation of the measured distances. The results demonstrate that deformation increased progressively with both the height of the backfill and the elapsed time since the beginning of backfilling works. The two curves also indicate different deformation rates at measurement points RP1 and RP2. Their comparison reflects the sequential nature of the backfilling process, with the deformation peak occurring first on the RP2 side.

As the laser rangefinders were not installed perpendicular to the tunnel walls and were not positioned with high-precision alignment, a discrepancy exists between the absolute distance measurements obtained from the two instruments. This discrepancy is not considered significant for the purposes of the present study, and a higher level of installation accuracy was not required.

The monitoring approach is based on the analysis of relative changes in the measurements rather than on the absolute distance values. Consequently, the deformation assessment relies on the difference between the initial baseline measurement and subsequent measurements recorded by the same laser rangefinder at the same location throughout the monitoring period.

Figure 5

The soil level (red line) at which the maximum deformation was reached



A comparison of the measured results with the calculated values specified in the design documentation showed that the maximum recorded deformation of 8 mm remained within the permissible limits. This confirms the adequacy of the selected backfilling procedure and the sufficient structural stiffness of the tunnel system.

The graph in Figure 6 clearly illustrates the deformation behaviour of the structure during the backfilling process. Noticeable fluctuations are observed in the range of measurements 60–97, which are most likely associated with temperature-induced effects within the structure. The laser distance meters were activated prior to the commencement of construction works, at approximately 09:00, and therefore the influence of solar radiation during sunrise may have contributed to additional thermal deformations during the monitoring period. Such effects are considered normal and, in this case, further demonstrate the sensitivity and reliability of the applied deformation monitoring method.

Furthermore, a comparison of the two trends obtained from the separate distance meters allows identification of the sequence of backfilling on different sides of the tunnel. Although this observation is not critical for structural assessment, it provides additional insight into the structural response and behaviour during construction. This represents a further advantage of the applied monitoring approach, enhancing its informational value for practical engineering applications.

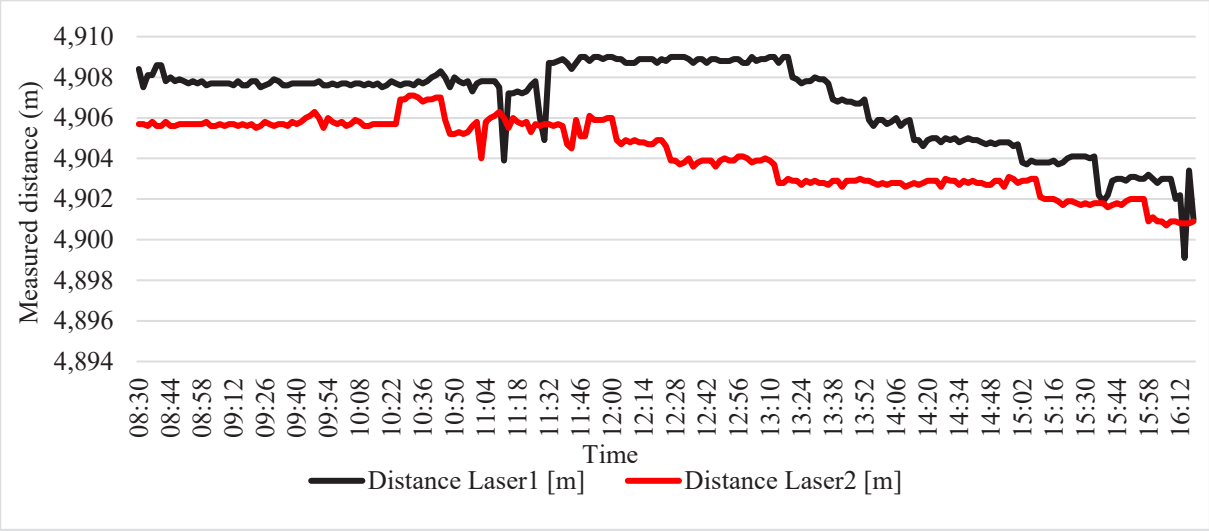
Given the relatively low cost of such devices, they can be deployed in large numbers across the monitored structure, enabling the acquisition of dense measurement data (Yang & Xu, 2021). This allows the reconstruction of a three-dimensional model of the structural behaviour under the influence of external dynamic factors during the construction process.

Despite the practical effectiveness of the proposed method, the use of laser distance meters in construction monitoring is subject to several limitations (Ma et al., 2023). The method requires an unobstructed line of sight between the instrument and the monitored point, is sensitive to changes in the position of the mounting system, and may be influenced by external factors, including vibrations and variations in ambient temperature. Under conditions typical of an active construction site, this necessitates maintaining instrument stability and carefully interpreting of short-term fluctuations in the recorded data. Such fluctuations are not always attributable solely to actual structural deformations and may instead result from external disturbances, for example when a person passes through and temporarily interrupts the laser beam during measurement.

The practical value of the proposed approach lies in its applicability not only to tunnel monitoring, but also to other infrastructure facilities that are sensitive to

deformation during construction. A similar monitoring scheme may be employed in the construction of bridges, retaining walls, and other engineering structures where prompt detection of geometric changes and control of structural response to external actions are required. In this context, the use of simple laser measurement devices may be considered a cost-effective solution for local construction monitoring, particularly in cases where the application of more complex systems is not justified.

Figure 6
Changes in the distance between tunnel walls



Conclusions

1. The application of the LBTU method during tunnel backfilling demonstrated its potential as a practical tool for monitoring geometric changes in structures during construction activities.
2. The measurement accuracy specified by the manufacturer (±1.5 mm) was sufficient to identify deformation trends and relative changes in the monitored structure during the observation period.
3. Due to its accessibility, low cost, and ease of deployment, the LBTU method may be applied at various stages of infrastructure construction projects requiring operational deformation monitoring.
4. The use of wireless laser distance meters enables the development of automated monitoring systems. Further software improvements allowing the integration of multiple sensors into a single data acquisition platform could increase the applicability of the method for larger monitoring networks (Ma et al., 2023).
5. The maximum tunnel convergence recorded during the backfilling process was 8 mm, which remained below the maximum permissible deformation limit of 10 mm specified for the reinforced concrete section of the structure.
6. The recorded measurements indicate that the method is capable of detecting not only deformation associated with construction loading but also short-term variations that may be related to thermal effects within the structure.

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STRATEGIC IMPLEMENTATION OF CIRCULAR MODULAR CONSTRUCTION IN INDIAN REAL ESTATE DEVELOPMENT

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Abstract
The construction industry is a major user of natural resources and a significant generator of construction and demolition (CDW) waste, particularly in fast-growing, urbanizing economies such as India. The linear approach to construction leads to excessive resource use and a larger environmental footprint. Circular modular construction (CMC) combines off-site modular production with on-site assembly, incorporating circular economy principles such as design for disassembly, material reusability, and lifecycle resource efficiency. Adoption of CMC in India's real estate sector remains constrained by supply chain fragmentation, high upfront capital investment, skilled labour shortages, and regulatory uncertainties. This study develops a context-specific strategic framework that embeds circular economy principles within India's regulatory, cultural, and supply chain realities. A mixed-methods approach combines semi-structured expert interviews and qualitative case studies with a quantitative survey of 100 construction and real estate professionals, validated through an India-specific project simulation modelling CMC adoption under varying conditions. The framework covers strategic alignment, supply chain integration, technological readiness, lifecycle management, and enabling governance and digital systems. Key findings identify high capital costs and supply chain constraints as primary barriers, while organization's with greater technological readiness demonstrate stronger implementation capacity. The proposed framework shows that CMC can significantly improve project efficiency, reduce lifecycle costs, and enhance environmental sustainability in India's construction sector.
Keywords: circular economy, circular modular construction, India, real estate development, sustainability.

Introduction

India has been experiencing rapid urbanization and infrastructure development, resulting in significant strain on the built environment. The pressure on residential and commercial real estate development continues to mount. The construction industry plays a vital role in the national economy by creating jobs and investing in capital (Lalawmpuii & Paul, 2024). This growth has exacerbated environmental issues such as increased greenhouse gas (GHG) emissions, construction and demolition waste, and inefficient use of materials (Construction Times India, 2025; Weerakoon et al., 2025a), highlighting the urgent need for sustainable building practices. The circular economy (CE) has emerged as a transformative paradigm for improving sustainability in the construction sector. Its principles emphasize resource efficiency, long material cycles, waste reduction, and regenerative design (Movaffaghi & Yitmen, 2023). Features of circular approaches in construction include design for disassembly, modular standardization, material traceability, and reverse logistics frameworks that support reuse of building components throughout their lifecycle (Jayawardana et al., 2023; Ding et al., 2023). Modular construction offers a practical method to apply CE principles, enabling prefabrication of standardized elements off-site in controlled factory environments and assembling them on-site. This approach improves quality, shortens project durations, and reduces waste materials (Ghannad et al., 2020). Empirical evidence suggests that modular construction is more productive and environmentally friendly compared to traditional methods (Jayawardana et al., 2023). The integration of CE principles within modular construction in Indian real estate remains underdeveloped despite its numerous benefits. Obstacles include discontinuous supply chains, a lack of technical skills, financial risks, and regulatory uncertainties (Zvirgzdins et al., 2025). Existing literature primarily treats CE strategies and modular construction as separate domains, offering limited insight into their potential combination for effective operation in emerging economies such as India. In addition to technological and material innovations, decision support tools play an increasingly important role in advancing sustainable construction practices (Weerakoon et al., 2025b). The complexity of construction projects requires stakeholders to evaluate multiple criteria simultaneously, including economic feasibility, environmental performance, resource efficiency, and project risks. Decision support systems and analytical frameworks enable planners, developers, and policymakers to systematically analyse these competing factors and identify optimal strategies for sustainable development (Senaratna & Šliogerienė, 2025). Such tools are particularly valuable in emerging approaches like circular modular construction, where decisions regarding design strategies, supply chain integration, material lifecycle management, and policy alignment must be assessed holistically to ensure effective implementation and long-term sustainability outcomes.

To address the identified research gap, this study investigates the factors contributing to the success of circular modular construction in the Indian real estate industry. The study identifies key drivers and inhibitors, explores how CE principles can be incorporated into modular systems, and proposes a strategic framework to promote broader adoption. A mixed-method approach comprising expert interviews, industry surveys, case studies, and project-based analysis was employed to develop actionable strategies to advance circular modular construction in India.

This study is guided by the following research

questions: (RQ1) What are the main drivers and barriers affecting the adoption of circular modular construction (CMC) in India's real estate sector? (RQ2) How can principles of the circular economy be effectively integrated into modular construction systems within the Indian context? (RQ3) What components of a strategic framework are necessary to facilitate scalable and sustainable CMC implementation? Based on these questions, the following hypotheses are proposed: (H1) Supply chain constraints and high initial capital requirements are the main barriers to CMC adoption in India; (H2) Organisations with higher levels of technological readiness and governance support are more likely to successfully implement CMC; (H3) A structured strategic framework that includes lifecycle management, digital systems, and regulatory alignment will significantly improve CMC adoption outcomes. The scope of this study is limited to the Indian real estate development sector and draws on empirical evidence from construction professionals, expert interviews, and project-based case analyses. The rest of this paper is structured as follows. The Literature Review section examines the relevant scientific literature. Research Methodology section outlines the methodological approach adopted in this study. Results and Discussion section presents and interprets the findings. The Conclusions section highlights main outcomes of this study, offers recommendations and suggests directions for future research.

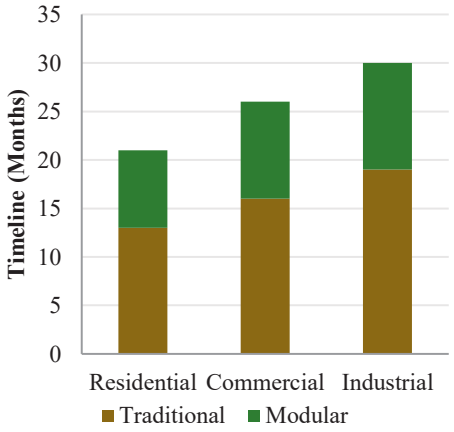
The concept of the CE has become essential for addressing issues such as resource depletion, environmental damage, and construction waste in the built environment (Zvirgzdins et al., 2019). Its foundational principles focus on efficient resource use, material reuse and recycling, and the preservation of life cycle values, from building disassembly and material traceability to reverse logistics throughout the life cycle of buildings (Movaffaghi & Yitmen, 2023). Implementing CE principles can significantly reduce embodied carbon emissions and construction waste while improving resource efficiency (Jayawardana et al., 2023). Circular waste reduction frameworks are available, such as the 3R and 6R models, with the 6R model adding refuse, rethink, and replace to the 3R model. Adopting these into mainstream construction, can offer a strong opportunity to align industry operations with national sustainability targets (Alotaibi et al., 2024). The shift from linear towards circular approaches in construction needs to be systemic and involves coordinated efforts across industry stakeholders, policy, and regulation (Ding et al., 2023). Policy instruments have become key enablers for bringing circular principles into national construction standards, including extended producer responsibility, green public procurement, and material passports (Dziedzic et al., 2024). These circular strategies are shown in the hierarchy in Figure 1 (Dung & Hong, 2021).

Figure 1
6Rs of Circular Economy (developed by the authors, based on Dung & Hong, 2021)



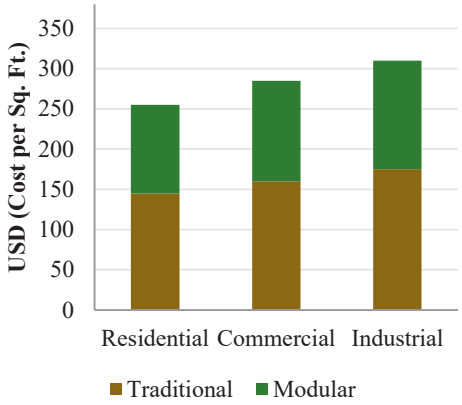
The modular construction method is more productive, offers better quality control and ensures schedule reliability compared to traditional construction methods (Ghannad et al., 2020). Figure 2 illustrates the reduction in project duration due to modular construction (Gómez & Sánchez, 2024).

Figure 2
Timeline Comparison between Modular and Traditional Construction (developed by the authors, based on Gómez & Sánchez, 2024)



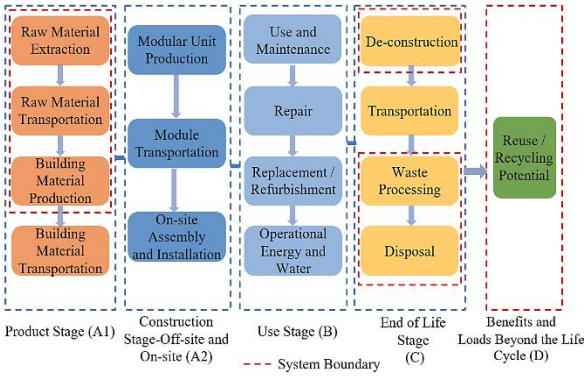
The integrated adoption of circular economy principles with modular construction remains limited across India's real estate sector (Dewagoda et al., 2024). Modular construction as a standalone approach is increasingly common in India's affordable housing and institutional infrastructure sectors. Supported by government initiatives such as the Smart Cities Mission and Pradhan Mantri Avas Yojana, its growth is driven by its scale (Lalawmpuii & Paul, 2024; Grand View Research, 2023). These economic advantages, including improved cost predictability, are shown in Figure 3 (Gómez & Sánchez 2024).

Figure 3
Cost Comparison between Modular and Traditional Construction (developed by the authors, based on Gómez & Sánchez, 2024)



Modular construction presents significant economic, environmental, and social benefits. Factory-based manufacturing minimizes workplace hazards, provides stable jobs, and supports local communities (Ferdous et al., 2019; Arif et al., 2012). Additionally, predictable schedules reduce community disturbance, and strict quality standards improve occupant comfort. In a circular economy context, these advantages are further enhanced since modules can be reused through multiple life cycles, as shown in Figure 4 (Jayawardana et al., 2023).

Figure 4
Circular Economy Framework Applied to Modular Construction (developed by the authors, based on Jayawardana et al., 2023)

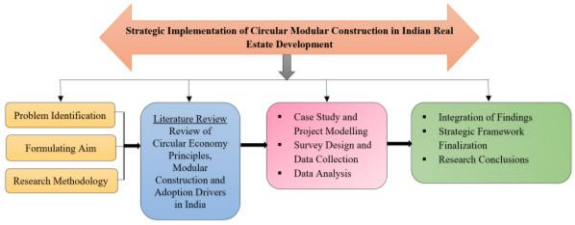


Building on the theoretical foundations of circular modular construction and a critical synthesis of the current drivers, barriers, and contextual realities within the Indian construction sector, this study outlines the research methodology employed to empirically examine and verify these dynamics.

Materials and Methods

This study utilizes a mixed-method research approach to investigate how circular modular construction is strategically implemented in India's real estate sector. The research follows a sequential design, where qualitative insights inform the subsequent quantitative analysis. This method enables an in depth comprehending the multifaceted factors driving, hindering and shaping the strategic adoption of circular modular construction. In the qualitative phase, the study includes case studies and semi-structured interviews with industry experts to gain specific perspectives. The quantitative phase then employs a structured survey to validate and extend the qualitative findings across a larger professional audience. Combining these methods strengthens the rigour and relevance of the results within India's dynamic market context. Figure 5 presents the overall study framework and the methodological steps followed.

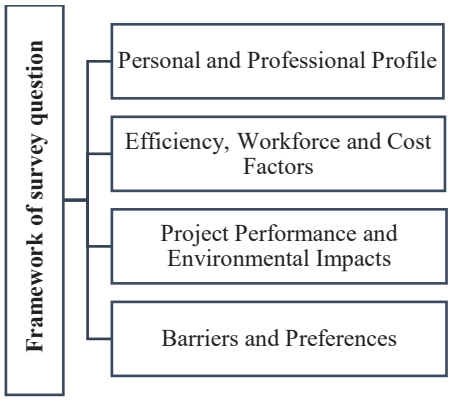
Figure 5
Circular Economy Framework Applied to Modular Construction (developed by the authors)



Initially, a systematic literature review was conducted to establish the theoretical framework underpinning the adoption of circular modular construction, focusing on strategic, organisational, and technological factors. The qualitative component included a case study of a residential duplex (20 ft. × 30 ft.), a scale deliberately chosen for three main reasons. Small-scale residential units are the most common building type in India's rapidly growing urban real estate market, making the findings broadly applicable. A limited footprint allows for precise control over key variables such as material quantities, assembly sequences, and lifecycle cost metrics, thereby improving methodological rigour. This dimension aligns with common modular grid setups frequently employed in prefabrication studies, enabling straightforward comparison between conventional and circular modular construction on a small scale within the real estate industry. AutoCAD and Autodesk 3ds Max were utilised for architectural layout and 3D visualisation, while Microsoft Project was used to model the construction schedule, resource allocation, and costs. Ten industry experts, including civil engineers, project managers, architects, contractors, and quantity surveyors, were interviewed using semi-structured methods, covering four themes: current construction practices, perceived benefits, implementation challenges, and the strategic importance of adoption. The interview transcripts were thematically analysed to identify recurring patterns. Insights gained from this qualitative phase informed the development of a structured questionnaire, which was subsequently distributed to construction and real

estate professionals to gather 100 valid responses, as shown in Figure 6.

Figure 6
Framework of Survey Question (developed by the authors)



The questionnaire consisted of four thematic sections, carefully designed to capture construction professionals' perceptions of circular modular construction, as shown in Figure 6. Questions Q1 and Q2 gathered data on respondents' occupational positions and years of professional experience within Section 1. Section 2 explored efficiency, workforce, and cost considerations, specifically perceived time efficiency, on-site labour requirements, and sensitivity to cost compared to traditional construction, covering questions Q3-Q5. Section 3 assessed project performance and environmental impact, including how frequently projects are delayed, the complexity of on-site coordination, material production, quality consistency, and whether circular modular construction is linked to environmental sustainability, addressing questions Q6-Q10. Section 4 examined barriers to adoption and preferences in construction methods through two questions, Q11 and Q12; however, these were not included in the reliability analysis due to their nominal response options. Internal consistency was evaluated using Cronbach's alpha, which was determined with the Formula 1:

$$\alpha = (k/k-1)\,(1 - \Sigma S_i^2/S^{t2}) \qquad (1)$$

where k represents the number of items,
S_i^2 denotes the variance of each individual item,
S^{t2} is the total variance of the composite score.
This calculation was carried out using IBM SPSS Statistics (version 27).

Results and Discussion

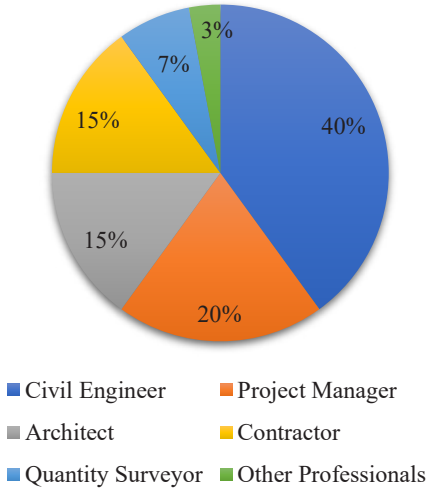
The following findings assess the feasibility, challenges, and professional perceptions of implementing circular modular construction. The internal consistency of the survey questionnaire was examined using Cronbach's alpha, which yielded a coefficient of α = 0.8884, indicating high reliability in accordance with George & Mallery (2003). Table 1 presents the descriptive statistics and item-total reliability coefficients for all ordinal scale items, which are measured on a five-point scale, with higher scores reflecting more positive perceptions of circular modular construction compared to traditional methods.

Table 1
Comparative Descriptive Statistics and Item–Total Reliability Analysis of the Questionnaire Items (N = 100) (developed by the authors, based on the IBM SPSS Statistics)

Item	Mean	SD	r	α
Q1	3.56	1.27	0.491	0.887
Q2	3.37	1.44	0.505	0.887
Q3	4.21	1.08	0.862	0.863
Q4	3.91	1.36	0.854	0.860
Q5	4.09	0.99	0.750	0.872
Q6	3.98	1.20	0.318	0.897
Q7	3.99	1.12	0.445	0.889
Q8	3.86	1.47	0.835	0.860
Q9	3.85	1.46	0.875	0.857
Q10	4.03	1.11	0.379	0.893
Overall Scale (Q1–Q10)				α=0.8884

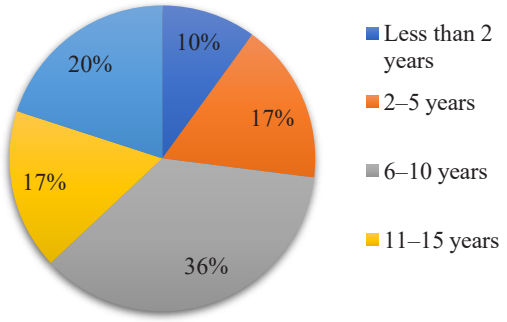
The corrected item-total correlations shown in Table 1, all surpass the minimum acceptable level of r = 0.30, indicating that every item plays a significant role in the overall construct and should not be removed from the scale. The overall Cronbach's Alpha coefficient of 0.8884 demonstrates strong internal consistency among the ten items of the ordinal scale, confirming the reliability and suitability of the questionnaire for measuring the perception of construction professionals regarding circular modular construction in the Indian real estate industry. The credibility of the findings will be with the respondents. Figure 7 shows that 40% of respondents are civil engineers, 20% are project managers, 15% are architects and contractors, and 7% are quantity surveyors.

Figure 7
Professional Background of Survey Respondents (developed by the authors)



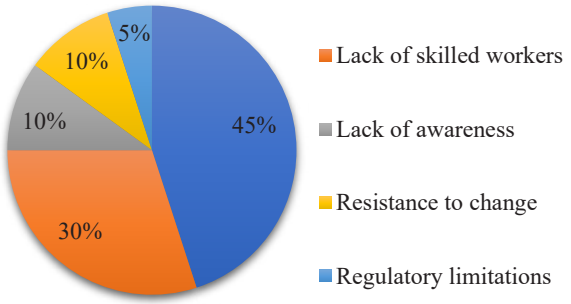
A significant number of participants had extensive professional experience, reinforcing the validity of the survey results. As illustrated in Figure 8, the participant group spanned a range of experience levels within the construction industry. A key segment included those with vast industry expertise, indicating their strong familiarity with construction practices and project management. Other participants were at different career stages, showcasing diverse professional backgrounds.

Figure 8
Distribution of Respondents by Years of Professional Experience (developed by the authors)



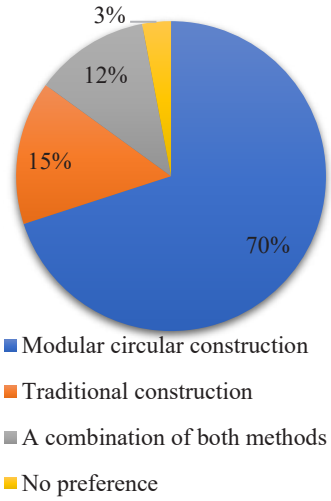
Previous studies indicate that off-site production improves coordination and reduces construction time by enabling parallel workflows and controlled manufacturing conditions (Ferdous et al., 2019). Figure 7 shows that most respondents believe modular construction is faster than traditional construction methods. The resource efficiency theory also highlights that production environments under factory control reduce waste and enhance process consistency. The innovation adoption theory points out that early stages of innovation introduction are associated with economic and organizational obstacles in new technologies used in construction. According to Figure 9, the respondents list high initial investment as the greatest challenge facing modular construction, followed by a lack of skilled labour.

Figure 9
Key Barriers Identified for the Adoption of Circular Modular Construction (developed by the authors)



The diffusion of innovations theory suggests that new technologies are gradually embraced as stakeholders recognize their relative benefits (Rogers, 2003). Figure 10 supports this trend, showing that 70% of practitioners are likely to adopt circular modular construction. The remaining 15%, who prefer traditional methods, probably reflect familiarity with established workflows, concerns about capital costs, and limited awareness, highlighting the importance of targeted education and policy incentives (Dziedzic et al., 2024).

Figure 10
Preferred Construction Method among Industry Professionals (developed by the authors)



The performance disparities shown in Table 2 are explained by the scheduling simulation. Traditional construction follows a strictly linear workflow, where each phase starts only after the previous one is finished, which limits efficiency and lengthens delivery times. In contrast, circular modular construction allows for concurrent processes, with offsite module manufacturing happening at the same time as on-site foundation work. This method reduces complexity, improves resource use, and cuts waste. These efficiencies lead to noticeable reductions in project duration and cost, confirming the operational and economic viability of circular modular construction.

Conventional construction involves many operations performed sequentially on site, which can lead to labour and time inefficiencies, and project delays. In contrast, modular construction shifts a considerable portion of production to controlled factory environments, where components are manufactured in a standardized, labour-intensive approach, which boosts labour productivity, enhances material management, and reduces construction waste. To analyze these operational differences, a case study of a 20 x 30 ft. duplex residential unit was conducted. Although the project size is modest compared to large-scale developments, the case study provides a

simplified and controlled model for examining construction workflows, scheduling logic, and resource allocation patterns.

Table 2

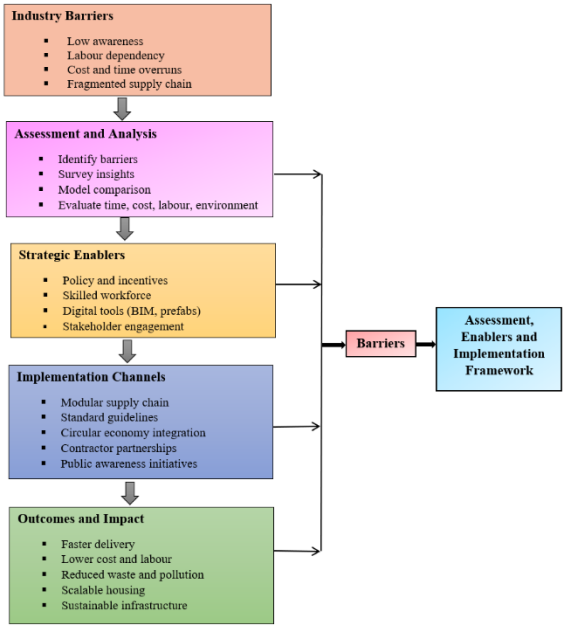
Comparative Analysis of Traditional and Circular Modular Construction (developed by the authors, based on the MS Project results)

Metrics	Traditional Construction	Circular Modular Construction
Total Project Duration	212 days	201 days
Total Project Cost	Rs. 6.09 million	Rs. 5.07 million
Construction Phase Duration	135+ days (sequential)	90 days (parallel)
Waste Generation	High (on-site construction)	Minimal (factory controlled)
Performance Outcome	Circular modular construction reduced project duration by 5.2% and achieved a total cost saving of approximately 16.7% due to parallel workflow efficiency	

The reason for summarizing the overall project results obtained during project execution is that traditional and circular modular construction processes differ in operation while keeping the modelling complexity manageable. The key construction processes, time dependencies, and resource allocation principles illustrated in this case reflect common practices and can offer insights applicable to larger developments. Using Microsoft Project, the scheduling simulation was developed by specifying construction activities, their durations, the necessary labour, and cost parameters for both methods. This approach enabled a systematic comparison of project cost-efficiency and environmental sustainability. In traditional construction, activities are represented as sequential operations, with each task starting only after its predecessor was finished. Conversely, the circular modular scenario adopts parallel workflows, allowing off-site module fabrication to occur simultaneously with on-site foundation and infrastructure preparations. These modelling assumptions enabled a systematic comparison of project duration, labour utilization, and cost performance between the two construction techniques. The strategic implementation framework for circular modular construction within the Indian real estate sector, as shown in Figure 11, is based on the findings of this analysis. This framework identifies the main industry barriers and combines them with survey analysis and project evaluations. It also highlights strategic enablers, such as policy support, workforce development, digital technologies, and stakeholder collaboration, as key facilitators (Fan & Wu, 2020). Ultimately, the framework demonstrates how these elements can support successful adoption, thereby improving project efficiency, cost management, and environmental sustainability in India's construction industry.

Figure 11

Strategic framework for the implementation of circular modular construction in the Indian real estate sector (developed by the authors).



This proposal's framework is designed specifically for the Indian real estate sector, targeting major challenges such as fragmented supply chains, limited skilled labour, high startup costs, and insufficient regulations for circular modular construction. While grounded in the widely accepted principles of the circular economy and modular building, it is tailored to India's unique context. The framework also provides valuable insights that other developing countries facing similar urbanization and sustainability issues can adopt.

The study's findings addressed the three research questions. RQ1, which focused on the primary drivers and obstacles to CMC adoption in India, was explored through expert interviews and an industry survey. Results revealed that significant initial capital demands and fragmented supply chains are the main obstacles. RQ2, which examined the incorporation of circular economy principles into modular construction systems, was explored through a case study and literature review, highlighting practical methods for disassembly, material reuse, and lifecycle management. RQ3, which dealt with the elements of a strategic framework, was addressed through the proposed implementation framework shown in Figure 11.

H1 was confirmed, with supply chain limitations and high capital demands as the main obstacles. H2 was confirmed, as organizations with higher technological readiness showed a greater inclination to adopt CMC. H3 was confirmed, as the structured strategic

framework, which includes lifecycle management, digital systems, and regulatory alignment, demonstrated measurable improvements in project efficiency and cost outcomes.

Conclusions

1. This study assessed the feasibility of circular modular construction as a way to enhance efficiency and sustainability in the real estate sector, thereby confirming its strategic viability as a practical alternative to traditional construction methods.
2. The analysis of the Microsoft Project scheduling simulation demonstrated that the combined execution of off-site fabrication and on-site construction operations yields measurable benefits in scheduling efficiency and notably shorten the overall project duration compared to the traditional, sequential construction process.
3. Factory-controlled standardisation has been shown to improve construction quality, ensure uniform performance of materials, significantly lessen on-site waste, and support circular economy principles throughout the entire lifecycle of the built environment.
4. A structured industry survey of construction and real estate professionals indicated that the advantages of circular modular construction regarding operational, environmental, and delivery reliability are broadly recognised by construction professionals. This reflects a positive level of industry awareness and a growing willingness to adopt circular modular practices more broadly.
5. The adoption of circular modular construction in the property sector faces significant challenges due to high initial capital costs, fragmented supply chain systems, shortages of skilled workers, and regulatory uncertainties. These factors together serve as the main obstacles to its wider implementation.
6. To overcome these barriers specifically, capital cost constraints, supply chain fragmentation, skilled labour shortages and regulatory uncertainties, coordinated and sustained industry engagement is essential, supported by enabling policy frameworks, systematic workforce development programmes, and the strategic deployment of digital technologies.
7. Based on the Microsoft Project scheduling simulation and structured industry survey findings, this study offers a strategic implementation framework that links identified industry challenges to practical enabling mechanisms, providing valuable guidance for policymakers, developers, and stakeholders.
8. Future research should explore the scalability of circular modular construction across various Indian real estate typologies, examine long-term lifecycle costs, and investigate the role of emerging digital technologies such as Building Information Modelling in promoting its wider adoption.

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IMPACT OF VOC EMISSIONS FROM RECYCLED BUILDING MATERIALS ON INDOOR ENVIRONMENTAL QUALITY

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Abstract
Volatile organic compounds (VOCs) emitted from construction materials are a major factor affecting indoor environmental quality and human health. As circular economy principles are increasingly adopted in the construction sector, recycled materials are being used more widely; however, their emission behavior remains insufficiently understood. This study evaluates how mechanical recycling processes affect VOC emissions from selected interior building materials, including wood-based, polymer-based, and mineral materials. A dataset reflecting realistic emission ranges reported in previous studies was used to compare total VOC (TVOC) concentrations before and after recycling. Mechanical recycling was represented by shredding, thermal exposure, and reprocessing steps, and one-way ANOVA was used to assess differences between initial and recycled materials. The results indicate that recycling may either increase or decrease VOC emissions, depending on material composition and processing conditions. The largest increases were observed for particleboard and laminate, whereas gypsum boards showed a decrease. These findings emphasize the need to integrate emission assessment into circular material design, product certification, and indoor air quality management so that environmental sustainability goals do not compromise healthy indoor environments. These findings highlight the critical importance of systematically evaluating VOC emissions throughout the entire lifecycle of construction materials, particularly when recycled content is introduced. Furthermore, they underline the necessity for developing standardized assessment frameworks that account for emission variability associated with recycling processes. Ensuring that circular economy strategies remain aligned with indoor environmental quality objectives is essential for achieving truly sustainable and health-conscious building practices.
Keywords: VOC, indoor pollutants, recycled composites, circular construction, sustainable indoor environment.

Introduction

Indoor air quality (IAQ) has become a critical concern in modern buildings, especially because improved airtightness and reduced ventilation rates in energy-efficient construction can intensify the accumulation of indoor pollutants (Wolkoff, 2013; World Health Organization, 2010). Among pollutants affecting IAQ, volatile organic compounds (VOCs) are particularly important due to their widespread presence and their potential adverse effects on comfort and health (Jones, 1999).

Building materials are a primary source of VOC emissions, especially in newly constructed or renovated indoor environments (Brown, 2002; Guo et al., 2003). Materials such as particleboard, paints, adhesives, and insulation products may release a broad range of organic compounds, including formaldehyde, benzene, and toluene (Salthammer et al., 2010). Previous research has shown that VOC emissions depend on material composition, manufacturing processes, environmental conditions, and ageing (Brown, 2002; ISO 16000-6, 2011; Yu & Crump, 2011). Wood-based materials such as particleboard and medium-density fiberboard (MDF) are known to emit formaldehyde and other aldehydes due to resin decomposition (Kim S. & Kim H. J., 2006), while polymer-based materials may release hydrocarbons, plasticizers, and degradation products (Yu & Crump, 2011).

At the same time, the construction sector is transitioning towards circular economy principles, which promote material reuse and recycling to reduce environmental impact (European Commission, 2020). Although this transition offers clear sustainability benefits, it also introduces new challenges. Recent studies on circular construction have emphasized the environmental advantages of recycling, yet the chemical implications of recycling processes remain less explored. Some authors suggest that recycling may reduce emissions because prior off-gassing has already occurred, whereas others indicate that mechanical and thermal processes may alter material structure and release previously bound VOCs (Nazaroff & Weschler, 2004; Salthammer, 2013). This inconsistency reveals an important knowledge gap regarding the emission behavior of recycled materials intended for indoor use.

Recent studies have increasingly focused on the relationship between circular construction practices and indoor environmental quality. Several authors have reported that recycled and low-carbon building materials may exhibit altered VOC emission behaviour depending on material composition, recycling technology, and ageing processes. In particular, recycled polymer-based and composite materials have been identified as potential sources of secondary VOC emissions in indoor environments (Huang et al., 2021; Li et al., 2023).

However, despite these recent advances, most published studies primarily focus on experimentally measured VOC emissions from either new or recycled building materials. Comparative assessment of emission changes associated with mechanical recycling processes using representative emission datasets remains limited. Therefore, the present study addresses this research gap by comparatively analysing representative TVOC emission ranges reported in previous studies to evaluate potential changes in VOC emissions following mechanical recycling.

This study aimed to evaluate how mechanical recycling processes influence VOC emissions from

selected building materials and to assess the potential implications for indoor environmental quality.

In addition, it is important to consider that human exposure to VOCs is not limited to individual compounds but rather to complex mixtures that may produce synergistic or cumulative health effects. Even low concentrations of multiple VOCs can contribute to sensory irritation, reduced cognitive performance, and long-term health risks. Therefore, evaluating total VOC (TVOC) levels alongside individual compound behavior is essential when assessing indoor environmental quality.

Furthermore, increasing attention is being paid to the life-cycle perspective of building materials (Kumar et al., 2021). While recycling reduces raw material consumption and waste generation, it may introduce unintended environmental trade-offs, particularly in terms of chemical emissions. The integration of indoor air quality considerations into circular economy strategies remains insufficiently developed, highlighting the need for interdisciplinary research that combines material science, environmental engineering, and public health perspectives.

Materials and Methods

The study included commonly used interior building materials: particleboard, medium-density fiberboard (MDF), laminate flooring, polyurethane insulation, painted gypsum boards, and PVC flooring.

Due to the exploratory nature of this study, representative TVOC emission values for selected building materials were comparatively analysed using emission ranges commonly reported in previous experimental studies (Brown, 2002; ISO 16000-6, 2011; ISO 16000-9, 2006; Yu & Crump, 2011). The dataset was compiled using representative TVOC emission values derived from previous experimental studies and was designed to reflect the variability commonly observed for comparable building materials under indoor conditions. Mechanical recycling conditions included shredding, thermal exposure, and material reprocessing, reflecting commonly applied recycling practices in the construction sector. These processes were considered in the comparative evaluation of VOC emission behaviour before and after recycling. The comparative analysis considered these recycling stages as the principal factors influencing changes in VOC emission behaviour between the initial and recycled material conditions. For each material group, ten representative TVOC values were used to characterise emission variability before and after recycling. One-way ANOVA was applied to assess differences between initial and recycled materials.

In addition to the selected materials, environmental parameters such as temperature and ventilation conditions were considered during interpretation of emission behaviour, as these factors are known to influence VOC emission rates. The analysis reflects emission behaviour under indoor conditions commonly described in previous experimental studies. Statistical analysis was complemented by descriptive evaluation of emission variability and changes in average TVOC levels after recycling, enabling a more comprehensive interpretation of material-specific behaviour following recycling processes.

Results and Discussion

The results demonstrated significant variation in VOC emissions depending on material type and recycling conditions. As shown in Table 1, particleboard exhibited the highest increase in TVOC emissions (+37.8%), while gypsum boards showed a reduction (−15.4%). Polymer-based materials, such as PVC, also demonstrated increased emissions after recycling.

Another relevant aspect is the potential influence of recycling-induced chemical transformations. Mechanical processing, combined with thermal exposure, may alter the chemical structure of materials, leading to the formation of new volatile compounds. These secondary emissions are not always well characterized but may contribute significantly to overall indoor pollutant loads.

From a practical perspective, the findings indicate that material selection in sustainable construction should not be based solely on environmental indicators such as recyclability or carbon footprint. Instead, a more holistic approach is required, incorporating emission performance as a key criterion. This is particularly relevant for materials used in enclosed or poorly ventilated spaces, where pollutant accumulation is more likely.

Moreover, the results underline the importance of standardized testing protocols for recycled materials. Current emission standards are primarily developed for new products, and their applicability to recycled materials remains limited. Expanding certification schemes to include recycled products would support the safer implementation of circular economy principles in the construction sector.

Figure 1 compares TVOC concentrations before and after recycling and includes standard deviations, enabling assessment of both emission magnitude and variability. The observed changes demonstrate that the effect of mechanical recycling differs among material types, indicating that VOC emission behaviour is strongly dependent on material composition and processing characteristics.

This divergence implies that the response to recycling is governed by differences in chemical composition and bonding mechanisms within the material matrix. Materials containing organic binders or additives appear more susceptible to emission increases, while mineral-based materials demonstrate comparatively stable or reduced emission profiles.

The increase in emissions from wood-based materials can be interpreted because of matrix disruption and enhanced mass transfer processes. Mechanical

fragmentation increases surface area, while thermal exposure may weaken chemical bonds within resin systems, facilitating the release of previously retained volatile compounds (Salthammer, 2013). This indicates that recycling not only reprocesses materials physically but also alters their emission kinetics.

These findings are consistent with recent studies investigating recycled composite and polymer-containing materials, which reported that mechanical processing and thermal treatment may increase VOC emissions and emission variability (Li et al., 2023).

Table 1

TVOC emissions from initial and recycled materials

Material	Initial	Recycled	Change, %
Particleboard	450	620	37.8
MDF	520	480	-7.7
Laminate	300	410	36.7
Insulation	270	350	29.6
Gypsum	390	330	-15.4
PVC	610	720	18.0

Figure 1

TVOC comparison before and after recycling

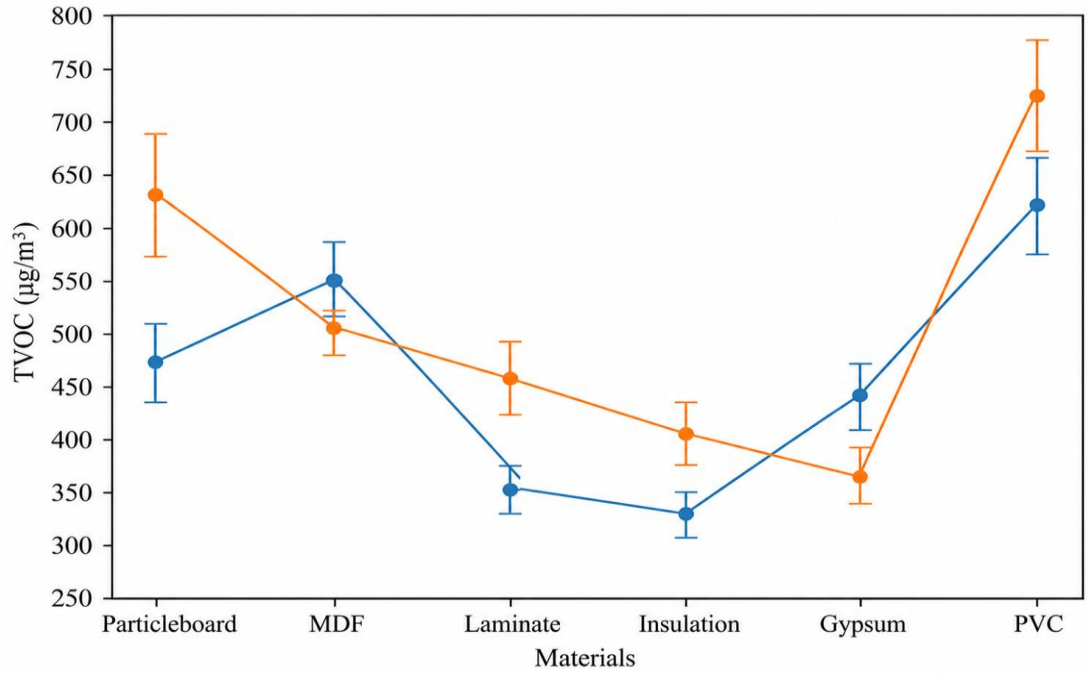


Figure 2 illustrates the percentage change in mean TVOC emissions after mechanical recycling, allowing comparison of the relative emission response among the investigated materials. The variability in percentage change reinforces that emission response is non-linear and cannot be generalized across material categories. Instead, it reflects the interaction between initial material properties and recycling conditions. Figure 3 illustrates the distribution of TVOC emissions before and after mechanical recycling, highlighting the increased variability observed for particleboard and PVC compared with the other investigated materials. This suggests that recycling introduces heterogeneity into the material structure, leading to less predictable emission behavior. From an indoor air quality perspective, such variability is critical, as it increases uncertainty in exposure assessment and complicates the application of standard emission limits. Therefore, evaluating recycled materials based solely on mean TVOC values may be insufficient, and greater emphasis should be placed on variability and material-specific response patterns when assessing their suitability for indoor use.

In contrast, reduced emissions in gypsum materials may be related to prior off-gassing and lower organic compound content (Brown, 2002).

Figure 2
Percentage change in mean TVOC emissions after mechanical recycling

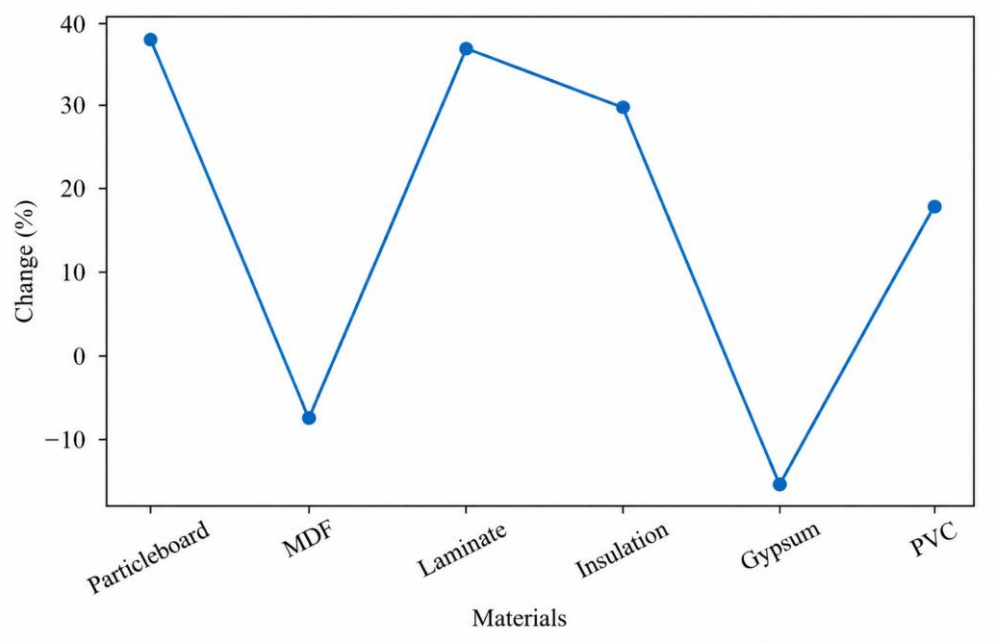
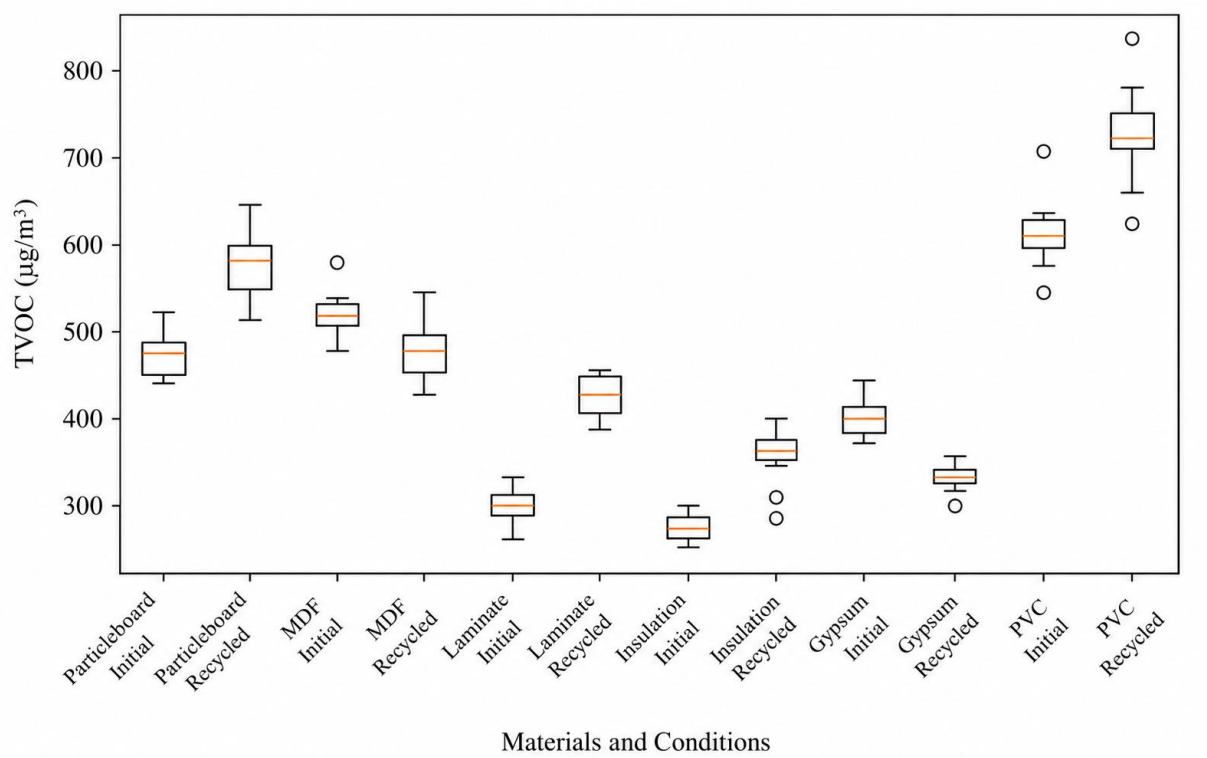


Figure 3
Distribution of TVOC emissions for initial and recycled materials based on measurements (n = 10)



One-way ANOVA revealed statistically significant differences in VOC emissions between initial and recycled materials ($F(1, 58) \approx 5.2–9.8$, $p < 0.05$), indicating that recycling processes significantly influence emission characteristics. These results confirm that the observed changes are not random but are systematically associated with the recycling process itself. The statistical significance further supports the assumption that mechanical and thermal treatment steps measurably alter emission behavior. From an environmental and engineering perspective, these findings highlight a critical trade-off in circular construction. While recycling improves resource efficiency and reduces environmental burdens associated with raw material extraction, it may negatively affect indoor air quality if emission behavior is not properly assessed (Hellweg & Milà i Canals, 2014). This trade-off underscores the need for

a more balanced evaluation framework that considers both environmental sustainability and human health impacts.

Therefore, VOC emissions should be systematically integrated into material certification systems, circular design strategies, and indoor air quality regulations. Current assessment frameworks often prioritize energy performance and material reuse, while emission-related aspects remain secondary. Incorporating emission criteria into these systems would enable more informed decision-making and reduce potential risks associated with recycled materials.

Although the present analysis reflects representative emission trends reported in previous studies, further laboratory-based validation remains necessary. Experimental studies under controlled conditions would help to confirm the observed patterns, reduce uncertainty, and support the development of standardized testing methods specifically tailored for recycled building materials.

Future Research Directions

Despite the results obtained in this study, several aspects of VOC emissions from recycled building materials require further investigation to ensure their safe and sustainable use in indoor environments. The findings provide important indications of changes in emission behaviour due to recycling; however, they do not fully represent the complexity of real-world emission dynamics under actual operating conditions. Therefore, future research should prioritize experimental validation under controlled laboratory conditions using emission test chambers in accordance with established international standards such as ISO 16000-9.

One important direction for future research is the assessment of long-term emission behavior. VOC emissions from building materials are known to change over time due to ageing processes, material degradation, and environmental influences. While this study focuses on initial emission changes after recycling, it does not address how emissions evolve during extended periods of indoor use.

In addition, further research should focus on the identification and quantification of individual VOC compounds rather than relying solely on total VOC (TVOC) values. Although TVOC is a useful indicator of overall emission intensity, it does not reflect the specific health risks associated with compounds, such as formaldehyde, benzene, or other hazardous substances.

Another critical area for investigation is the influence of different recycling technologies on emission behavior. This study considers mechanical recycling processes, including shredding and thermal exposure; however, other recycling methods, such as chemical recycling or hybrid processes, may produce different emission outcomes.

Furthermore, the interaction between recycled materials and indoor environmental conditions should be explored in greater detail. Factors such as temperature, humidity, ventilation rate, and the presence of reactive pollutants (e.g., ozone) can significantly affect emission rates and secondary pollutant formation.

The increased variability in emissions observed in this study also highlights the need for improved standardization and quality control of recycled materials. Future work should investigate the sources of this variability, including differences in feedstock composition, processing conditions, and material heterogeneity. Developing more consistent recycling practices and classification systems for recycled materials could reduce uncertainty and improve the predictability of emission performance.

Finally, there is a need to integrate VOC emission considerations into life cycle assessment (LCA) and circular economy frameworks. While recycling offers clear environmental benefits in terms of resource efficiency and waste reduction, its potential impact on indoor air quality is often overlooked. Future interdisciplinary research combining material science, environmental engineering, and public health perspectives would support the development of more comprehensive evaluation tools that balance sustainability and human health**.**

Conclusions

1. Recycling processes significantly influence VOC emission behavior in building materials. The results of this study indicate that mechanical recycling, including shredding and thermal exposure, can measurably and systematically alter emission characteristics.

2. Both increases and decreases in emissions were observed, depending on material composition and processing conditions. This indicates that recycling does not produce a uniform effect but rather acts as a modifying factor influenced by the material's chemical and structural properties.

3. Wood-based and polymer materials tended to show increased emissions after recycling, whereas gypsum boards showed lower emissions. The observed increase in emissions from wood-based materials can be associated with the degradation of resin systems and increased surface area, while the relatively stable behavior of mineral-based materials reflects their lower organic compound content.

4. In addition to changes in average emission levels, recycling was associated with increased variability in VOC emissions. This suggests that recycled materials may exhibit less predictable emission behavior, which can complicate indoor air quality assessment and risk management in real-world building environments.

5. The findings of this study support the integration of VOC emission assessment into circular construction strategies and material certification systems. Current sustainability frameworks often prioritize resource efficiency and waste reduction, but this study's findings highlight the need to also consider potential impacts on indoor environmental quality and human health.

6. From a practical perspective, the selection of building materials for indoor use should not rely solely on environmental indicators such as recyclability or carbon footprint. Instead, a more comprehensive approach is required, with emission performance as a key decision-making criterion, particularly in low-ventilation or energy-efficient buildings.
7. Future research should focus on laboratory validation, long-term emission studies, and standardized testing methods for recycled materials, as well as on identifying specific VOCs and their health implications.
Overall, this study highlights the complex relationship between material recycling and indoor environmental quality. While recycling is essential for sustainable resource management and supports the transition towards a circular economy, its impact on VOC emissions cannot be overlooked. The results demonstrate that emission behavior is highly material-dependent and influenced by processing conditions, emphasizing the importance of integrating emission considerations into material design, certification, and building practices. A balanced approach is therefore required to ensure that environmental sustainability goals are achieved without compromising healthy indoor environments.

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SUSTAINABLE DEVELOPMENT DRIVERS IN THE LATVIAN CONSTRUCTION INDUSTRY

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Abstract
Nowadays, the impact of globalization on the world economy has contributed to the expansion of international markets and increased competition, labor mobility and the associated knowledge flow, the need for innovation and the introduction of technological processes. In the last decade, increased attention within the European Union has been devoted to promoting environmentally friendly construction, energy efficiency and reduction of greenhouse gas emission reductions, to facilitate the implementation of the European Green Deal and the transition to a sustainable and climate-neutral environment. The construction industry is one of the most important driving forces of the national economy, significantly influencing not only the country's economic growth, but also the environmental sustainability and the quality of life for society. The development of the construction industry is proceeding differently in different countries, and this raises a discussion about the causes of these differences and the sensitivity of the industry. The aim of the research is to analyse the development of the Latvian construction industry and identify the key drivers contributing to the sustainable growth of the industry. The Latvian construction sector is a labour-intensive industry that is primarily driven by domestic market demand and public investment. Growing sustainability requirements, rapid technological advancements, and workforce availability challenges highlight the need to enhance the sector's development potential through investments in human capital and market expansion. Fostering growth will boost national economic performance and help achieve the European Union's broader objectives.
Keywords: construction, innovations, growth, technologies.

Introduction

The construction industry is one of the most important driving forces of the national economy, significantly influencing not only the country's economic growth, but also environmental sustainability and society's quality of life (European Parliament, 2023). In the European Union, the construction industry is strictly regulated, with a particular emphasis on ensuring quality, safety and sustainability, while promoting digitalization, innovation and the implementation of circular economy principles (European Parliament, 2024b). Over the past decade, in the European Union has devoted increasing attention to promoting environmentally friendly construction, energy efficiency, and the reduction of greenhouse gas emissions (European Parliament, 2023) to facilitate the implementation of the European Green Deal and the transition to a sustainable, climate-neutral environment (European Parliament, 2024a).

In recent years, the development of the construction industry in the European Union and the Baltic States has been significantly affected by Russia's war in Ukraine. After the war started, in 2022, the construction industry faced significant disruptions in the supply of building materials, price increases, and rise in the cost of energy resources, which significantly affected the costs and planning of construction work. Meanwhile, there was an increase in the demand for defence and security infrastructure, construction and reconstruction of strategic buildings, as well as expansion of the housing stock. Although the upheavals caused by the war initially hindered the growth of the construction industry, in the long term they served as a powerful stimulus for change, encouraging the Baltic States to purposefully move towards energy independence, strengthening security, and reinforcing the principles of sustainable development in the field of construction.

Research aim – to analyse the development of the Latvian construction industry and identify the key drivers contributing to the sustainable growth of the industry. To reach the aim, the following tasks were put forward: 1) to select indicators for assessing the development of the construction industry; 2) to analyze the development trends of the construction industry in the Baltic States; 3) to identify the drivers determining the sustainable growth of the Latvian construction industry.

Several methods and software tools were used in the development of the research.

Materials and Methods

The European Union and the Latvian construction industry is an industry of the national economy consisting of 4 sub-industries – construction of buildings, civil engineering, specialised construction activities – which belong to the secondary economic sector, and architectural and engineering activities technical testing and analysis, which are a part of the tertiary economic sector (Central Statistical Bureau, 2025a). Sub-industries consist of several sectors and their sub-sectors, which differ in their type of activity and have different development potential.

The socio-economic indicators used in this study were selected based on widely recognized approaches in the scientific literature for assessing industry competitiveness, development, and economic impact. The number of enterprises (Bakri, 2021) characterizes business activity and market structure within the industry. The number of employed persons (Solvell et al., 2003; Shah, 2024) and the educational attainment of employees (OECD, 2025) reflect the availability and quality of human capital, which are important determinants of industry competitiveness and

productivity. Labour costs (Musarat et al., 2022) and labour productivity (Porter, 1990) describe the efficiency of resource utilization and business competitiveness. Gross value added (Liu et al., 2021) reflects the industry's contribution to the national economy, while export value (Abdmoulah, 2023) indicates international competitiveness and the industry's ability to generate value in external markets. The shadow economy index (Buszko, 2020) was selected as an indicator for assessing the impact of informal economic activity on industry development, whereas foreign direct investment (Irandoust, 2016) reflects the industry's attractiveness to investors and its development potential. The scientific literature was used as a theoretical basis for the selection of the indicators included in the study and for substantiating their relevance to the analysis of the construction industry's development.

The study employs general scientific, statistical, and mathematical research methods. The theoretical part of the research is based on the analysis of scientific literature, legal and regulatory acts, policy planning documents, and other information sources in order to identify the factors influencing the development of the construction industry, evaluate aspects of industry competitiveness, and justify the selection of the indicators used in the study. Statistical research methods, including data collection and grouping, comparative analysis, structural analysis, and time-series analysis, were applied to characterize the phenomenon under investigation and identify its development trends. Mathematical methods (including correlation analysis) were used for quantitative data analysis, the identification of relationships between variables, and the assessment of development trends. Analysis and synthesis methods were employed for the formulation of conclusions and recommendations. Microsoft Excel was used for data processing, analysis, and visualization of the research results.

The analysis covers the period from 2011 – 2023. For certain reporting years, data are not available or cannot be published due to lack of information and confidentiality. The availability and quality of the data determined the level of details and the results.

Results and Discussion

Development of the Construction Industry in the Baltic States

The construction industry in the Baltic States has become an important segment of economics in recent decades, reflecting both the dynamics of the region's development and trends in sustainable architecture and technological innovation. At the same time, the industry faces several challenges that require a thoughtful approach and interdisciplinary cooperation to ensure sustainable development.

Labour costs in the Baltic States are considerably lower than in the EU on average, but with a tendency to increase (Figure 1a). The cheap labour in the Baltic States may choose work with equivalent working conditions in another industry or abroad, but for a much more competitive work remuneration, which can thus create increasingly greater fluctuations in labour flows and affect the construction capacities of companies.

Labour productivity in the Baltic States falls significantly behind the average in the EU (Figure 1b). Moreover, the labour costs in all the Baltic States grow faster than productivity. An increase in labour costs that is not matched by a proportional rise in productivity may diminish the profits of companies in the construction industry, thereby hindering their capacity to invest in their further development.

Over the past 10 years, the exports of the Baltic States have quadrupled, reaching 1.41 billion euros in 2023 (Figure 1c). Until 2020, Estonia was the export leader among the Baltic States, but since 2021 it is Lithuania. The increase in the proportion of construction industry exports in relation to the gross domestic product points to the growth of the industry in the Baltic States and indicates the increasing competitiveness of the services of the industry's companies in international markets.

An average of 1.18 billion EUR is invested annually in the development of the construction industry in the Baltic States (Figure 1d). Investments in Latvia's construction industry have long exceeded those in Lithuania and Estonia, driven by an active investment attraction policy, favorable real estate development conditions, increasing urbanization, and the absorption of EU funds that enabled ambitious infrastructure projects. Over the past 3 years, the Lithuanian construction industry has become more attractive to foreign investors.

The development of the construction industry in the Baltic States is hampered by the slow transformation to knowledge-intensive activities – the use of low-skilled labour, slow adoption of modern technologies and lack of mechanisation, underutilised digitalization potential, as well as the weak integration of industry companies into global value chains. The growth of the industry is also hindered by insufficient investment in research and development, as well as a lack of cooperation with scientific institutions in creating innovations.

Development of construction industry in Latvia

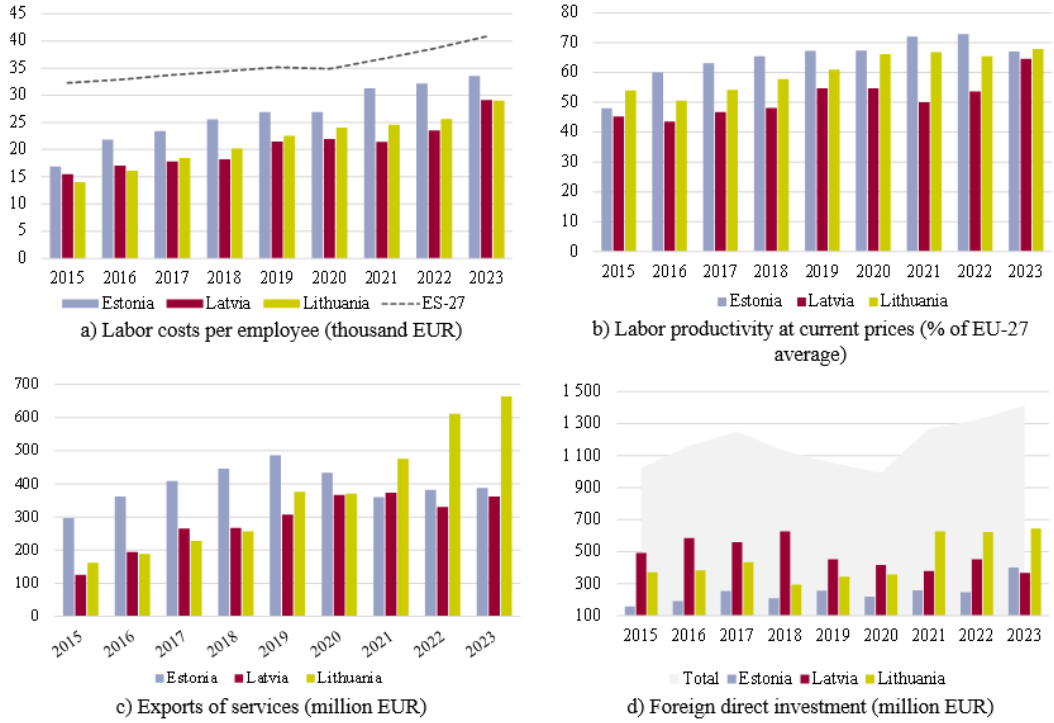
In 2023, there were 13,17 thousand economically active companies in the Latvian construction industry, the vast majority of which (87%) were micro-enterprises (Figure 2a). Construction companies employed more than 70 thousand employees, or 8% of the total number of persons employed in the country (Figure 2b). The construction industry can be described as a labour-intensive industry – it held the position of the 7th largest employer among all the industries of the national economy in Latvia.

The gross value added of the construction industry in 2023 reached 2.44 billion EUR, accounting for nearly 7% of the total value added of the Latvian economy (Figure 2b). Fluctuations in the share of the industry's

value added in the overall national economy of the country are mainly related to the more rapid development of other industries of the national economy. The construction industry is highly correlated with the overall economic situation in the country – it develops cyclically alongside the broader economy, serving as a direct mirror of the economic growth.

Figure 1

The structure of the construction industry in the EU-27 and Latvia (created by the author according to Eurostat, 2026)



Note: The available data on the construction industry, excluding architectural and engineering activities, technical testing and analysis.

The internal consumption of construction works in the domestic market has increased by 85% since 2015, reaching 3.23 billion EUR in 2023 (Central Statistical Bureau, 2026b). The highest consumption was observed in construction of buildings, which can be explained by the inflow of the EU funds and financial instruments into the Latvian national economy, leading to a growing demand for government-ordered buildings, office buildings, and residential houses. Construction consumption also increased in specialised construction activities and civil engineering. Companies operating in the Latvian construction industry mainly serve the local market; therefore, the industry is closely linked to total investments in the national economy and is highly dependent on public procurement. The industry is poorly oriented towards entering export markets, even though exports have tripled over the past ten years (Figure 2c).

The construction industry has a large impact not only on the labour market, but also on migration. Insufficient demand for construction work reduces the industry's need for labour, causing some of those who have lost their jobs to reorient themselves toward equivalent work in another industry or emigrate to other countries. In turn, under conditions of rapid economic growth and high demand for construction work, the industry may create a disproportionately high demand for labour and compete for workers with other industries. From the perspective of balanced economic growth, it is important to ensure that the construction industry develops without rapid declines and increases.

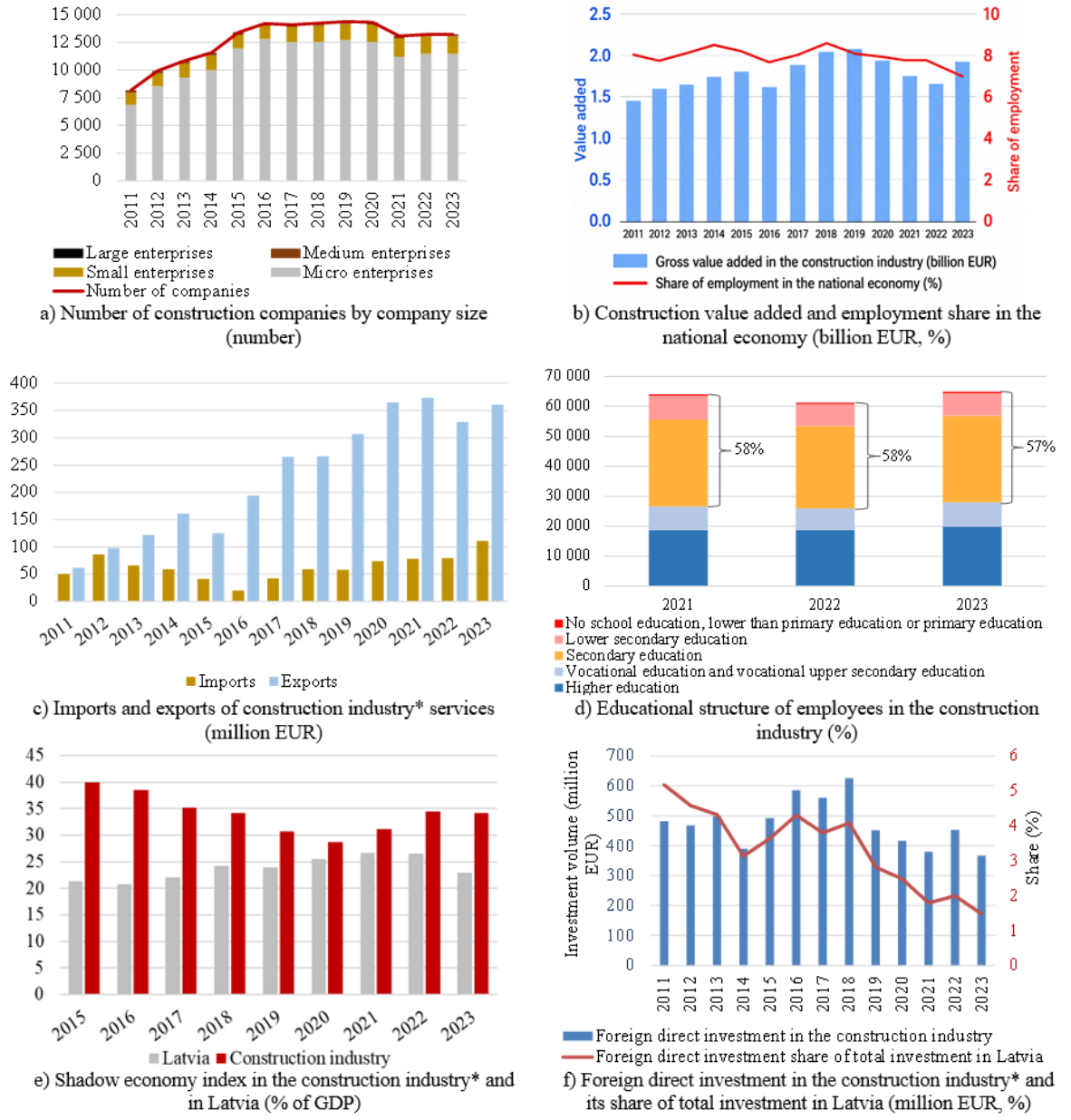
Activity of the Latvian construction industry is based primarily on low-skilled (Figure 2d) and therefore low-cost labour, rather than on technological advancement and innovations. The average monthly gross work remuneration of workers in the construction industry (excluding architectural and engineering activities, technical testing and analysis) in 2023 was EUR 1449 a month (Central Statistical Bureau, 2026b), which was 6% less than the average work remuneration in the Latvian national economy. Employees in the specialised construction, building construction, and micro and small industrial enterprises earned less than the average remuneration in the construction industry and Latvia overall.

The proportion of the persons employed who receives the minimum wage or less has decreased from 37% in 2011 to 16% in 2023. Although the average gross work

remuneration in the construction industry has increased twice since 2011, which was significantly influenced by the concluded General Agreement, it is still not competitive in either the local or the EU labour market. Due to the uncompetitive remuneration and high working environment risks in construction the companies may face difficulties in attracting qualified labour, and these factors can contribute to the spread of envelope wages, failing to achieve the desired effect in combating the shadow economy (Figure 2e).

Figure 2

Development Indicators of the Latvian Construction Industry 2011–2023 (calculated and created by the author according to Central Statistical Bureau, 2026b; Latvia Bank, 2026; Stockholm School of Economics in Riga, 2025)



*Note: *The available data on the construction industry, excluding architectural and engineering activities, technical testing and analysis.*

Foreign direct investments in the Latvian construction industry are on a downward trend – since 2011, the volume of the investments has fallen by 24%, reaching 367 million EUR in 2023 (Figure 2f), which can be explained by instability in the global economy and the increased geopolitical risks. Investments in the construction industry are rather inconsistent and their volatility is influenced by both the availability and cyclicality of the EU funds, as well as adjustments to private sector investment plans in line with changes in the state of market. Investment inflows are also hampered by high energy costs, low lending levels, and complex construction processes.

Conclusions

1. In recent years, the construction industry in Lithuania has experienced the fastest growth among the Baltic States. This development has been driven by the implementation of large-scale infrastructure projects, high labor productivity, and an active real estate market, which has contributed to attracting significant investments. The stable growth of Lithuania's construction industry has promoted the development of an investment-friendly environment and increased the country's attractiveness to foreign investors, strengthening its competitiveness within the Baltic region.
2. Latvia's construction industry is a labor-intensive sector primarily oriented toward the domestic market and public procurement, developing cyclically in line with the country's overall economic situation. Although growth has been observed in the construction sector in recent years, the industry as a whole is still insufficiently focused on the adoption of new knowledge and technologies, as well as the implementation of innovations. The growth of Latvia's construction industry should be promoted through investments in human capital, technology transfer, and innovation development. The sector should establish close and long-term cooperation with universities and scientific institutions both nationally and internationally to foster networking, facilitate the knowledge and experience transfer, and support a shift toward higher-productivity activities. Strengthening the construction industry can contribute not only to enhancing public quality of life, but also to driving national economic growth and advancing broader European Union objectives more effectively.

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A LITERATURE REVIEW OF STEEL FIBRE REINFORCED CONCRETE BEAMS FAILING IN SHEAR

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Abstract
This article presents a literature study on the shear behaviour and failure of Steel Fibre-Reinforced Concrete (SFRC) beams, with a particular focus on the effects of fibre volume fraction, fibre geometry and distribution, as well as the interaction between the steel fibres and shear reinforcement. The literature study discusses the findings from numerous published experimental researches involving various fibre types and how steel fibres increase shear strength via crack bridging, shear force redistribution and improvement in post cracking behaviour. A comprehensive database collected from the literature covers the findings of a variety of shear tests performed on SFRC beams, both with and without fibres. The review analyses the effect of different key parameters including fibre volume fraction, specimen size, aspect ratio, $\frac{a}{d}$ (shear span to depth ratio) and crack width on shear strength. The review suggests that enhancing the fibre amount (up to 2%) increases shear strength and minimizes the crack width. However, higher $\frac{a}{d}$ ratios diminish shear capacity due to a fall in the arching action. The review suggest that specimen size strongly impacts shear strength, with smaller specimens revealing a higher normalized shear strength. Although there have been wide range improvements in experimental ways and techniques, shear strength models of SFRC beams have insufficient correlation with experiments' results and reveals minimal sensitivity to the mechanical properties of the fibres, fracture kinematics and size effects. These drawbacks emphasize the importance of developing more precise predictive models that incorporate the essential concepts governing shear resistance in Steel Fibre Reinforced Concrete (SFRC).
Keywords: steel fibre-reinforced concrete (SFRC), shear strength, fibre reinforcement, fibre geometry, stirrups.

Introduction

Shear Problem in RC Beams

Shear failure in reinforced concrete (RC) beams is one of the most essential structural issues owing to its brittle character, speed, and the fact that they cannot give sufficient warning before their collapse (Lantsoght, 2019; Arslan et al., 2017). Compared with flexural stiffness failure which is governed by the yielding of longitudinal reinforcement and shows great ductility, the shear failure is controlled by major principal tensile stresses with limited capacity for stress redistribution and results in unstable crack propagation and sudden failure in loss of load carrying capacity (Zhao et al., 2018).

Shear resistance in shear capacity RC beams is given by combination of concrete contribution, mixture interlock, dowel action of longitudinal reinforcement and transverse reinforcement in form of stirrups. However, experimental evidence shows that after the composite of diagonal cracks, these mechanisms lose their stability quickly, especially because of the loss of aggregate interlock, leading to extremely unstable post-cracking behaviour (Lantsoght et al., 2019). While stirrups increase the shear capacity and delay the size of crack, they do not prevent crack processes and may be inappropriate for brittle shear failure control in unfavourable geometrical and detailing restrictions in beams.

Justification on the use of Shear Steel Fibre Reinforced Concrete

Steel fibre reinforced concrete (SFRC) has been more and more studied as a mechanism-based technique for improving the shear performance by improving post-cracking load transfer. Following the formation of the diagonal crack, the steel fibres act as discrete bridging elements across the crack surfaces. This helps to transfer tensile stresses and limit crack openings, thereby controlling crack propagation (Saudi Abdul-Zaher et al., 2016; Amin & Foster, 2016).

The main role of fibres in the shear direction is not to increase the pre-cracking strength but to increase the post-cracking shear capacity transfer mechanisms.

This behaviour is especially relevant in stirrup reinforcement where shear critical applications are evolved and the spacing (stirrup reinforcement) requirements, congestion problems or construction issues limit the spacing for stirrup reinforcement. By addressing directly, the deficiency about post-cracking shear transfer, SFRC helps to offer a complementary reinforcement mechanism to make the structure more robust against brittle diagonal tension failure.

Fragmentation and Inconsistencies in Available Literature

After some research work on the shear attributes of SFRC beam, reported results show great variance because of variation in fibre type, volume fraction, $\frac{a}{d}$, and the presence or absence of stirrups (Arslan et al., 2017; Demakos et al., 2021; Zhao et al., 2018).

Moreso, loading configurations, beam dimensions, boundary conditions from different studies (Demakos et al., 2021) shows how the parameters and the crack evolution affect the shear failure and mechanism-consistent design, formulations may be developed.

Review Gap and Contribution

Existing reviews on steel fibre reinforced concrete mainly stay on the matter of material properties, flexural behaviour or overall character of the concrete with little attention on the beam scale shear mechanisms (Behbahani et al., 2011). Although various research studies on hybrid fibre systems have been conducted providing information on the subject, they are still fragmented and there is no established understanding about shear specific behaviour at the structural level (Akbulut et al., 2025).

Consequently, there is a critical gap in linking the experimental evidence, governing parameters, and the mechanistic interpretation of post-cracking shear transfer and the evolution of failure of the SFRC beams. Steel fibres are assumed as the main reinforcement mechanism because of their dominant importance in crack bridging and stress transfer while others are considered in the rest of the paper, where they are important for mechanistic understanding (de Resende & Cardoso, 2023; Zhao et al., 2018).

Both SFRC beams with and without conventional stirrups are studied in order to analyse interaction effect of fibre bridging and transverse reinforcement on controlling shear behaviour (Amin & Foster, 2016; de Resende & Cardoso, 2023).

Materials and Methods

Review type and its Position

This study provides a critical review and synthesis of experimental evidences regarding the shear behaviour and failure mechanisms in steel fibre-reinforced concrete (SFRC) beams. Unlike reviews that focus solely on material-scale properties from coupon tests, the present review examines beam-scale behaviour to ensure direct relevance to structural performance and design applications (Lantsoght et al., 2019).

Instead of focusing solely on ultimate strength prediction, the review emphasizes shear transfer principles, crack evolution, and failure modes. Consequently, this approach provides mechanistic insight into the interaction between steel fibres and concrete reinforcement under shear stress, particularly regarding post-cracking bridging and stress redistribution, which are crucial for SFRC behaviour (de Resende & Cardoso, 2023).

By grounding up the review in experimental evidence at the beam level and focusing analysis on core mechanics, this study ensures that its conclusions are technically defensible, relevant to engineering practice, and directly linked to key gaps in the literature. This approach aligns with the rigour of the database-derived and crack-bridging analyses, thereby providing a transparent and credible synthesis of the shear behaviour of SFRCs (Lantsoght et al., 2019).

Inclusion Criteria

The scope of this review was purposefully designed to ensure direct relevance to shear-critical behaviour in steel fibre-reinforced concrete (SFRC) beams. Only studies that met the following inclusion criteria were considered:

1) Experimental Studies on SFRC Beams. The present review was restricted to beam-scale experimental studies and does not include material coupon or flexure-only tests. This restriction ensures that all findings directly relate to the structural performance and mechanistic understanding of deformation and shear failure (Amin & Foster, 2016; Zhao et al., 2018).

2) Loading Configuration. The included studies reflect results from three-point or four-point bending tests, which are the standard configurations for evaluating shear-critical responses and diagonal crack formation in RC beams (Amin & Foster, 2016; Yuan et al., 2020).

3) Shear-Critical Conditions. Only beams subjected to shear-dominated stress states were included. Studies addressing flexural behaviour alone - or those focussing solely on global capacity without explicitly evaluating shear transfer mechanism - were excluded.

Both beams with and without transverse reinforcement or stirrups were included which allowed to compare the fibre contribution for various cases of shear reinforcement (i.e. with and without stirrups) (Amin & Foster, 2016; Yuan et al., 2020; Zhao et al., 2024).

By applying these strict inclusion criteria, this review employs a rigorous method that yields transparent, defensible results, ensuring all conclusions are grounded in high-quality experimental evidence on SFRC shear behaviour.

Exclusion Criteria

To maintain rigorous validation, explicit measures were taken to exclude studies where findings could not be attributed directly to shear behaviour.

The following categories were excluded from this review:

1) Purely numerical studies lacking experimental validation to verify model accuracy.

2) Material-level testing on non-beam specimens (e.g., pull-out tests, notched prisms, or small-scale coupons), unless the study established an explicit link between material-level response and beam-scale shear behaviour. This avoids over-generalising material-level properties to structural performance (Khan et al., 2022).

3) Investigations focused solely on flexural capacity, impact resistance, or durability with no specific regard for shear transfer mechanisms or failure mode development. While informative on other structural aspects, such studies do not contribute directly to the primary objective of evaluating SFRC shear behaviour (Meda et al., 2012; He et al., 2022).

These exclusions align directly with the review's scope, which emphasises beam-scale shear behaviour and failure mechanisms. This focus distinguishes the present study from broader SFRC reviews that cover general material or flexural properties (Meda et al., 2012).

Results and Discussion

Overview of the Compiled Database and General Shear Behaviour Trends

A comprehensive database was compiled from the reviewed experimental investigations, comprising of Figure 1 to Figure 6, shear-critical tests on SFRC beams both with and without stirrups. The results extracted from the compiled studies are presented in Figures 1-6, displaying total shear strength across a wide range of parameters. Key variables include fibre volume fraction (V_f ranging from 0% to approximately 3%), longitudinal reinforcement ratio (ρ_l from 0% to 3%), and shear span-to-depth ratio (a/d from approximately 0.5 to 4.5). Data points from Figure 1 and 6 differentiate between graphs with fibres

(filled circles) and without fibres (triangles), as well as beams without stirrups and with stirrups. Author-specific series are colour-coded for traceability (e.g., Zhao et al., 2018 in pink/magenta, Amin & Foster, 2016 in red).

Overall trends confirm that the addition of steel fibres consistently increases post-cracking shear capacity relative to plain reinforced concrete (RC) beams. Fibres activate immediately upon diagonal crack formation, providing crack-bridging tensile stresses that stabilise crack propagation, preserve aggregate interlock, and enable stress redistribution. This transforms the inherently brittle shear failure of conventional RC into a more ductile, gradual process, even in the absence of stirrups. The graphs further reveal synergistic effects when fibres are combined with stirrups, with enhanced post-peak load-carrying capacity and reduced crack widths. These observations align directly with the mechanistic justification presented in Section 1.2 and address the literature fragmentation noted in Section 1.3.

Effect of Fibre Volume Fraction (V_f) on Shear Stress

The influence of fibre volume fraction is one of the most pronounced parameters, as evidenced by Figures 1 and 2. Figure 1 presents normalised shear strength (τ/f_c) versus $V_f(\%)$ for beams without stirrups. A clear positive correlation is apparent in several author series, notably Zhao et al. (2018) (pink series), where stress increases from approximately 0.26 atV_f = 0% to 0.29 at $V_f \approx 2\%$. Other series (e.g., Amin & Foster, 2016 in red) show modest but consistent gains with rising V_f, while a minority exhibit flatter or slightly declining trends attributable to specific fibre geometries or workability issues at higher dosages. Critically, specimens with fibres (filled circles) generally plot above the without-fibre triangles at equivalent V_f = 0, confirming the fibre-bridging contribution. The upper-bound trend line (magenta) across the dataset rises gently up to $V_f \approx 2\%$, beyond which marginal returns diminish consistently with practical limits on workability and fibre orientation efficiency.

Figure 2 extends this analysis to beams with stirrups and reveals even stronger benefits. Multiple linear regression trends (e.g., Zhao et al., 2018 in purple) demonstrate steep positive slopes, with τ/f_c rising from ~0.15 at V_f = 0% to over 0.22 at $V_f \approx$ 2–2.5%. Demakos et al. (2021) (yellow-green) and Kevinly et al. (2025) (green) series similarly confirm upward trajectories. The synergy arises because fibres reduce tensile demands on stirrups, delay crack widening, and maintain shear transfer mechanisms longer into the post-cracking regime. Mechanistically, higher V_f increases the number of crack-bridging elements per unit crack area, enhancing direct tension and dowel-like action across inclined cracks (de Resende & Cardoso, 2023; Zhao et al., 2024). These graphs therefore substantiate the review's assertion in the abstract that fibre contents up to 2% markedly improve shear stress while minimising crack widths.

Failure Modes and Mechanisms of transitions & Their Classification of Failure Modes

SFRC beams develop three major failure modes: brittle shear failure, mixed shear-flexural failure and flexure dominated failure. Experimental studies indicate that fibres affect the stability and evolution of these modes in contrast to introducing new mechanics (Saudi Abdul-Zaher et al., 2016; Lantsoght, 2019).

Effect of Shear Span-to-Depth Ratio $\left(\frac{a}{d}\right)$ (1)

where:

a is the shear span,

d is the effective depth of the beam.

The shear span-to-depth ratio exerts a dominant influence on arching action and the transition from shear-compression to diagonal-tension failure. Figure 5 (representative of the a/d plots provided) shows a clear decreasing trend in τ/f_c with increasing a/d for beams without stirrups. At low a/d (≈1.0-1.5), stress reach 0.10 - 0.15 (e.g., Demakos et al., 2021 yellow-green and Kevinly et al., 2025 teal series), reflecting pronounced arching. As a/d rises beyond 2.0, values drop sharply to 0.03 - 0.07, with fitted trend lines (magenta and yellow) confirming the inverse relationship. Fibre-reinforced circles maintain higher residuals than without-fibre triangles at all a/d levels, demonstrating that fibres partially mitigate the loss of arching by sustaining crack-bridging stresses. Higher $\frac{a}{d}$ also correlates with wider cracks and more brittle post-peak response unless compensated by adequate V_f (Arslan et al., 2017; de Resende & Cardoso, 2023).

Initiation of Shear Crack of SFRCs Beams

Shear cracks in steel fibre reinforced concrete (SFRC) beams initiate in similar way as the conventional reinforced concrete beams, which is initiated when principal tensile stresses exceed the tensile capacity of concrete matrix (Arslan et al., 2017; Zhao et al., 2018). Available experimental evidence shows that the use of steel fibres has little effect on the diagonal cracking load, especially at low to moderate fibre volume fraction level, as fibre contribution before forming the crack is minimal (Arslan et al., 2017; Zhao et al., 2018).

Influence of Longitudinal Reinforcement Ratio (ρ_l)

Longitudinal reinforcement ratio (ρ_l) contributes to shear resistance through dowel action and confinement of the compression zone. Figure 3 illustrates τ/f_c versus ρ_l (%) for beams without stirrups. The data exhibit moderate scatter, yet a general positive trend emerges within individual author clusters. For example, Zhao et al. (2018) (pink) and Zhi et al. (2025) (magenta) points at higher ρ_l (≈2–3%) achieve τ/f_c values exceeding 0.25-0.30, while lower-ρ_l specimens (ρ_l < 1%) cluster below 0.05 - 0.10 in some series.

Without-fibre triangles (at $\rho_l \approx$ 2 - 3%) typically fall below fibre-reinforced circles, underscoring that fibres compensate for lower ρ_l by sustaining post-crack tensile capacity. The teal trend line (Meda et al., 2012) shows a modest upward slope, indicating that increased ρ_l enhances dowel action, which fibres further stabilise.

Figure 1
Normalized Shear stress ($\frac{\tau}{f_c}$) versus fibre volume fraction (V_f) for beams without stirrups

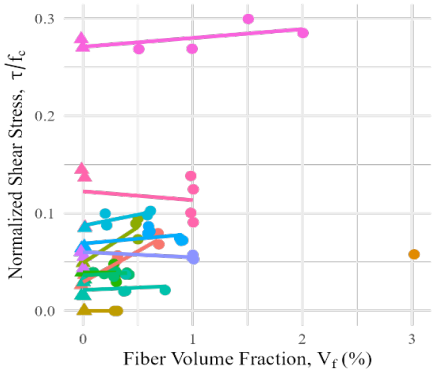


Figure 2
Normalized Shear stress ($\frac{\tau}{f_c}$) versus fibre volume fraction (V_f) for beams with stirrups

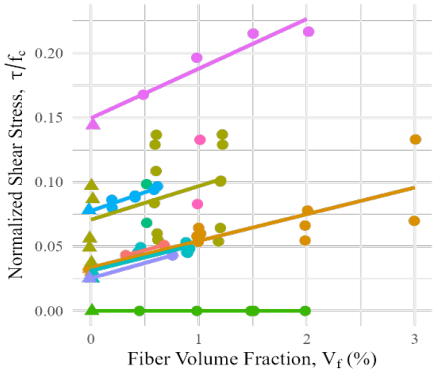


Figure 3
Normalized Shear stress ($\frac{\tau}{f_c}$) vs longitudinal reinforcement ratio (ρ_l) for beams without stirrups

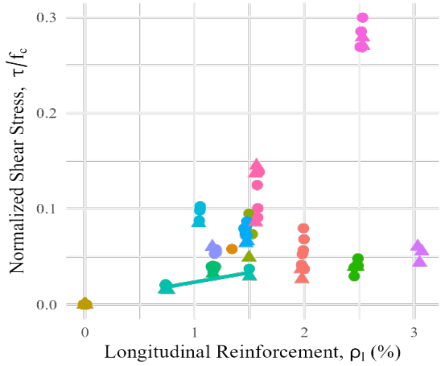


Figure 4
Normalized Shear stress ($\frac{\tau}{f_c}$) versus longitudinal reinforcement ratio (ρ_l) for beams with stirrups

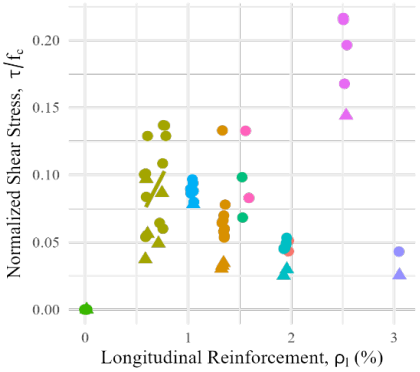


Figure 5
Influence of shear span-to-depth ratio ($\frac{a}{d}$) on shear stress ($\frac{\tau}{f_c}$) without stirrups

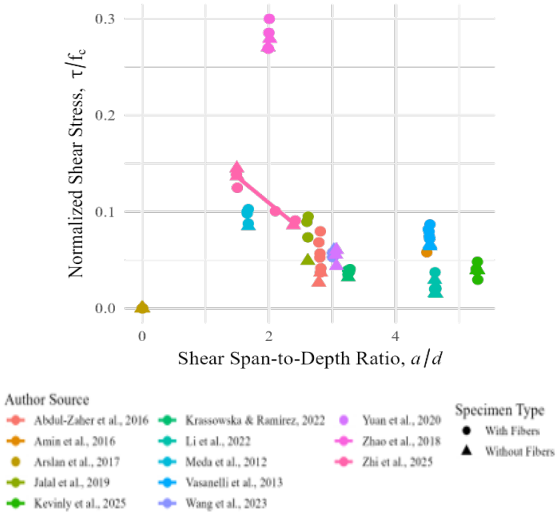


Figure 6
Influence of shear span-to-depth ratio ($\frac{a}{d}$) on shear stress ($\frac{\tau}{f_c}$) without stirrups

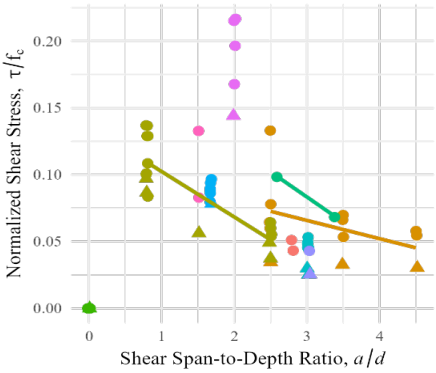


Figure 4 repeats the analysis for beams with stirrups. Here, the scatter is wider, but positive correlations are evident in Zhao et al. (2018) (purple) and Demakos et al. (2021) (yellow-green) series, where τ/f_c from ~0.05 at low ρl to over 0.20 at $\rho_l \approx 2.5$ - 3%. Without-fibre triangles again plot lower, confirming the complementary role of fibres even when stirrups are present. The interaction is mechanistic: higher ρ_l improves arching and dowel resistance, while fibres control diagonal crack opening, allowing stirrups to yield more gradually and thereby increasing overall ductility (Amin & Foster, 2016; Yuan et al., 2020).

Crack Evolution, Failure Modes, Post-Cracking Shear Transfer, and Interaction with Stirrups

Diagonal cracks initiate at loads comparable to plain RC, yet fibres engage instantaneously, limiting initial crack widths and enabling multiple secondary cracks. Post-cracking shear transfer occurs via fibre bridging (direct tension across crack faces), residual aggregate interlock, and enhanced dowel action mechanisms that remain effective even at crack openings up to several millimetres. Failure modes shift from sudden diagonal tension (plain RC) to gradual shear-compression or flexure-shear in SFRC, with fibres and stirrups together producing the most ductile response. The graphs in Figures (1-6) collectively illustrate that hybrid reinforcement yields the highest τ/f_c and smoothest post-peak behaviour, allowing reduced stirrup congestion without sacrificing capacity or robustness (Amin & Foster, 2016; Zhao et al., 2024).

Limitations and Future Research Directions

The compiled results from the illustrated Figures 1-6 indicate longitudinal reinforcement ratio and fibre volume ratio. This Figure indicates that shear resistance in SFRC beams is postulated by a fibre interaction, aggregate interlock, cracks development.

No comparison with the existing predictive models was carried out. Therefore, the data Figures models cannot be indicated from the current data.

Future research should focus on:

- Experimental measurement of crack width, crack slip, and fibre pull-out behavior.
- Large-scale beam tests to quantify size effects on shear resistance.
- Development of models that incorporate fibre efficiency through Figure 1-6 such as fibre aspect ratio ($\frac{l_f}{d_f}$), volume fraction (V_f), and bond effectiveness.

The results confirm that steel fibres contribute to post-cracking shear resistance by limiting crack widths and improving stress transfer across diagonal cracks. However, incorporating these into a design models requires further research and experimental validation.

Propagation of Crack and Post Cracking Stabilized

Following crack initiation, the propagation behaviour of diagonal cracks of SFRC beams is out of line with that in the case of conventional reinforced concrete. Depending on the beam's type, diagonal cracks usually spread quickly to the compression area causing unstable failure in beams that have no fibres. In contrast, experimental researches indicate that fibre reinforcement is responsible for reducing crack propagation rate and promoting the crack branching, which leads to a more distributed cracking pattern (de Resende & Cardoso, 2023).

Experimental results reported by Demakos et al. (2021) suggest that fibre reinforced beams have enhanced deformation capacity with controlled crack widening which can be interpreted as the post-cracking stability. This behaviour is assumed to be attributed to fibre bridging which seems to provide resistance across crack faces and thereby delays localization.

Crack Width development and Distributions

Crack width evolution is an intervening property of SFRC shear behaviour. Experimental studies have always shown that SFRC beams develop more than one and finer diagonal crack instead of single dominant crack, meaning that stress distribution among several cracking planes takes place (Arslan et al., 2017; Saudi Abdul-Zaher et al., 2016).

Direct experimental measurements by de Resende & Cardoso (2023) confirm that fibre bridging helps in delaying the localization of the crack as well as allows to sustain higher shear stresses at similar crack widths. However, such behaviour is conditional. When the fibre pull-out or rupture occurs, the crack widening starts to accelerate rapidly, and there is a lack of shear transfer capacity (Zhao et al., 2018; Zhao et al., 2024).

Effect of Shear-Span to Depth Ratio $\frac{a}{d}$

The ratio of the shear-span to depth (a/d) controls the inclination of crack and predominate load transfer mechanism. Experimental evidence indicates that low $\frac{a}{d}$ ratios lead to steep diagonal cracks and strongly shear-dominated behaviour which reduces the effectiveness of fibre bridging (Arslan et al., 2017; Demakos et al., 2021).

On the contrary, higher a/d ratios enable more gradual crack development and more interactions between fibres and crack surface to improve post-cracking shear resistance (Picazo et al., 2025). This suggests that the effectiveness of the fibre is thus geometry-dependent, and not intrinsic.

Interaction between Fibre Bridging and Stirrups

In beams where fibres and stirrups are used together, the shear resistance depends on the interaction between the member rather than independent contribution. Amin & Foster (2016) proved that the fibres are responsible for crack opening reduction and stirrup yielding, delaying them by transferring the tensile stress over diagonal cracks.

Yuan et al. (2020) further showed that fibre contribution is more significant in the early post-cracking stages while stirrups are a major factor at larger crack widths. This pushing after-pulling type of interaction shows the complementary nature of fibre and conventional shear reinforcement.

Crack localization and Onset of Failure

Despite improvements in the control of cracks, SFRC beams ultimately fail by localization of a critical diagonal. Experimental evidence shows that failure

occurs due to the fibre bridging capacity which either subdues the pull-out or rupture effect through which cracks are rapidly widened, and aggregate interlock is lost (Zhao et al., 2018, 2024).

Fibres provide delayed, and not enough, eliminating brittle shear failure, especially in deep beams or at insufficient fibre content (Saudi Abdul-Zaher et al., 2016; Demakos et al., 2021). This is a confirmation that fibre reinforcement alters the process of failure, and not the basic mechanism.

Duration of Brittle Shear Failure

Brittle shear failure is also a possibility in SFRC beams. Experimental results show that the beams with low fibre content have behaviour similar to conventional reinforced concrete with only moderate improvements in the strength (Saudi Abdul-Zaher et al., 2016).

Zhao et al. (2018) stated that fibre bridging delays the localization of the crack, but when the pull-out capacity is exceeded, it does not prevent the failure. This shows that the nature of fibre reinforcement will not change fundamentally the mechanism of shear failure.

It is observed that with a sufficient fibre volume fraction, a transition to mixed shear-flexural behaviour takes place, leading to stable crack growth and an enhanced ability to deform (de Resende & Cardoso, 2023; Saudi Abdul-Zaher et al., 2016).

Arslan et al. (2017) showed that the crack localization is delayed, i.e., the failure process is more gradual, with increasing the fibre volume fraction.

Flexure-Dominated Failure

Flexure-dominated failure can be observed when the shear resistance is sufficiently improved with the help of fibre reinforcement. This behaviour is observed in beams with higher $\frac{a}{d}$ ratios and sufficient fibre content mostly (Lantsoght, 2019; Resende & Cardoso, 2023).

Amin & Foster (2016) demonstrated that adding fibres reduces the strain demand in stirrups and postpones their yielding.

Yuan et al. (2020) demonstrated that beams with lower stirrup ratios can still achieve equivalent shear performance due to the contribution of steel fibres, thereby confirming the existence of interaction effects.

Conclusions

1. Hooked-end fibres are also associated with better anchorage and higher pull-out resistance, which leads to better crack bridging.
2. Increasing fibre content enhances shear resistance and delays crack localization. However, excessive fibre content reduces ductility and can cause fibre balling.
3. Low $\frac{a}{d}$ ratios favour shear primary behaviour which reduces effectiveness of fibres. Increased ratios increase fibre interaction; increased beam depth makes the fibre less active due to the effect of the stress mixture.
4. It shows that steel fibre primarily elevates the post cracking shear behaviour and the ductility of the reinforced concrete beams by stabilizing the dispersion of the diagonal cracks and improving the crack distribution. While fibres may postpone the localisation of the crack and favour the mixed shear-flexural mode of failure, they do not fundamentally eliminate the shear failure, particularly those in deep beams or those with low shear-span-to-depth-ratio configurations. The effectiveness of fibre is very conditional to fibre type, volume fraction, anchorage, geometry of the beam and arrangement of reinforcement with hooked-end fibre and slender beams showing maximum benefits. Experimental evidence suggest that fibres perform a complementary reinforcement instead of a complete replacement of stirrups. Current modelling approaches and design provisions are still limited in terms of including fibre bridging, size effects, and staged fibre-stirrup interaction, and there is a need for mechanism-based numerical modelling and large-scale experimental validation. Overall, steel fibres have great potential to improve shear ductility and post-cracking performance, but the contribution of steel fibres must be carefully incorporated into design and code development through geometry-aware and evidence-based approaches.

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EXPERIMENTAL INVESTIGATION OF BUCKLING STABILITY OF NON-COMPOSITE-SECTION MULTI-LAYER PANELS UNDER AXIAL COMPRESSION

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Abstract
This paper addresses the buckling stability of multi-layer sandwich wall panels with non-composite connections, where only one layer is subjected to axial compression, whilst adjacent layers enhance its buckling resistance despite the absence of composite action between layers. The aim is to experimentally investigate whether a non-composite connection between a loaded and an unloaded layer can enhance the buckling stability of slender structural elements, to optimise sandwich wall panel design. Small-scale physical models were used for the investigation. Critical buckling height was determined analytically using Euler's formula. Two specimen groups were tested: 300 mm high specimens corresponding to 2.2 times the critical height and 400 mm high specimens corresponding to 3 times the critical height. Each group included plain steel plates (control group) and a series of specimens strengthened with a plywood plate fixed at a distance. Compression load was applied only to the steel plate (5 × 100 mm cross-section). Lateral deflections and ultimate load capacity were measured. Results demonstrate that adjacent layers with non-composite connection improve structural stability. Specimens strengthened with the plywood plates exhibited 43% increase in load-bearing capacity for the 300 mm series and 69% increase for the 400 mm series compared with plain plates. These findings suggest that the loaded layer of sandwich wall panels with non-composite connections can exhibit higher load-bearing capacity. This has important implications for optimising lightweight sandwich panel construction, where mechanical fastening creates a similar non-composite interaction between structural and non-structural layers.
Keywords: buckling resistance, thin-walled structures, sandwich panels, non-composite action, shear connectors.

Introduction

Sandwich-type wall structures (SW) can be used as any other structural wall, with the advantage of having an insulation layer between two concrete layers (PCI Committee on Precast Sandwich Wall Panels, 2011). This configuration allows for improved quality and reduced time and cost of construction work.

To increase the effectiveness of SW, many researchers propose reducing the thickness of the layers. This can be achieved by replacing conventional steel reinforcement, which requires thick concrete cover, with other more advanced types of reinforcement (Kim & You, 2015; Lameiras et al., 2013; O'Hegarty et al., 2019; Sylaj & Fam, 2021). The thickness of the layers in thin-layer SW ranges between 20 and 75 mm (Kim & Allard, 2020; Mugahed Amran et al., 2020; Tawil et al., 2022).

Due to the slender layers, one of the main challenges is preventing the loaded layer from buckling. A strategy is to ensure composite action between the layers to increase the overall stiffness of the cross-section and, consequently, the critical load. Although composite action in SW results in structural advantages, such as flexural stiffness and increased buckling resistance, there are some shortcomings as well. First, achieving full composite action is difficult, as most shear connectors provide only partial composite behaviour (Puzanova & Skadins, 2025). Second, SW with composite action is subjected to bowing, resulting in higher stresses (Skadiņš et al., 2023; Tomlinson & Fam, 2016).

A previous numerical study suggests that even non-composite connection between the loaded and the adjacent layers can increase the load-bearing capacity of SW by postponing buckling of the loaded layer (Skadiņš et al., 2023). To the authors' knowledge, there is no systematic analysis of the buckling performance of thin-layer SW with non-composite connections. Such a configuration of SW would simplify the manufacturing process, prevent the walls from bowing due to temperature or solar radiation loading, and create combined action between the layers to increase the stability of the loaded layer.

This study presents an experimental investigation using small, slender steel plates strengthened with unloaded plywood plates. The aim is to investigate the effect of the adjacent (unloaded) layer on the buckling of a loaded, slender layer connected with non-composite connectors. The following hypothesis is proposed: a non-composite mechanical connection between a loaded slender layer and an adjacent unloaded layer can increase the buckling load compared to an unstrengthened loaded layer. To achieve and the stated aim, the following tasks were set: (1) design and fabricate small-scale test specimens representing loaded and unloaded layer configurations; (2) determine critical buckling height analytically; (3) conduct axial compression tests and measure lateral deflections and ultimate load capacity; (4) compare load-bearing capacity of plain and strengthened specimens. The obtained results can later be applied to improve design strategies for real SW panels manufactured from concrete or combined concrete and cross-laminated timber.

Materials and Methods

In this study, four series of small-size specimens (12 specimens in total) were fabricated and tested under axial compression until failure to evaluate the effect of the adjacent unloaded layer.

Specimens

The test specimens consisted of one or two elements – a slender steel plate and, in two series, a plywood plate.

The loaded layer was made of S235 grade steel, while the unloaded layer was 18 mm thick birch plywood. A total of four series were tested under axial compression: two series of plain plates (30 and 40) and two series of strengthened plates (30_18 and 40_18). Each series included three specimens with identical cross-sectional dimensions of the load-bearing steel plate element, measuring 5×100 mm. The specimen parameters of all series are summarised in Table 1. The elements were connected with M4 mm threaded rods, with horizontal spacing $s_x = 60$ mm and vertical spacing $s_{y1} = 110$ mm; in series 4 and 4_18, $s_{y2} = 120$ mm. The edge distances were $e_v = 30$ mm in the vertical direction and $e_x = 20$ mm in the horizontal direction. The clear distance between layers was $h_0 = 60$ mm, creating a non-composite gap connection between the loaded and unloaded elements, as illustrated in Figure 1.

Figure 1
Schematic representation of specimen geometry. (1 – steel plate, 2 – birch plywood layer, 3 – M4 threaded rod connector, 4 – screw nut)

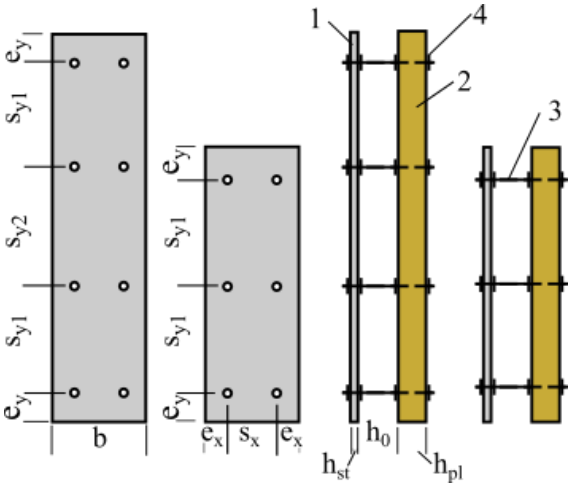


Table 1
Test specimen parameters

Series	Number of spec.	Height, mm	Strengthening element
30	3	300	–
30_18	3	300	18 mm plywood
40	3	400	–
40_18	3	400	18 mm plywood

The steel plate was selected as the primary test material due to its isotropic nature – meaning its mechanical properties are uniform in all directions – making it the most suitable material for initial experimental investigation. The steel material properties adopted in this study are assumed to be consistent with the values specified in Eurocode 3 (CEN, 2005) and summarised in Table 2. Birch plywood properties for 18 mm are adopted from Ozola (2018) and are summarised in Table 3.

The critical buckling length l_{cr} was determined using formula (3), derived from Euler's buckling equation (1), where the critical stress σ_{cr}(2) is replaced by the yield strength f_y of steel, ensuring that the specimen failure occurs due to buckling rather than material yielding.

Table 2
Mechanical properties of steel S235

Property	Symbol	Value	Unit
Modulus of elasticity	E_s	210000	MPa
Yield strength	f_y	235	MPa
Ultimate tensile strength	f_u	360	MPa

Table 3
Mechanical properties of birch plywood

Property	Symbol	Value	Unit
Modulus of elasticity	E_{pl}	10000	MPa
Bending strength	f_m	40.2	MPa
Tensile strength	f_t	39.2	MPa
Compressive strength	f_c	27.2	MPa
Shear strength	f_v	9.5	MPa
Density	ρ	680	kg/m^3

$$F_{cr} = \frac{\pi^2 \cdot E \cdot I}{l^2} \quad (1)$$

$$\sigma_{cr} = \frac{F_{cr}}{A} \quad (2)$$

$$l_{cr} = \sqrt{\frac{\pi^2 \cdot E \cdot I}{f_y \cdot A}} \quad (3)$$

I is the second moment of area of the cross-section about the axis of least resistance, E is the modulus of elasticity of the material, l – effective length of the specimen, and A is the cross-sectional area of the loaded steel plate.

The critical buckling length l_{cr} determined according to formula (3) for a steel plate with strength class S235 and the cross section of 5×100 mm for the axis of least resistance is 135.6 mm.

The slenderness ratio of the steel plate λ, as well as the critical height determined with respect to the axis of least resistance, was calculated according to formulas (4) and (5), where i_{min} denotes the minimum radius of gyration:

$$\lambda = \frac{\mu \cdot l}{i_{min}} \quad (4)$$

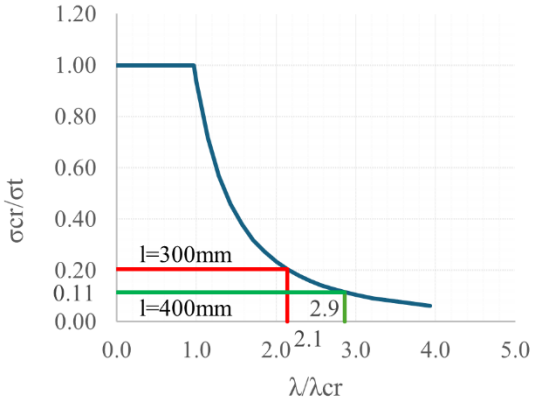
$$i_{min} = \sqrt{\frac{I}{A}} \quad (5)$$

The effective length factor was taken as $\mu = 1$, corresponding to pin-ended boundary conditions. In the experimental setup, these conditions were achieved by providing appropriate supports – pinned at the bottom and roller support at the top as shown in Figure 3.

The length of the specimens (300 and 400 mm) was selected for experimental testing, corresponding to ratios of critical stress to yield stress of 0.2 and 0.11, respectively, as illustrated in Figure 2. These values were chosen to ensure that the specimens fail due to buckling rather than reaching strength criteria and to evaluate the effect of the slenderness.

Figure 2

Normalized critical stress versus normalized slenderness ratio for S235steel with a 5×100 mm cross-section



Test set-up

The specimens were loaded using a servo-hydraulic testing machine Form-Test Delta-5. The load was applied axially along the longitudinal axis of the specimen, ensuring controlled and incremental loading as illustrated in Figure 3.

Lateral deformations were measured at mid-span of the steel plate using a linear variable differential transformer (LVDT) type transducer with a measurement resolution of 1/1000 mm. Measurements were recorded continuously throughout the loading process, allowing the acquisition of complete load–deformation curves and enabling analysis of the specimen's structural behaviour.

Prior to loading, the initial geometric imperfections of all steel plates were measured using a feeler gauge (range: 0.002–1.00 mm). The measured imperfection values range from 0.1 to 0.5 mm and are summarised in Table 4.

Results and Discussion

The experimentally obtained maximum loads and corresponding statistical parameters for all four series are summarised in Table 5 and illustrated in Figure 4.

Behaviour of the specimens

In all cases, with the increase of vertical load, the horizontal displacement at the middle of the specimen increased, thus, increasing second order bending moments in the loaded plate. In some series, the magnitude of the displacement is strongly related to the initial imperfections given in Table 4. In some cases, the initial displacement developed in one direction; however, at a certain load level it started to deform in the opposite direction. This might be explained by the form of the initial imperfections. For some specimens, a twisted shape of the plate was observed.

Figure 3

Test setup: a) schematic representation of sample test setup b) specimen of series 30_18 in the test rig (1 – steel plate, 2 – plywood layer, 3 – M4 threaded rod connector, 4 – double acting roller support, 5 – displacement transducer, 6 – roller support)

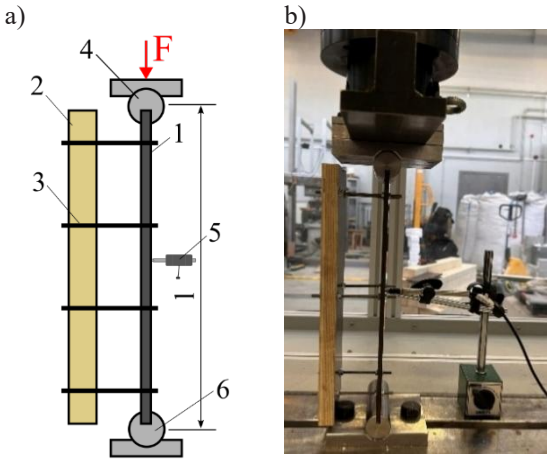


Table 4

Steel plate initial imperfections

Series	Imperfections, mm		
	Specimen		
	1	2	3
30	0.25	0.1	0.15
30_18	0.2	0.09	0.15
40	0.25	0.2	0.25
40_18	0.1	0.4	0.5

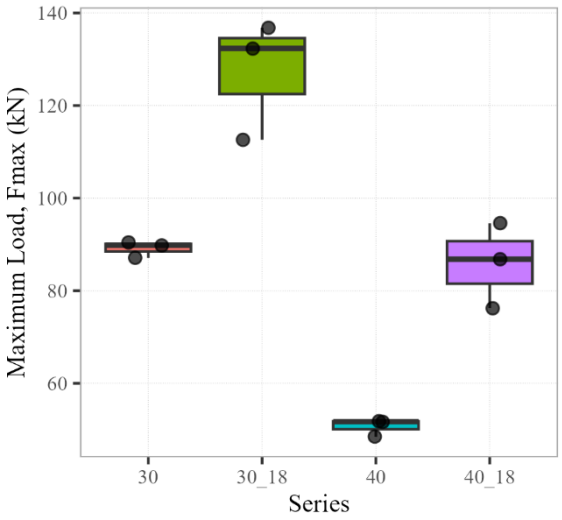
All of the specimens failed by reaching the yield strength of the steel, except for series 40, where elastic buckling was observed. The specimens of the series 30 failed at the middle of the height, resulting in plastic deformations as it is seen in Figure 7, which corresponds to the section of maximum second order moment. The strengthened specimens of series 30_18 and 40_18 show higher load bearing capacity if compared to the corresponding plain plates without any strengthening. The specimens failed at a section between the horizontal connectors, not in the middle of the height of the specimen. That shows that the adjacent plywood slab and the horizontal connectors provided horizontal supports stiff enough to prevent the slender steel plate from buckling.

Maximum load

The plain plate series 30 achieved a mean maximum load of 89.1 kN with a standard deviation of 1.75 kN,

indicating highly consistent behaviour among the three specimens. Similarly, the plain plate series 40 showed a mean maximum load of 50.7 kN with a standard deviation of 1.94 kN, confirming good repeatability.
The strengthened plate series 30_18 achieved a mean maximum load of 127.2 kN, an increase of approximately 43% over the plain plate series 30. However, the standard deviation of 12,87 kN was notably higher, reflecting greater variability among the specimens. The strengthened plate series 40_18 achieved a mean maximum load of 85.9 kN, corresponding to an increase of approximately 69% relative to the plain plate series 40, with a standard deviation of 9.21 kN.
The coefficient of variation (CV) is used to measure the consistency of results within each series. The plain plate series showed low variability, with CV values of 2.0% for series 30 and 3.8% for series 40, resulting in an average CV of 2.9% for the plain plate series. In contrast, the strengthened plate series exhibited considerably higher variability, with CV values of 10.1% for series 30_18 and 10.7% for series 40_18, giving a mean CV of 10.4%. This difference in variability between plain and strengthened plates can be attributed to uncertainties in the strengthening system - specifically, the inherent material variability of birch plywood and the precision of the mechanical fasteners.

Figure 4
Maximum load by specimen series



The load–horizontal deflection curves for all series are shown in Figures 7 and 8. For the plain series 30, all three specimens displayed similar behaviour: horizontal deflections increased gradually with load, reaching a maximum of approximately 2 mm at peak load, followed by a gradual post-peak decline characteristic of elastic-plastic buckling. The strengthened plate series 30_18 achieved notably higher peak loads while maintaining similar horizontal deflections at failure – about 2 mm, indicating that the plywood layer effectively restrained lateral displacement and delayed the onset of buckling. For the plain plate series 40, the specimens developed larger horizontal deflections of up to 6 mm before failure, with no signs of material yielding, which is characteristic of elastic buckling. The strengthened series 40_18 also showed higher peak loads, but with a different lateral deflection response of approximately 4–5 mm. The samples of observed failure modes are illustrated in Figures 5 and 6.

Figure 5
Failure of specimen 30-1

a) b)

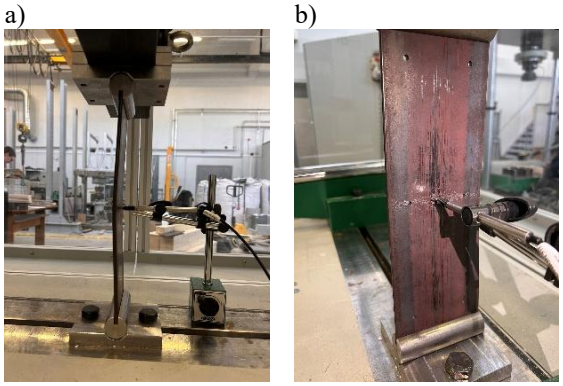


Figure 6
Failure of specimen 30_18-1

a) b)

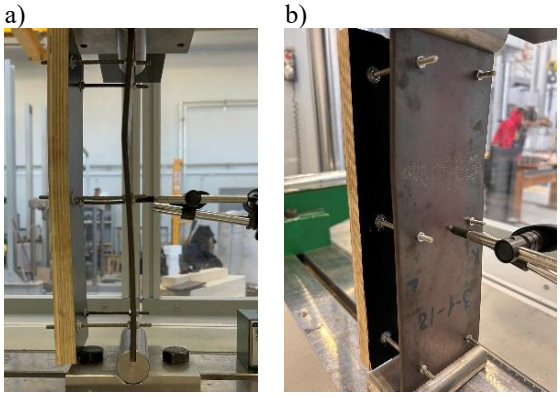


Table 5
Experimentally obtained maximum loads and corresponding statistical parameters

Nr.	Sample series	n	Mean F_{max}	Standard deviation	Min F_{max}	Max F_{max}	Coefficient of variations
			kN		kN	kN	%
1	30	3	89.1	1.749	87.11	90.38	2.0
2	30_18	3	127.2	12.873	112.6	136.78	10.1
3	40	3	50.7	1.939	48.44	51.88	3.8
4	40_18	3	85.9	9.206	76.24	94.58	10.7

Figure 7

Experimentally obtained load versus lateral displacement curves for series with length 300 mm: Series 30 – plain plates; Series 30_18 – strengthened plates

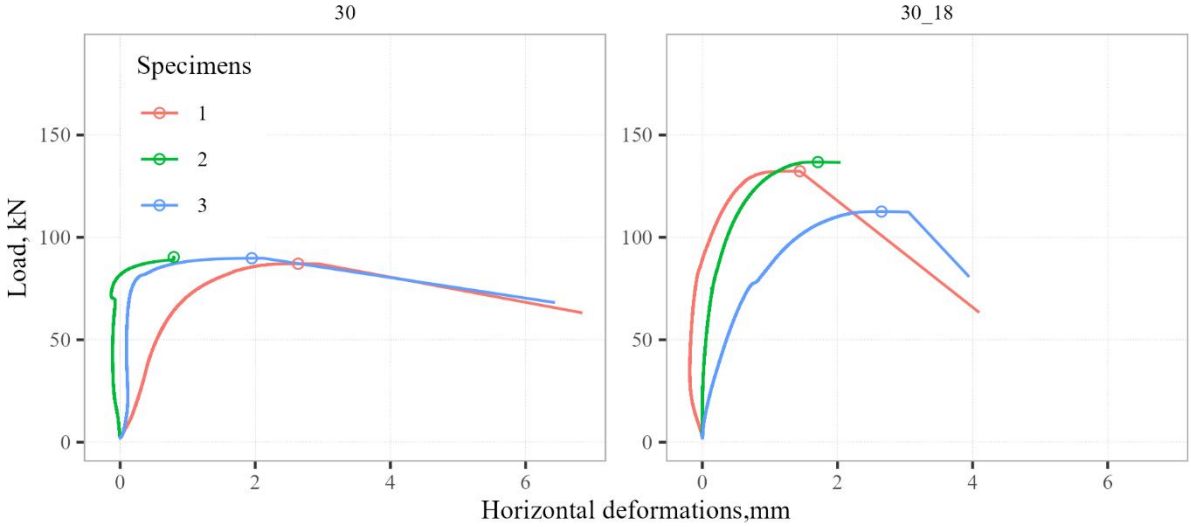
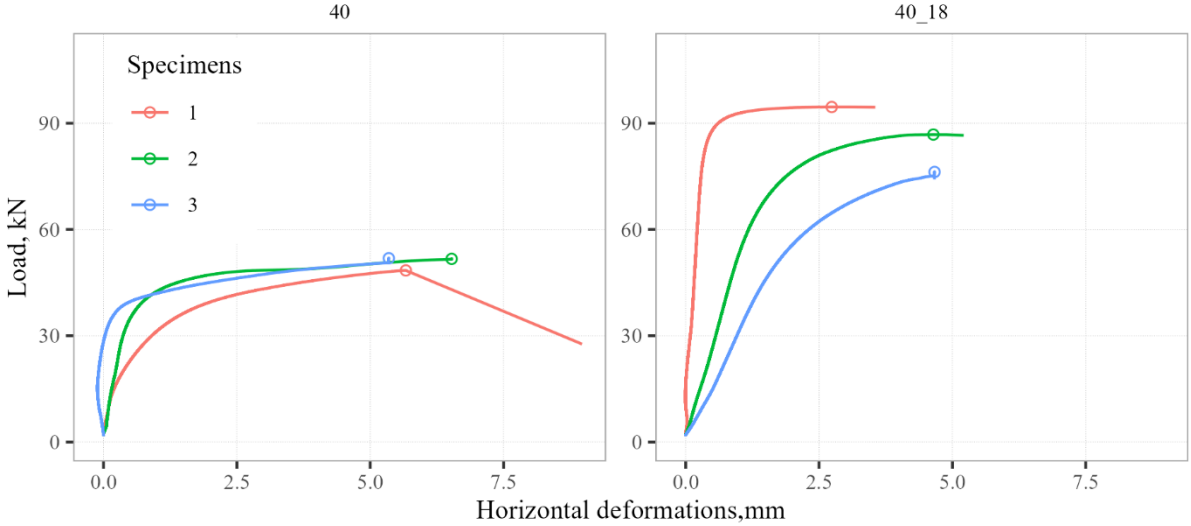


Figure 8

Experimentally obtained load versus lateral deflection curves for series with length 400 mm: Series 40 – plain plates; Series 40 18 – strengthened plates



Sandwich walls

The results of this study demonstrate that the load-bearing capacity of slender steel plates under axial compression can be improved by attaching an adjacent unloaded plywood layer. The bending stiffness of the steel plate is $E_s I_{s,z} = 21875\ kNmm^2$, while the bending stiffness of the 18 mm birch plywood layer is $E_{pl} I_{pl,z} = 486000\ kNmm^2$, which is 2.2 times stiffer than the steel plate.

This suggests that non-composite connections between the loaded and its adjacent unloaded layers can be used to design SW with more economic cross-sections. As a result, SW structures with increased load bearing capacity and the advantages of non-composite cross-section (no bowing effect, more simple connections) can be obtained. These experimental findings align with the numerical results reported by Skadins et al. (2023), where the results of numerical analysis showed that SW with non-composite connections between the loaded and adjacent layers can increase the load-bearing capacity of SW panels by delaying the onset of buckling.

To apply the findings to real SW, a further research is needed. There are several parameters that could influence the load bearing capacity. Some of them are: 1) stiffness of the adjacent layer compared to the loaded one; 2) axial stiffness and spacing of the connectors; 3) presence of the insulation layer and its mechanical properties. The root cause of these uncertainties must be clearly understood.

Conclusions

1. The proposed hypothesis is confirmed: small-scale experimental testing confirmed that adding an

unloaded plywood layer connected to the loaded steel plate with non-composite mechanical fasteners enhances the load-bearing capacity of the slender steel plate under axial compression – by 43 % for 300 mm specimens and 69 % for 400 mm specimens.

2. Pure elastic buckling failure was observed only in the plain plate series with a height of 400 mm. In all other series, the failure was governed by the second-order moments, resulting in plastic deformations at a critical section.

3. A clear correlation was observed between the size of initial geometric imperfections and the lateral deformation response during loading. In several specimen series, larger initial imperfections led to increased horizontal displacements at similar load levels, affecting the development of second-order bending moments and the ultimate failure load. However, this trend was not consistent across all series, indicating that other factors like connector accuracy and plywood variability also played a role in the observed behaviour.

4. The results confirm that even non-composite connections between the loaded and adjacent unloaded layers can substantially enhance buckling stability. This has practical implications for the design of thin-layer sandwich wall panels, where mechanical fastening creates a similar non-composite interaction between structural and non-structural layers.

5. Further research is necessary to evaluate how key parameters affect the load-bearing capacity of sandwich wall panels with non-composite connection, including (1) the relative bending stiffness of the adjacent layer relative to the loaded layer, (2) connector axial stiffness and spacing, and (3) the presence and mechanical properties of the insulation layer.

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IMPACT OF UNIFORMLY DISTRIBUTED LOAD TYPES ON DEFLECTION OF SFRC FLAT SLABS

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Abstract
In full-scale tests conducted in 2023 on two steel fibre-reinforced concrete (SFRC) and steel fibre-reinforced self-stressing concrete (SFRSSC) flat slabs, a cumulative increase in deformation and cracking was observed due to daily temperature variations. Slabs measuring 15 × 16 m and 150 mm thick were loaded with a uniformly distributed load (UDL) of 26 kN/m^2 using sandbags as the loading unit. Deformations due to daily temperature variations increased stepwise, and after 7 days of sustained loading, deflections increased by 2.5 times for the SFRC slab and 2 times for the SFRSSC slab, rising from 3.6 to 9 mm and from 3.1 to 6.5 mm, respectively. In 2024, similar tests were conducted on identical slabs to those in 2023. Two slabs were loaded with a uniformly distributed load of 30 kN/m^2 using concrete blocks arranged with a gap between them to prevent arching. Deflections were monitored along with the temperature variations over time. After the load was applied, the instantaneous deflections of both slabs were about 1.0 mm. Over the next five months, deformations increased by only 0.4 mm. Instead of the stepwise increase seen in the previous test, a cyclic daily fluctuation in deformations was observed due to temperature variations. After cracking, deflections increased over five months for about 2.6 mm (0.13 mm per week) for SFRC and 1.6 mm (0.08 mm per week) for SFRSSC slabs, respectively. Those findings indicate that the type of loading may influence long- term deflection and cracking of slabs.
Keywords: full-scale test, long-term load, steel fibre reinforced concrete (SFRC), temperature load, creep.

Introduction

Experimental tests on full-scale elevated steel fibre reinforced concrete (SFRC) slabs are reported in several scientific papers (Destrée et al., 2019) and reports (ACI Committee 544, 2015). Most of these tests focus on the instantaneous behaviour of the slabs under a point load (Aidarov et al., 2021; Parmentier et al., 2016). Several tests have been performed using uniformly distributed loads (UDL) (Popescu & Täljsten, 2023; Suta et al., 2024). However, few experimental studies have reported analyses of the long-term behaviour of SFRC slabs subjected to UDL (Aidarov et al., 2021; Salehian & Barros, 2015). While some tests show stable deflections (Aidarov et al., 2021; Salehian & Barros, 2015), others report significant increases in deflections over time (Popescu & Täljsten, 2023; Skadiņš et al., 2024).

Several processes or conditions cause time-dependent effects in SFRC slabs: 1) creep of concrete subjected to compression results in an increase in deflections over time; 2) creep of a cracked section of SFRC causes further widening of cracks (Abrishambaf et al., 2015; Casucci et al., 2019); 3) cyclic loading can increase crack width over time due to the irreversible part of the crack opening and closing process (Boulekbache et al., 2016; Menna et al., 2023; Sherif et al., 2018); 4) combination of the above-mentioned processes, e.g., combined action of cyclic loading and creep (Kern et al., 2021, 2024; Koh et al., 1997).

Cyclic loading is induced by temperature and solar radiation, causing differences in elongation between the top and bottom surfaces (Zhang et al., 2025). These differences result in bending moments and deflections of the slab. Both solar radiation intensity and temperature fluctuation throughout the day, driving daily temperature load cycles. Due to these daily cycles, a stepwise increase in deflections and crack widths was observed in two elevated SFRC/SFRSSC test slabs in Jelgava, Latvia, in 2023 (Skadiņš et al., 2024, 2026), with deflections increasing from 3 mm to 9 mm over a single week. The authors of the study suggest that this may be due to the arrangement of the UDL, achieved with tightly packed sandbags that can prevent slabs from returning to their original shape once the imposed temperature load is removed, resulting in an arching effect.

To confirm the hypothesis that the observed increase in deflections was mainly due to the way the load was applied, another pair of SFRC/SFRSSC slabs was tested a year later under a UDL using concrete blocks with gaps between them to prevent the arcing effect. The load was sustained for more than a year, and data on deflections and daily temperature variations were recorded and compared to the previous tests.

The aim of this study is to evaluate the effect of load arrangement on the behaviour of flat slabs subjected to cyclic loading, based on the results from the two pairs of full-scale experimental tests mentioned above, comparing the relationship between deflection behaviour and temperature variations.

Materials and Methods

In 2023, two full-scale slabs (later referred to as SFRC-1 and SFRSSC-1) were produced and tested in Jelgava, Latvia. Dimensions of the slabs were 15 × 16 m in the plane and 150 mm in thickness. The slabs were supported by round reinforced-concrete columns 300 mm in diameter, with spans up to 3 m. More detailed descriptions of the slabs are published by Suta et al. (2024). The concrete design for both slabs was identical, except for a chemical component that introduced the prestressing effect. One cubic meter of concrete mix contains 360 kg of CEM II/A-LL 52,5, 162 kg of water (w/c ratio 0.45), 952 kg of sand, 914 kg of dolomite gravel (5 – 16 mm), 3.6 kg of admixture PrīmX Flow HRWRA, 50 kg of 60 mm long 0.9 mm in diameter hooked-end steel fibres as an only reinforcement of the slab, and 40 kg PrīmX DC (only

for SFRSSC-1).

A load level of 26 kN/m² was achieved using sandbags as the loading units (Figure 2a). Each bag weighed 10 kN, and they were arranged in three layers. Deflections of the slab were measured using linear displacement transducers with a measuring range of 75 mm. There were five sensors that took measurements at different locations on the bottom surface of the slab (Figure 1a). A pair of Rissfox Mini data loggers with Rissfox Multisensor expansion modules was used to collect the data. Along with the slab deflection, the temperature near the bottom layer of the slab was also recorded.

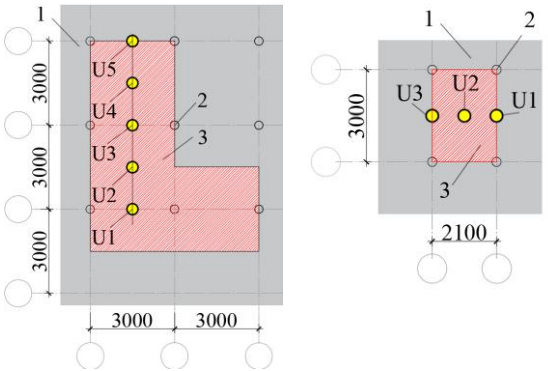
The following year, similar tests were conducted on two slabs that were geometrically identical to those in 2023 (later referred to as SFRC-2 and SFRSSC-2). The design of both slabs was the same, except for a chemical component that provided the prestressing effect. One cubic meter of concrete mix contains 360 kg of CEM II/A-LL 52,5, 165 kg of water (w/c ratio 0.467), 783 kg of sand, 1091 kg of dolomite gravel, 3.24 kg of admixture PrīmX Flow HRWRA, 50 kg of 60 mm long 0.9 mm in diameter hooked- end steel fibres, and 40 kg of PrīmX DC (only for SFRSSC-2). No complementary reinforcement was added.

Slabs were loaded with concrete blocks (Figure 2b) measuring 600×600×600 mm. Each block weighed 5.20 kN, and they were arranged in three layers, creating a uniformly distributed load of 30 kN/m^2. Blocks were placed with a gap between them to prevent arching effects.

Deflections of the slabs were measured at three points at the bottom surface of the slabs using the same linear displacement transducers as in the 2023 tests. The loading area and sensor arrangement are shown in Figure 1b.

Figure 1

Arrangement of deflection sensors U1...U5 on slabs: a) SFRC-1 and SFRSSC-1 and b) SFRC-2 and SFRSSC-2 (1 – slab; 2 – column; 3 – loaded area)



a) b)

Concrete material properties, such as compressive and post-cracking flexural strength, were obtained from specimens produced alongside the full-scale slabs. The obtained material properties are shown in Table 1.

Compressive strength was determined in accordance with EN 12390-7 using 300 mm high concrete cylinders with a diameter of 150 mm.

Table 1

Material properties

Property	SFRC-1		SFRC-2		SFRSSC-1		SFRSSC-2	
	Value	CoV, %	Value	CoV, %	Value	CoV, %	Value	CoV, %
Compressive strength, MPa	41.03	4.3	50.90	2.9	49.29	1.6	52.80	5.1
Post-cracking flexural strength, MPa								
$f_{R,L}$	4.93	8.1	5.43	6.0	6.63	4.3	6.03	7.0
$f_{R,1}$	5.13	18.2	5.32	32.0	7.83	15.4	6.27	21.0
$f_{R,2}$	6.18	14.1	6.35	36.0	9.38	10.3	7.00	20.0
$f_{R,3}$	6.13	9.7	6.18	34.0	8.66	9.4	6.95	18.0
$f_{R,4}$	6.10	10.1	5.85	32.0	8.05	15.2	6.57	22.0

Figure 2

Slab loading with (a) sandbags and (b) with concrete blocks



a) b)

For loading, a Matest hydraulic press (2000 kN, Class 1) was used. The post-cracking flexural strength was determined in accordance with EN 14651 using concrete prism specimens subjected to three–point bending tests. The specimens were tested in the Matest Hydraulic press (Form + Test Delta 5-300, Class 1). The tests were controlled by crack mouth opening displacement (CMOD) using a Pi- shape displacement transducer, PI-5-50 (Tokyo Measuring Instrument Lab), with a gauge length of 50 mm.

Results and Discussion

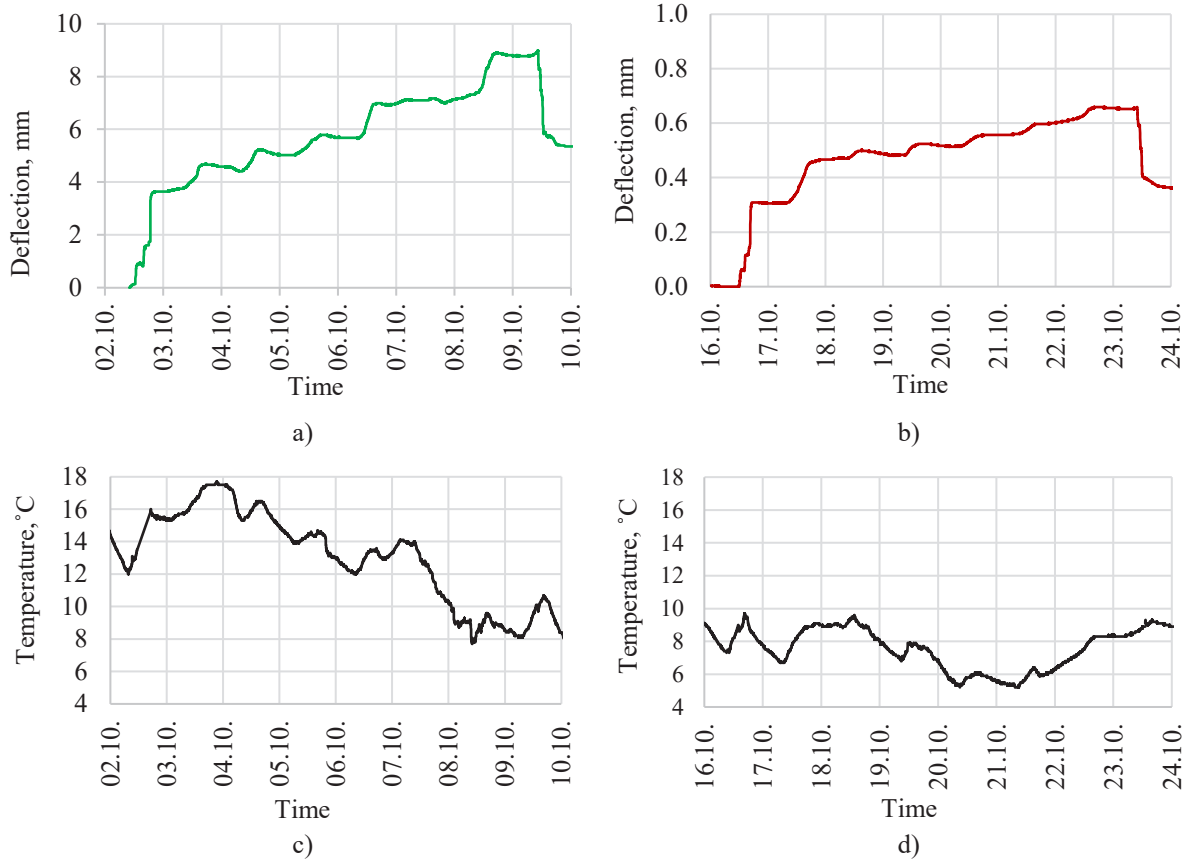
The deflection comparison is analysed at position U2 (Figure 1), which is in the middle of the spans, where the largest deformations were observed.

In 2023, deformations gradually increased due to daily temperature fluctuations. After 7 days of sustained loading, deflections increased stepwise by 2.5 times for the SFRC-1 slab and by 2 times for the SFRSSC-1 slab, rising from 3.6 to 9 mm and from 3.1 to 6.5 mm, respectively (Figure 3). The temperature variations during the week were 10 °C for the SFRC-1 slab and 5 °C for the SFRSSC-1 slab, with a decreasing trend. The daily variations in surface temperature during that period ranged from 2.0 to 2.5 °C. During the daytime, when the temperature increases by 1 °C, deformations grow by 1 mm for the SFRC-1 slab and by 0.3 to 0.5 mm for the SFRSSC-1 slab. During the night, when the temperature dropped by about 2.5 °C, deformations decreased by only 0.1 – 0.15 mm. After the load was removed, irreversible deformations measured 5.1 mm for the SFRC-1 slab and 3.6 mm for the SFRSSC-1 slab.

In the 2024 test, after the load was applied, the instantaneous deflections of both slabs were approximately 1.0 mm (Figure 4a), and no cracks were observed. After one week of sustained loading, deformations fluctuated during the daily temperature variations, but showed no increase in general. The temperature variations during the first week of the test were 7.5 °C. The daily fluctuations in surface temperature during that period ranged from 3 to 4 °C (Figure 4c). During the daytime, when the temperature increased by 4 °C, deformations increased by 0.2 to 0.3 mm and decreased by the same amount at night (Figure 4b). Instead of the stepwise increase seen in the previous test, a cyclic daily fluctuation in deformations was observed. Over the next five months, deformations increased by only 0.4 mm. After cracking, deflections increased over five months for about 2.6 mm (0.13 mm per week) for SFRC-2 and 1.6 mm (0.08 mm per week) for SFRSSC-2 slabs.

Figure 3

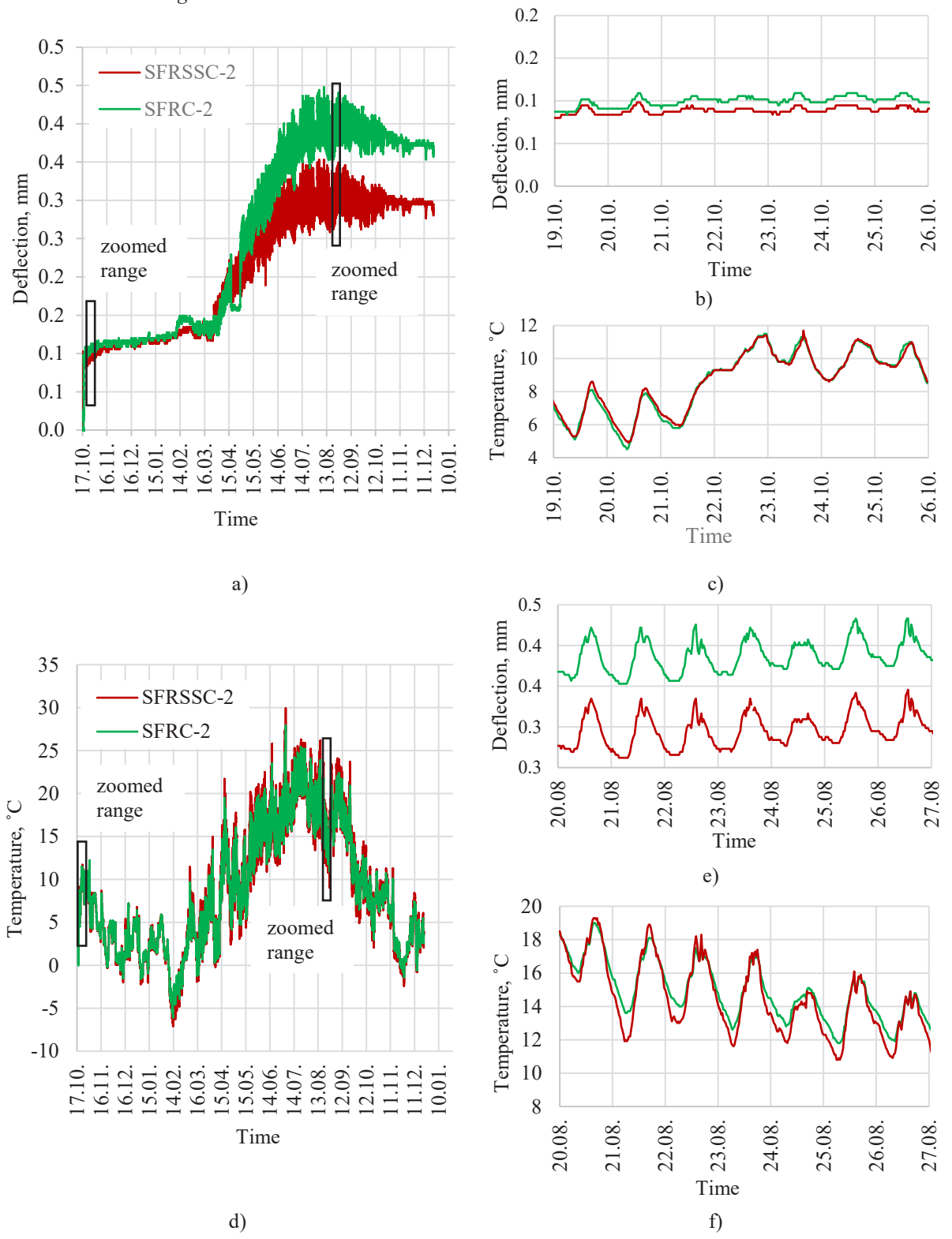
Recorded variations of: a) deflections at the midspan (U2) of SFRC-1, b) deflections at the midspan (U2) of SFRSSC-1 and c), d) temperature



In the cracked stage, the slabs' deformations due to the daily temperature fluctuations showed the same cyclic pattern as in the uncracked stage, instead of the stepwise pattern observed in the test in 2023 (Figures 4e and 4f). The temperature variations during the week of long-term loading were 7–8 °C. The daily fluctuations in surface temperature during that period ranged from 4 to 7 °C During the daytime, when the temperature increases by 7 °C, deformations grow by 0.7 to 0.8 mm.

Figure 4

Recorded variations of: a) deflections at the midspan (U2), d) temperature and b), c), e), f) corresponding zoomed one-week range



To compare the results and evaluate the influence of creep (Equation (1), irreversible cracking (Equation (2), and loading type (Equation (3)) in 2023 tests, the week deformations from the 2024 tests for cracked and uncracked concrete are compared with the total deformations over a week period in the 2023 tests.

$$u_{creep} = \frac{\Delta_{u,week,creep,2024}}{\Delta_{u,week,total,2023}} \cdot 100\% \quad (1)$$

$$u_{irr} = \frac{\Delta_{u,week,irr,2024}}{\Delta_{u,week,total,2023}} \cdot 100\% \quad (2)$$

$$u_{LT} = 100\% - (u_{creep} - u_{irr}) \quad (3)$$

where u_{creep} – deformations caused by creep; u_{irr} – deformations caused by irreversible cracking, u_{LT} – deformations caused by loading type (tightly packed sandbags), $\Delta_{u,week,total,2023}$ – total deformations over a week period in 2023, $\Delta_{u,week,creep,2024}$ – deformations in 2024 tests over a week period caused by creep (uncracked concrete), $\Delta_{u,week,irr,2024}$ – deformations in 2024 tests over a week period caused by irreversible cracking (cracked concrete).

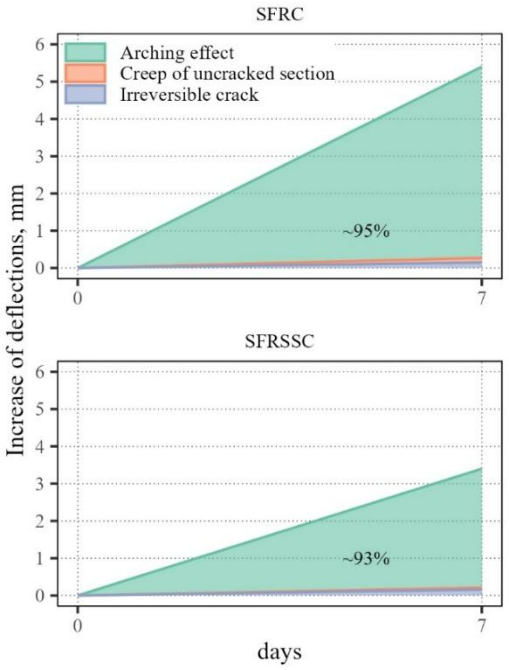
A creep effect on the deflections of the slabs tested in 2024 can be observed. In the uncracked stage, the deflections increased by about 40% (from 1.0 mm to 1.4 mm) over five months. This could be caused by creep deformations in the compression zone, resulting in an increase in the curvature. Although the observed increase developed faster in the first month, it is rather small, with a 0.05–0.12 mm increase in the first week of loading, which is 2% of the increase observed in the 2023 test.

In the cracked stage of the 2024 test, an increase in deflections is observed as well. This could be attributed to either creep of the cracked SFRC section (Abrishambaf et al., 2015; Casucci et al., 2019) and/or the partly irreversible nature of SFRC at cracks subjected to cyclic loading (Boulekbache et al., 2016; Menna et al., 2023; Sherif et al., 2018). However, the magnitude of the increase in deflections over a single week is just about 0.15 mm (Figure 4e), which is 3–5% of the increase observed in the 2023 test.

Based on the data obtained from the 2024 test, the total contribution of creep and the irreversible nature of the cracked section to the increase in deflections in the 2023 test could be about 5 –7 %. The value should be adjusted considering the differences in material properties and the level of normal stresses developed in both tests. However, these effects represent only a small fraction of the observed increase (Figure 5). The comparison of results from both tests shows that the UDL arrangement has a significant influence on the time-dependent load–deflection behaviour of flat slabs. Given that similar load levels were applied and concrete with similar compressive strength was used in both tests, the interaction effect between the deformed slab and the tightly packed sandbags, as suggested by Skadiņš et al. (2024), is the most plausible explanation of the extremely large increase in deflection over a single week.

These findings are important not only for the design of full-scale tests, but also for structures loaded with sand-like materials and subjected to daily temperature variations. Such structures might include retaining walls, outdoor material storage facilities, raft foundations for car parks, and others. To better explain the observed increase in deflections of cracked slabs in the 2024 test, further long-term tests are needed, where the effect of cyclic loading on the creep of cracked SFRC sections is evaluated.

Figure 5
Possible causes of increased deformation in slabs



Conclusions

In this study, the effect of load arrangement on the behaviour of flat slabs subjected to cyclic loading, based on the results from the two pairs of full-scale experimental tests, was evaluated, and the relationship between deflection behaviour and temperature variations was compared. The following conclusions can be made:

1. Deflections of the slabs loaded with tightly packed sandbags increased with the increase of daily temperature, showing no recuperation of the deflection after the drop in temperature.
2. Deflections of the slabs loaded with concrete blocks with gaps between them increased and decreased following the pattern of the temperature variations – no significant accumulation of deflections over a period of a week was observed.
3. Those findings indicate that the type of loading influences long-term deflection and cracking of slabs.
4. Further investigation should be conducted to observe the possible creep effects, excluding the daily temperature fluctuations.

Acknowledgements

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LONG-TERM CHANGES IN ARABLE LAND, MEADOWS AND NATURAL PASTURES, ORCHARDS IN LITHUANIA

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Abstract
The analysis is based on official statistical data covering the period 2005–2025 and includes Lithuania and its ten counties. Using statistical analysis and grouping methods, the structure of land use and its temporal changes were assessed, with particular attention to arable land, meadows and natural pastures, and orchards. The results reveal a clear transformation of Lithuania's agricultural land-use structure. Arable land remains the dominant form of land use and its share and importance have increased over time, confirming a long-term trend of agricultural intensification of land-use systems. In contrast, the areas of meadows and natural pastures, as well as orchards, have significantly declined, indicating a gradual weakening of extensive land-use forms and a reduction in land resources important for livestock farming and traditional rural landscapes. Territorial differences among counties persist and highlight a pronounced regional differentiation of land-use structures. Arable land is more dominant in regions characterized by intensive agricultural activity, whereas the relative proportion of meadows, natural pastures, and orchards remains higher in less intensively used areas. These spatial patterns indicate ongoing landscape homogenization alongside continued restructuring of rural land-use systems. The study demonstrates a consistent shift towards a land-use structure increasingly dominated by arable land in Lithuania, accompanied by the decline of meadows, natural pastures, and orchards, as well as the strengthening of regional land-use differentiation.
Keywords: land-use change, structure of agricultural land, change in agricultural land areas.

Introduction

Changes in the structure of agricultural land constitute one of the key indicators of territorial development, landscape transformation, and sustainability. Scientific literature emphasizes that land-use change reflects not only economic processes but also political decisions, technological progress, demographic trends, and societal attitudes toward environmental protection (Turner et al., 2007; Lambin & Meyfroidt, 2011). It is therefore particularly important to analyze the dynamics of individual agricultural land categories—arable land, meadows and natural pastures, and orchards—because changes in each category have distinct effects on ecosystem functions, biodiversity, and landscape structure.

At the European scale, changes in agricultural land use, particularly shifts in arable land, meadows and natural pastures, and perennial land uses such as orchards, are associated with ongoing landscape transformation processes that may contribute to the reduction of semi-natural habitats and changes in the structural diversity of agricultural landscapes (Plieninger et al., 2016; European..., 2017).

In the scientific literature, changes in arable land—often linked to agricultural intensification driven by economic pressures, technological development, and market forces—are closely associated with the restructuring of agricultural land-use systems. Within this process, intensified production practices, particularly in arable farming, are commonly characterized by increased use of agrochemicals and mechanization, which can contribute to changes in soil properties and affect the ecological stability of agricultural landscapes, including adjacent semi-natural land-use types such as meadows, natural pastures, and orchards (Foley et al., 2011; Tilman et al., 2011).

Studies at the European Union level show that arable land areas increase or remain stable in the most productive regions, whereas in areas less favorable for agriculture they decline due to land abandonment or natural succession processes (Eurostat, 2023).

The Common Agricultural Policy (CAP) is considered one of the most influential factors shaping arable land dynamics in Europe. Direct payments and investment support have promoted the expansion of crop production and farm specialization, particularly in Central and Eastern European countries (Pe'er et al., 2019). Research indicates that the CAP has also indirectly contributed to the ploughing of grasslands and the simplification of landscape structure (Stoate et al., 2009).

Lithuanian scientific studies indicate that after 2004, the expansion of arable land became the most economically attractive form of land use, especially in fertile regions (Stravinskienė et al., 2015; Vitunskienė, 2018).

Meadows and natural pastures represent important components of agricultural land-use systems alongside arable land and orchards, forming semi-natural land-use types that contribute to landscape diversity. These land categories are typically maintained through extensive agricultural practices, particularly livestock grazing and low-intensity management, and their persistence is closely linked to changes in agricultural land-use structure and farm specialization processes (Habel et al., 2013; Eurostat, 2025).

Europe has diverse natural and semi-natural grasslands shaped by long-term human–nature interactions, serving as biodiversity hotspots and cultural heritage. Despite their large extent, only about half are of high

nature value, and ongoing decline and fragmentation are driven by agricultural intensification, abandonment of traditional farming, and urbanization. Under Anthropocene conditions, these ecosystems are experiencing increasing pressure, highlighting the need to reassess conservation and restoration strategies (Mahy et al., 2024).

The literature identifies two main pathways of grassland decline: intensification and abandonment. Intensification manifests through the conversion of grasslands into arable land, while abandonment leads to natural succession in areas less suitable for agricultural production (Plieninger et al., 2016).

Stoate et al. (2009) emphasize that the decline of livestock farming is one of the most important factors contributing to the loss of meadows and pastures. Lithuanian studies further show that these processes are particularly pronounced in regions dominated by crop production specialization (Stravinskienė et al., 2015).

Orchards represent an important component of traditional agrarian landscapes, contributing to structural diversity, aesthetic values, and the preservation of cultural heritage (Plieninger & Bieling, 2012). Although orchards typically occupy a relatively small share of agricultural land, their ecological significance is disproportionately high. Orchards provide a wide range of ecosystem services, including biodiversity conservation and soil carbon sequestration (Demestihas et al., 2017). Traditional orchards are a key feature of Central European cultural landscapes with high ecological value; however, their extent is rapidly declining (Grosse-Stoltenberg et al., 2024).

Many authors agree that the long-term dominance of arable land, combined with the decline of grasslands and orchards, reduces landscape ecological resilience and increases the risk of soil degradation and biodiversity loss (Lal, 2015; Pe'er et al., 2019). Consequently, contemporary literature increasingly emphasizes the concept of multifunctional and integrated land use, which seeks to balance economic, ecological, and social objectives (Eurostat, 2025).

Agriculture represents a dominant form of land use, and its structural transformation has direct implications for the balance between arable land, meadows and natural pastures, and orchards. The shift from traditional, extensive land-use practices toward more intensive and specialized agricultural systems has contributed to changes in land-use structure, including the decline of semi-natural land-use types and the increasing dominance of arable land. These processes may increase the dependence on external inputs and reduce the resilience of agricultural landscapes at regional scale (Agnoletti & Santoro, 2022).

An extended review of the scientific literature demonstrates that changes in the areas of arable land, meadows and natural pastures, and orchards are complex processes reflecting interconnected economic, policy, and socio-demographic drivers, which jointly shape the long-term restructuring and spatial differentiation of agricultural land-use systems. Despite extensive literature on land-use change in Lithuania and Europe, existing studies predominantly focus on national-scale trends or individual land-use categories, while systematic comparative analyses at the county level remain limited. Consequently, there is insufficient understanding of spatially differentiated land-use dynamics within Lithuania, particularly regarding how arable land, meadows and natural pastures, and orchards vary across counties and contribute to regional land-use restructuring. This study addresses this gap by providing a consistent county-level assessment of land-use change over the 2005–2025 period.

The novelty of this research lies in its systematic long-term comparative analysis of land-use changes across all ten Lithuanian counties. Unlike previous studies that mainly emphasize national-scale trends or single land-use categories, this study integrates spatial differentiation and simultaneously evaluates the dynamics of arable land, meadows and natural pastures, and orchards. This approach enables a more detailed understanding of regional heterogeneity in land-use transformation and reveals spatial patterns of agricultural restructuring that are not evident in aggregated national statistics.

The object of the study is the structure and dynamics of agricultural land use in the Republic of Lithuania, including arable land, meadows, natural pastures, and orchards, over the period 2005–2025.

The aim of the study is to analyze changes in the extent and distribution of different types of agricultural land in Lithuania and its counties between 2005 and 2025, and assess the factors driving these changes.

1. To analyze the current state of arable land, meadows and natural pastures, and orchards in Lithuania and its counties.
2. To examine the changes in the areas of arable land, meadows and natural pastures, and orchards between 2005 and 2025.
3. To identify the causes of changes in the analyzed land areas.

Materials and Methods

The analysis was based on official Lithuanian national statistical data on the area and structure of agricultural land for the period 2005–2025 (ZISIS, 2005–2025). The dataset includes the total area of agricultural land (ha), as well as the areas of arable land, meadows and natural pastures, and orchards by county (ha). The data were processed at both county and national levels. The analysis covered all ten counties of Lithuania: Alytus, Kaunas, Klaipėda, Marijampolė, Panevėžys, Šiauliai, Tauragė, Telšiai, Utena, and Vilnius.

Data processing was carried out at both county and national levels. County-level values were aggregated from official statistical records, and consistency checks were performed to ensure comparability across the study period.

Descriptive statistical analysis methods were applied in the study, and a grouping method was used for the preparation of the article.

Changes in land-use area were calculated using absolute and relative indicators. Absolute change (Δha) was calculated as, Formula 1:

$$\Delta ha = A_{(2025)} - A_{(2005)} \quad (1)$$

Percentage change (%) was calculated as, Formula 2:

$$\% \text{ change} = [(A_{(2025)} - A_{(2005)}) / A_{(2005)}] \times 100 \quad (2)$$

where $A_{(2025)}$ and $A_{(2005)}$ represent land-use areas in the respective years.

Lithuanian counties were grouped according to the percentage share of arable land and meadows and natural pastures. Classification thresholds were defined based on the distribution of empirical data and in accordance with approaches used in previous Lithuanian land-use studies applying similar proportional classification methods, ensuring comparability and interpretability of regional differences.

The grouping scheme was as follows: arable land—high (>55%), medium (44–54%), low (<44%); meadows and natural pastures—high (>6%), medium (4–6%), low (<4%). Orchards were analysed using both absolute (ha) and relative (%) indicators due to their low spatial extent and high inter-regional variability.

The study presents an analysis of land-use change. Changes in area (ha) and percentage change (%) were calculated. The results were visualized using bar charts and pie charts (Figures 1–7), which clearly illustrate the distribution of agricultural land, temporal changes, and the grouping of counties according to land-use intensity. The processed data are presented in tables.

Both quantitative and qualitative analyses of the drivers of land-use change were conducted, identifying the main factors behind the expansion of arable land and the decline of meadows, pastures, and orchards.

Finally, it should be noted that the study relies on secondary statistical data, which may be affected by changes in land classification methodologies over time and potential limitations in administrative data accuracy. However, the use of a harmonized national statistical database minimizes these inconsistencies and ensures overall data comparability across the study period.

Results and Discussion

Current Situation

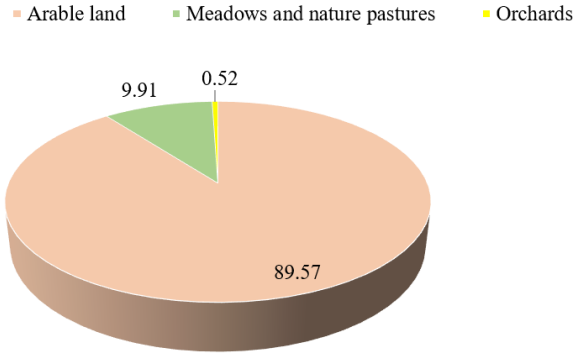
In 2025, agricultural land in Lithuania accounted for 3,365,699.61 ha (51.55% of national territory). The structure was strongly dominated by arable land, which covered 3,014,651.09 ha (46.18% of total land area and 89.57% of agricultural land), confirming a highly crop-oriented agricultural system (Figure 1).

Semi-natural and perennial land uses remained marginal: meadows and natural pastures occupied 333,385.5 ha (5.11%), while orchards covered 17,663.02 ha (0.27%). Although limited in spatial extent, these land-use categories represent key components of ecological infrastructure, particularly in supporting habitat diversity and ecosystem functions within agricultural landscapes.

The land-use structure indicates a high degree of agricultural specialization and limited functional diversification at the national scale.

Figure 1

Distribution of agricultural land in the Republic of Lithuania in 2025 (%)



Arable land distribution in 2025 exhibited marked regional heterogeneity. High concentrations in Šiauliai, Panevėžys, and Marijampolė counties reflect favourable biophysical conditions and consolidated commercial farming systems (Table 1). Medium levels in Kaunas, Tauragė, Klaipėda, and Telšiai indicate mixed agricultural regimes, where crop production coexists with more diversified land uses. Lower shares in Alytus, Vilnius, and Utena counties correspond to less favourable conditions and more fragmented land-use structures.

Table 1

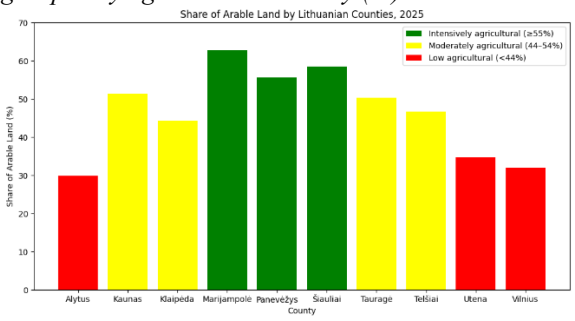
Arable land area (ha and %) by county in Lithuania, 2025

County	Arable land area in 2025 (ha)	Arable land area (%)
Alytus	161,736.73	29.87
Kaunas	414,870.21	51.33
Klaipėda	233,516.59	44.27
Marijampolė	280,164.57	62.73
Panevėžys	438,681.46	55.69
Šiauliai	499,916.71	58.55
Tauragė	221,754.54	50.32
Telšiai	203,381.35	46.77
Utena	249,319.86	34.66
Vilnius	311,309.06	32.00

(ZISIS, 2005-2025).

Based on these results, Lithuanian counties were classified into three groups according to the share of arable land (Figure 2): high (≥55%), medium (44–54%), and low (<44%). This classification highlights clear regional differentiation in agricultural intensity, driven by both natural conditions and land-use structure. As noted above, in 2025, *meadows and natural pastures* in Lithuania covered approximately 5.11% of the country's total area.

Figure 2
Share of arable land by Lithuanian counties in 2025, grouped by agricultural intensity (%)



Meadows and natural pastures show pronounced spatial variability across Lithuanian counties, reflecting differences in agricultural intensity and biophysical conditions (Table 2). In absolute terms, the largest areas were recorded in Utena county, while the smallest were observed in Marijampolė county (15,424.32 ha).

Figure 3 illustrates the proportion of meadows and natural pastures across Lithuanian counties in 2025. Based on their relative share, counties are classified into three groups—high, medium, and low—highlighting clear spatial differentiation in the distribution of meadow and natural pasture systems.

Table 2
Meadows and natural pastures in Lithuanian counties, 2025 (ha and % of county area)

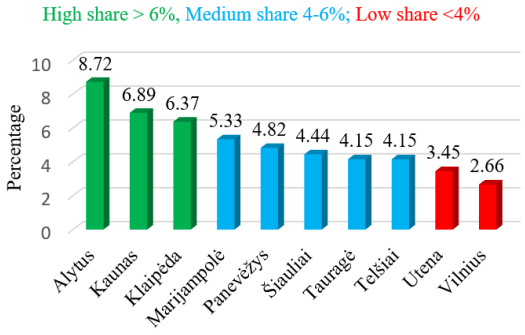
Counties	Area of meadows and natural pastures in 2025 (ha)	Meadows and natural pastures (%)
Alytus	26,101.95	8.72
Kaunas	32,889.29	6.89
Klaipėda	36,001.98	6.37
Marijampolė	15,424.32	5.33
Panevėžys	32,729.83	4.82
Šiauliai	22,748.73	4.44
Tauragė	23,505.48	4.15
Telšiai	19,308.65	4.07
Utena	62,705.42	3.45
Vilnius	61,969.87	2.66

(ZISIS, 2005-2025).

The high-share group (Alytus, Kaunas, Klaipėda) indicates stronger persistence of extensive land-use systems. The medium-share group (4–6%) includes Marijampolė, Panevėžys, Šiauliai, Tauragė, and Telšiai counties, reflecting transitional land-use structures with a balanced mix of intensive and extensive agricultural practices. The low-share group (<4%) consists of Utena and Vilnius counties, where meadows and natural pastures are least prevalent, suggesting a higher degree of land-use intensification and reduced presence of meadows and natural pastures.

In 2025, the largest area of *orchards* was recorded in Panevėžys county (3,109.11 ha). Relatively high orchard areas were also observed in Kaunas (2,596.02 ha) and Utena (2,461.15 ha) counties, indicating localized concentrations of perennial horticultural land use. In contrast, the smallest orchard areas were found in Klaipėda (770.54 ha) and Telšiai (833.38 ha) counties, Table 3.

Figure 3
Share of meadows and natural pastures by counties in Lithuania, 2025



When expressed as a proportion of total county area, Panevėžys county again shows the highest share of orchards (0.39%), followed by Tauragė (0.35%), Utena (0.34%), and Kaunas (0.32%) counties. The lowest proportions are observed in Klaipėda county (0.15%) and in Telšiai, and Vilnius counties (0.19% each), reflecting the marginal role of orchards in the land-use structure of these areas.

Table 3
Orchard area (ha and %) by county in Lithuania, 2025

Counties	Orchard area in 2025 (ha)	Orchard area (%)
Alytus	1,183.74	0.22
Kaunas	2,596.02	0.32
Klaipėda	770.54	0.15
Marijampolė	1,313.12	0.29
Panevėžys	3,109.11	0.39
Šiauliai	2,065.86	0.24
Tauragė	1,521.2	0.35
Telšiai	833.38	0.19
Utena	2,461.15	0.34
Vilnius	1,808.92	0.19

(ZISIS, 2005-2025).

Overall, the analysis of the current land-use situation shows substantial regional variation in the share of arable land across Lithuanian counties, ranging from

29.87% in Alytus county to 62.73% in Marijampolė county. This wide range indicates that agricultural activity in Lithuania is predominantly oriented towards intensive crop production, particularly in the most productive regions.

Meadows and natural pastures account for between 2.66% in Vilnius county and 8.72% in Alytus county, reflecting generally limited allocation of land to livestock-oriented and extensive farming systems. Despite their relatively small spatial extent, these land-use types remain important for maintaining ecological stability and landscape heterogeneity.

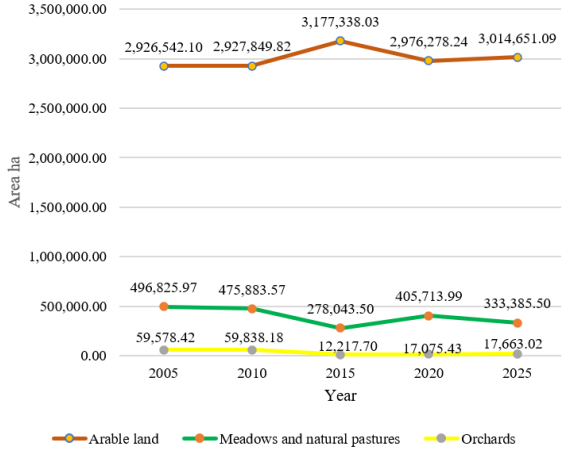
Orchard areas vary from 0.15% in Klaipėda county to 0.39% in Panevėžys county, indicating that horticultural land use plays a minor role in the overall agricultural structure. Nevertheless, its spatial distribution suggests a supplementary but regionally differentiated contribution to agricultural diversification and rural landscape complexity.

Analysis of Land-Use Changes in Lithuania, 2005–2025

Figure 4 shows that between 2005 and 2025, the structure of agricultural land in Lithuania underwent substantial changes, characterized by a shift toward intensive farming, with increasing arable land and declining meadows, natural pastures, and orchards.

Figure 4

Changes in the area of arable land, meadows and natural pastures, and orchards in Lithuania, 2005–2025 (ha)



Source: (ZISIS, 2005-2025).

Nationally, *arable land* increased by 88,108.99 ha (+3.01%) over the study period, indicating a modest but persistent intensification trend (Table 4).

Between 2005 and 2025, the area of *meadows and natural pastures* in Lithuania declined by 163,440.47 ha (32.89%), indicating a considerable contraction of extensive land-use systems. These processes are most evident in regions with intensive agriculture, where the loss of semi-natural land covers has been greatest.

During the same period, *orchard areas* in Lithuania declined by 41,915.40 ha (70.34%). The observed decline in orchard areas reflects a broader restructuring of agricultural land use, characterized by a decreasing role of traditional perennial systems. As a result, orchard landscapes are becoming increasingly fragmented and spatially limited, with a growing tendency toward their integration into other dominant land-use types. This trend indicates a gradual shift in the functional role of orchards within the overall agricultural structure.

Table 4

Changes in arable land, meadows and natural pastures, and orchards in Lithuania, 2005–2025 (ha and %)

Land-Use Type	Change (ha)	Change (%)
Arable land	+88,108.99	+3.01
Meadows and natural pastures	-163,440.47	-32.89
Orchards	-41,915.40	-70.34

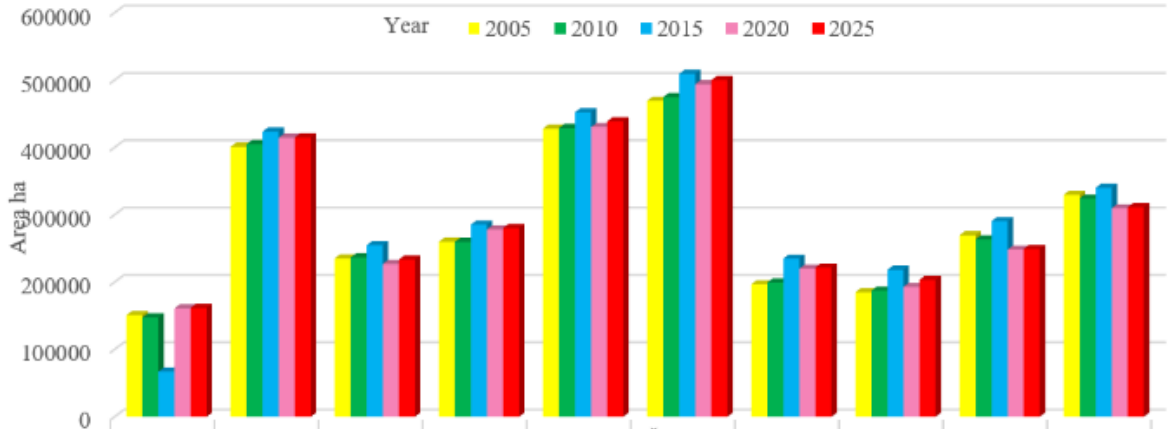
The results demonstrate a consistent long-term transformation of agricultural land structure in Lithuania, characterized by the expansion of intensively used arable land and the substantial contraction of meadows, natural pastures, and orchards. This continued transition toward increasingly specialized, production-focused land management is reshaping the structure of rural landscapes and affecting their ecological balance. It leads to a simplification of spatial patterns and a reduction in the variety of natural and semi-natural habitats. These changes may weaken ecological networks and reduce the resilience of ecosystems, while also influencing rural development pathways and limiting the multifunctional roles traditionally provided by agricultural land.

The analysis of changes in *arable land* between 2005 and 2025 at the county level indicates that arable land expanded in seven out of ten Lithuanian counties, while a decline was observed in Vilnius, Utena, and Klaipėda counties (Figure 5).

Over the 20-year period, the most pronounced relative increases in arable land were recorded in Tauragė, Telšiai, and Marijampolė counties, suggesting a strong intensification of agricultural land use in these regions. In absolute terms, the greatest expansion of arable land occurred in Šiauliai and Tauragė counties, reflecting their role as key areas of agricultural production and land-use restructuring (Table 5).

Conversely, declines in Vilnius and Utena (-5.60% and −7.55%) reflect urban pressure, land-use diversification, and partial withdrawal from intensive agriculture (Table 5). These contrasting trajectories highlight increasing spatial polarization between core agricultural regions and peri-urban or less productive territories.

Figure 5
Arable land areas by county in Lithuania, 2005–2025 (ha)



	Alytus	Kaunas	Klaipėda	Marijam	Panevėž	Šiauliai	Tauragė	Telšiai	Utena	Vilnius
2005	151185.3	401153.9	235381.9	260043.7	428100.3	469401.4	196836.3	185001.7	269682.5	329755
2010	147681.5	404969.9	236856.6	259829.7	428957.7	474825	199520	187462.2	263582.9	324164.3
2015	67358.58	423758.5	254970.3	285523	452310.2	509301.2	235019.4	218370.3	290637.5	340089.1
2020	161317.1	414540.6	227031.4	278329.5	430245.1	493867	219987.8	192974.8	248247.5	309737.6
2025	161736.7	414870.2	233516.6	280164.6	438681.5	499916.7	221754.5	203381.4	249319.9	311309.1

Source: (ZISIS, 2005-2025).

The analysis of changes in *meadows and natural pastures* across Lithuanian counties between 2005 and 2025 reveals pronounced long-term dynamics characterized by an overall declining trend interrupted by short-term fluctuations (Figure 6).

Table 5
Changes in arable land area in Lithuanian counties, 2005–2025 (ha and %)

Counties	Change (ha)	Change (%)
Alytus	+10,551.39	+6.98
Kaunas	+13,716.30	+3.42
Klaipėda	–1,865.34	-0.79
Marijampolė	+20,120.83	+7.74
Panevėžys	+10,581.12	+2.47
Šiauliai	+30,515.29	+6.50
Tauragė	+24,918.24	+12.65
Telšiai	+18,379.67	+9.94
Utena	–20,362.63	-7.55
Vilnius	–18,445.89	-5.60

During the analysed period, the largest decreases in meadow and natural pasture areas were recorded in Šiauliai, Marijampolė, Telšiai, and Tauragė counties (Table 6). Moderate declines were observed in Alytus, Panevėžys, and Kaunas counties, while the smallest changes were recorded in Klaipėda and Vilnius regions.

An exceptional case is Utena county, where meadow and natural pasture areas remained relatively stable (367.65 ha or 0.59%). This suggests a degree of regional stability in land use, potentially related to lower farming intensity, a higher proportion of natural areas, and limited opportunities for the development of intensive crop production.

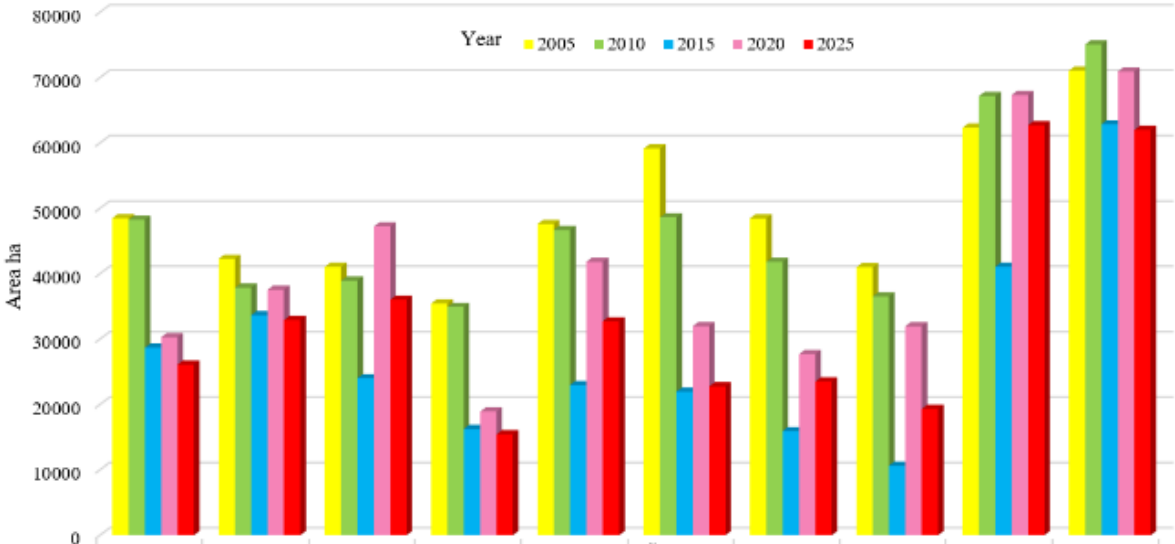
These trends indicate a long-term shift towards a more intensive land-use model which, while enhancing agricultural productivity, poses challenges for sustainable landscape management.

To strengthen the interpretation of the results, it is important to place the observed land-use changes in Lithuania within the broader European context. The results of this study are consistent with broader European evidence on long-term agricultural land-use change. The observed increase in arable land and the concurrent decline of meadows and natural pastures in Lithuania align with well-documented patterns of agricultural intensification across Europe, where farm specialization and policy-driven restructuring have led to the simplification of agricultural landscapes and the reduction of meadows and natural pastures (Stoate et al., 2009; Pe'er & Dicks, 2014). Similar processes have been identified in Central and Eastern Europe, where changes in post-accession agricultural frameworks and rural development policies have accelerated the conversion of meadows and natural pastures into arable land and reinforced production-oriented farming systems (Pe'er & Dicks, 2014).

At the same time, European studies highlight regional heterogeneity in meadows and natural pastures dynamics. While intensification dominates in many productive agricultural regions, Western Europe increasingly experiences meadows and natural pastures loss driven not only by intensification but also by land abandonment and rewilding processes, leading to divergent landscape trajectories (Plieninger et al., 2014). In contrast, Lithuania's land-use change is primarily

characterized by active agricultural restructuring and expansion of arable farming rather than large-scale abandonment, reflecting its relatively high agricultural suitability and post-Soviet land reform legacy.

Figure 6
Meadows and natural pasture areas in Lithuanian counties, 2005–2025 (ha)



	Alytus	Kaunas	Klaipėda	Marijamp	Panevėž	Šiauliai	Tauragė	Telšiai	Utena	Vilnius
2005	48498.3	42257.45	41059.18	35443.99	47584.46	59133.21	48470.12	40986.7	62337.77	71054.79
2010	48250.28	37857	38929.31	34921.77	46704.82	48615.09	41830.87	36525.07	67167.48	75081.88
2015	28673.82	33643.48	24033.46	16259.03	22970.06	21954.92	15938.99	10638.85	41063.03	62867.86
2020	30299.67	37537.52	47223.61	18913.4	41827.22	31981.07	27699.31	31971.51	67331.27	70929.41
2025	26101.95	32889.29	36001.98	15424.32	32729.83	22748.73	23505.48	19308.65	62705.42	61969.87

Source: (ZISIS, 2005-2025).

Table 6
Change in meadows and natural pasture areas in Lithuanian counties, 2005–2025 (ha and %)

Counties	Change (ha)	Change (%)
Alytus	−22,396.35	−46.19
Kaunas	−9,368.16	−22.17
Klaipėda	−5,057.20	−12.32
Marijampolė	−20,019.67	−56.49
Panevėžys	−14,854.63	−31.23
Šiauliai	−36,384.48	−61.54
Tauragė	−24,964.64	−51.51
Telšiai	−21,678.05	−52.88
Utena	+367.65	+0.59
Vilnius	−9,084.92	−12.78

The analysis of *orchard* area changes during 2005–2025 revealed a significant decline in orchard areas across all Lithuanian counties, with the most pronounced decrease occurring between 2005 and 2015 (Figure 7).

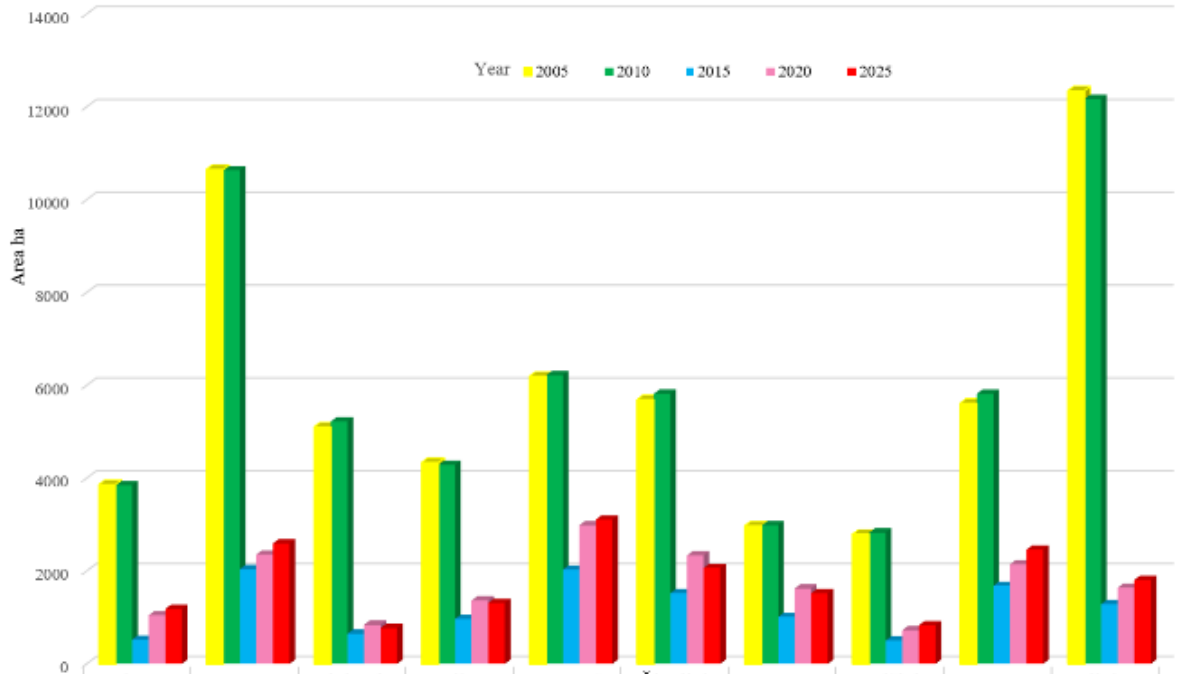
The most pronounced decline in orchard areas, both in absolute and relative terms, was observed in Vilnius county, where orchard land decreased by 10,537.58 ha (85.34%) over the 2005–2025 period. Similarly strong reductions were recorded in Kaunas (8,057.23 ha; 75.64%) and Klaipėda (4,333.84 ha; 84.93%) counties, indicating a substantial long-term contraction of orchard systems in both urban and agricultural regions. In contrast, the smallest absolute reductions were identified in Tauragė and Telšiai counties, where orchard areas declined by 1,453.27 ha and 1,959.45 ha, respectively. When expressed in relative terms, the lowest percentage losses were observed in Tauragė (48.85%) and Panevėžys (49.80%) counties suggesting comparatively higher persistence of orchard land in these regions (Table 7).

The decline of orchards observed in Lithuania is also consistent with broader European trends, where traditional orchard systems have been gradually disappearing due to agricultural modernization and structural transformation of rural economies (Demestihas et al., 2017). However, in some Mediterranean regions, orchards remain more stable due to specialization in high-value perennial production systems, indicating important spatial differences in land-use trajectories across Europe.

The results indicate a pronounced long-term restructuring of Lithuania's agricultural land-use system over the 2005–2025 period, characterized by increasing agricultural intensification and a progressive simplification of land-use patterns.

These findings highlight the need for integrated land-use planning strategies that balance agricultural productivity with ecological sustainability and the preservation of semi-natural and traditional landscape elements.

Figure 7
Orchard areas in Lithuania, 2005–2025 (ha)



	Alytus	Kaunas	Klaipėda	Marijamp	Panevėž	Šiauliai	Tauragė	Telšiai	Utena	Vilnius
2005	3862.31	10653.25	5104.38	4340.98	6194.65	5693.87	2974.47	2792.83	5615.18	12346.5
2010	3849.84	10632.82	5223.89	4287.03	6219.02	5821.07	2987.75	2829.01	5818.77	12168.98
2015	521.39	2040.31	650.94	967.71	2029.49	1523.27	1011.5	502.92	1684.39	1285.78
2020	1047.21	2355.34	842.45	1369.29	2987.18	2336.87	1624.75	726.51	2145.3	1640.53
2025	1183.74	2596.02	770.54	1313.12	3109.11	2065.86	1521.2	833.38	2461.15	1808.92

Source: (ZISIS, 2005-2025).

Table 7
Changes in orchard areas in Lithuanian counties, 2005–2025 (ha and %)

Counties	Change (ha)	Change (%)
Alytus	−2,678.57	−69.34
Kaunas	−8,057.23	−75.64
Klaipėda	−4,333.84	−84.93
Marijampolė	−3,027.86	−69.75
Panevėžys	−3,085.54	−49.80
Šiauliai	−3,628.01	−63.73
Tauragė	−1,453.27	−48.85
Telšiai	−1,959.45	−70.16
Utena	−3,154.03	−56.18
Vilnius	−10,537.58	−85.34

Causes of Land-Use Change

Land-use change in Lithuania is shaped by a complex interplay of economic, policy-related, technological, and socio-environmental factors, rather than by a single dominant driver. A key mechanism underlying observed transformations is the increasing economic efficiency and profitability of crop production, particularly within cereal-oriented farming systems. This has encouraged a gradual reallocation of land from less productive uses toward arable farming, especially in areas with favourable agronomic conditions.

Policy frameworks have played a significant facilitating role in this process. The Common Agricultural Policy (CAP) has indirectly promoted land-use restructuring through support mechanisms that prioritize productivity and investment in agricultural modernization. These incentives, combined with advances in mechanisation and farming technologies, have enabled the cultivation of land previously considered marginal or less suitable for intensive agriculture.

At the same time, structural changes in the livestock sector have reduced the demand for permanent grassland. The long-term decline in animal husbandry has weakened the economic function of meadows and pastures, accelerating their gradual conversion into arable land and contributing to broader simplification of agricultural landscapes.

Urban expansion represents an additional pressure factor, especially in peri-urban zones surrounding major cities and regional centres. In these areas, agricultural land is increasingly converted into residential, infrastructural, or commercial uses, thereby reducing the continuity of traditional agricultural landscapes.

The decline of meadows and natural pastures is closely linked to these combined structural changes. It reflects a broader shift from extensive, livestock-based systems toward more intensive crop production, supported by economic and policy incentives. As

grassland systems lose their economic relevance, they are progressively replaced or abandoned, contributing to habitat loss and reduced landscape diversity.

Similarly, the reduction in orchard areas is associated with long-term restructuring of rural economies and demographic change. Horticultural systems have become increasingly vulnerable due to high labour requirements, production costs, and market competition, which often makes them less economically viable compared to arable farming. As a result, many orchards are converted to alternative land uses, a process further reinforced by rural depopulation, agricultural specialization, and shifting consumption patterns.

Taken together, these processes indicate that land-use change in Lithuania is primarily driven by internal agricultural restructuring rather than by large-scale external abandonment dynamics. The overall trajectory points toward increasing dominance of arable farming, reduced land-use diversity, and progressive simplification of rural landscapes, with important implications for ecological integrity, landscape functionality, and long-term sustainability of agricultural systems.

Conclusions

1. The study demonstrates a pronounced long-term restructuring of agricultural land use in Lithuania, characterized by the growing dominance of arable land and the parallel contraction of meadows, natural pastures, and orchards. These shifts indicate a transition toward a more production-oriented and specialized agricultural system, reflecting broader processes of agricultural intensification and functional simplification of rural land use.
2. Spatial differences across counties reveal a persistent regional differentiation in land-use structure, where areas with more favourable agricultural conditions are increasingly oriented toward intensive arable farming, while less intensive regions retain relatively higher proportions of semi-natural and perennial land-use forms. This spatial pattern highlights the continuing imbalance in agricultural development trajectories within the country.
3. The substantial reduction of meadows and natural pastures has important implications for biodiversity conservation and ecosystem functioning. The loss of these semi-natural habitats reduces landscape heterogeneity, weakens ecological connectivity, and negatively affects species dependent on grassland ecosystems. From a territorial planning perspective, this trend increases the vulnerability of rural landscapes to ecological degradation and limits opportunities for multifunctional land use.
4. The decline of orchards reflects the ongoing marginalization of traditional, low-intensity land-use systems, which historically contributed to landscape diversity and cultural heritage. Their reduction signals not only economic restructuring but also the gradual erosion of structurally diverse agricultural landscapes, which play an important role in maintaining both ecosystem services and local identity.
5. Future research should focus on more detailed spatial modelling of land-use transitions, the integration of socio-economic drivers at farm level, and the assessment of ecosystem service losses associated with the decline of semi-natural land uses. In addition, scenario-based studies would be valuable for evaluating policy options aimed at balancing agricultural productivity with biodiversity conservation and sustainable land management objectives.

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MOSS-BASED VERTICAL BARRIERS AS HYBRID INFRASTRUCTURES FOR URBAN PM MONITORING AND MITIGATION

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Abstract
Air pollution remains a major environmental and public health challenge in urban areas, particularly due to fine particulate matter ($PM_{2.5}$), which can penetrate deeply into the respiratory system. According to the World Health Organisation, $PM_{2.5}$ is among the air pollutants with the highest documented impact on human health, especially in urbanised settings. This study evaluated a moss-based vertical barrier as green infrastructure for local mitigation under real outdoor urban conditions. The experimental system consisted of a freestanding moss-covered panel equipped with paired low-cost $PM_{2.5}$ sensors positioned on the street-facing and park-facing sides of the barrier. Monitoring was conducted in Riga, Latvia, from 1 November 2025 to 31 January 2026 under winter conditions characterised by variable wind, temperature, and precipitation. Quantitative interpretation was based on the validated Riga dataset comprising 80,302 observations processed using a 60-minute moving average; the results showed that $PM_{2.5}$ concentrations behind the moss barrier were lower than on the street side in 53.3% of observations. The average relative reduction reached 6.68%, corresponding to an absolute reduction of 1.33 μg m^{-3}. Barrier performance varied with wind direction, indicating the importance of atmospheric flow conditions for local mitigation efficiency. The findings demonstrate that moss-based vertical barriers can provide modest but measurable $PM_{2.5}$ attenuation while also functioning as decentralised environmental monitoring units within hybrid urban green infrastructure systems.
Keywords: moss wall, $PM_{2.5}$, urban air pollution, green infrastructure, environmental monitoring.

Introduction

Air pollution remains one of the most significant environmental challenges in urban areas and is currently associated with millions of premature deaths annually worldwide. Fine particulate matter ($PM_{2.5}$) is considered particularly harmful because particles smaller than 2.5 μm can penetrate deeply into the respiratory system, enter the bloodstream, and affect multiple organs, including the cardiovascular and nervous systems (World Health Organisation, 2021). According to the World Health Organisation (WHO), $PM_{2.5}$ is among the air pollutants with the highest documented impact on public health, especially in densely populated urban regions where exposure is continuous. Urbanisation intensifies this problem because pollutant emissions from transport, domestic heating, construction, and industrial activities accumulate in areas where atmospheric dispersion is restricted by street canyons and built structures (Anderson et al., 2011; Liang et al., 2021). In Europe, almost all urban populations are exposed to $PM_{2.5}$ concentrations exceeding recommended health guidelines, with particularly elevated values observed in Central and Eastern European cities (European Environment Agency, 2024). In Riga, $PM_{2.5}$ remains one of the dominant air-quality concerns, influenced by traffic emissions, winter heating, and regional transport from industrial and port-related activities. The concentration and movement of $PM_{2.5}$ in urban air depend strongly on meteorological conditions. Wind direction, wind speed, precipitation, humidity, and temperature influence pollutant transport, dilution, and deposition processes (Jing et al., 2020; Yang et al., 2017; Xie et al., 2022). Strong winds usually enhance dispersion, whereas low wind speed and atmospheric stability promote local accumulation. In winter, thermal inversions and reduced vertical mixing often increase $PM_{2.5}$ concentrations in near-ground air layers, making local mitigation particularly relevant in pedestrian environments. As conventional urban air-quality policies often focus on emission reduction at the city scale, increasing attention has been given to local nature-based solutions capable of reducing pollutant exposure at micro-scale locations. Vegetated barriers, green walls, roadside hedges, and other green infrastructure elements may modify local turbulence, intercept airborne particles, and increase deposition onto biological surfaces (Hewitt et al., 2019; Kumar et al., 2019; Medl et al., 2017). Vertical vegetation systems are especially relevant where horizontal space for planting is limited. Among biological materials, mosses have advantages for atmospheric applications because they lack a cuticle, possess high surface roughness, and absorb airborne particles directly through their surface. Mosses are widely used in biomonitoring studies because they accumulate particulate and trace-element pollution efficiently (Capotorti et al., 2013; Giordano et al., 2005). Their ability to function as passive particulate collectors suggests additional potential for engineered mitigation systems integrated into urban infrastructure. Previous studies have demonstrated that vegetation can reduce local particulate concentrations, but most experiments have focused either on laboratory conditions or on conventional vascular plants (Weber et al., 2014; Ren et al., 2023). Evidence for moss-based vertical barriers under outdoor winter conditions in temperate European cities remains limited. In addition, the integration of biological filtration surfaces with low-cost digital PM sensors introduces new possibilities for digital infrastructures capable of both mitigation and continuous environmental observation. This study evaluates a freestanding moss-based vertical barrier installed in *Viesturdārzs,* Riga (Latvia) under winter outdoor conditions. The study aimed to assess $PM_{2.5}$ concentration differences across the barrier, determine

the influence of wind direction on local barrier performance, and evaluate the suitability of moss-based systems as decentralised urban monitoring elements. Quantitative interpretation was based on the validated primary dataset.

Materials and Methods

The study was conducted in Riga, in the urban green area of *Viesturdārzs*, where a freestanding moss-based vertical barrier was installed as an experimental nature-based infrastructure for particulate matter monitoring and local mitigation. The site is located in a dense urban environment influenced by road traffic, nearby transport corridors, and atmospheric transport from port-related industrial activities situated in the northern part of the city. The barrier was positioned perpendicular to the dominant air flow to intercept airborne particles transported between the street and park zones. The experimental system consisted of autonomous vertical panels covered with moss vegetation and equipped with paired low-cost $PM_{2.5}$ sensors installed on both sides of the structure (Figure 1).

Figure 1

Moss barrier placed in Riga, Viesturdarzs



The moss panels consisted of vertically mounted modular frames supporting moss-covered substrate layers designed to maximise surface roughness and air contact. The structure allowed passive airflow through the vegetation layer, facilitating particle interception and deposition. The $PM_{2.5}$ measurements were obtained using calibrated low-cost optical sensors (Pollutrack system), operating with a temporal resolution of 1-minute intervals. One sensor was positioned on the street-facing side to measure incoming particulate concentration, while the second sensor was placed on the park-facing side to detect concentration after air passage across the barrier (Figure 2).

Sensor performance was monitored throughout the study period, and maintenance procedures included regular visual inspection and cleaning of sensor inlets to prevent obstruction by moisture or particulate accumulation. Sensor malfunction was identified based on abnormal readings, including persistent extreme values, lack of temporal variability, or unrealistic divergence between paired sensors. Data from sensors exhibiting such anomalies were excluded from further analysis.

Figure 2

Close-up of a sensor placed on the barrier



Two installations were operated during the study period: medium (sized 3x5m) and large (sized 3x7m). However, quantitative interpretation in this study was based only on the medium installation because the Riga large display park-side sensor produced anomalously high values that indicated probable clogging or sensor malfunction. Therefore, the large display data was excluded from efficiency calculations. Monitoring was performed continuously from 1 November 2025 to 31 January 2026 under winter outdoor conditions characterised by variable temperature, humidity, precipitation, and wind regimes. The validated dataset of 80,302 observations was obtained after applying quality-control procedures, including removal of missing values, elimination of outliers exceeding physically plausible $PM_{2.5}$ concentration ranges, and exclusion of data segments affected by identified sensor malfunction. Data smoothing using a 60-minute moving average was applied to reduce short-term fluctuations and ensure comparability between measurement points. Barrier efficiency was evaluated using two indicators: absolute reduction and relative reduction. Absolute reduction was calculated as the mean difference between street-side and park-side $PM_{2.5}$ concentrations:

Absolute reduction = Mean (Street − Park)

Relative reduction was calculated as:

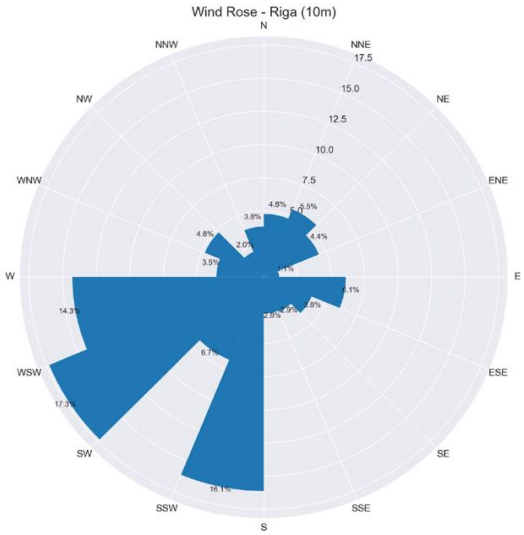
Relative reduction (%) = 100 × Mean (Street − Park) / Mean (Street).

Negative differences indicated lower particulate concentration behind the moss barrier and were interpreted as local attenuation effects. Meteorological influence was assessed using ERA5 atmospheric data. Particular attention was given to wind direction (Figure 3) because barrier performance depends strongly on airflow orientation.

Westerly winds (250°–290°) were considered the main transport direction from the street towards the park,

while easterly winds (70°–110°) represented the opposite flow configuration. Wind-direction analysis was used to interpret changes in barrier performance under different atmospheric transport conditions.

Figure 3
Wind rose for Riga during the monitoring period from 1 November 2025 to 31 January 2026



A limitation of the study is the reliance on low-cost sensors, which may introduce measurement uncertainty under high humidity and winter conditions. However, paired sensor configuration and data validation procedures were applied to minimise this effect.

Results and Discussion

The quantitative analysis of the validated medium panel display installation was based on 80,302 $PM_{2.5}$ observations collected during the monitoring period from 1 November 2025 to 31 January 2026. Comparison of concentrations measured on both sides of the moss barrier showed measurable spatial differences between the street-facing and park-facing sensors. In 42,780 observations (53.3%), $PM_{2.5}$ concentration on the park side was lower than on the street side, whereas in 37,522 observations (46.7%), the opposite relationship was observed. This distribution indicates a slight predominance of lower particulate concentrations behind the moss barrier under outdoor urban winter conditions.

For observations where $PM_{2.5}$ concentration behind the barrier was lower than on the street side; the mean relative reduction reached 6.68%, corresponding to an absolute reduction of 1.33 μg m^{-3}. To evaluate whether the observed differences between street-side and park-side $PM_{2.5}$ concentrations were statistically significant, paired comparison analysis was performed.

The mean difference between paired observations was calculated, and variability was assessed using standard deviation. Although the reduction effect was modest, the consistent predominance of lower concentrations behind the barrier suggests that the observed attenuation effect is unlikely to be solely the result of random variation. Future analysis should include formal hypothesis testing (e.g., paired t-test) to further quantify statistical significance.

Table 1
Validated $PM_{2.5}$ reduction results for the Riga moss barrier installation

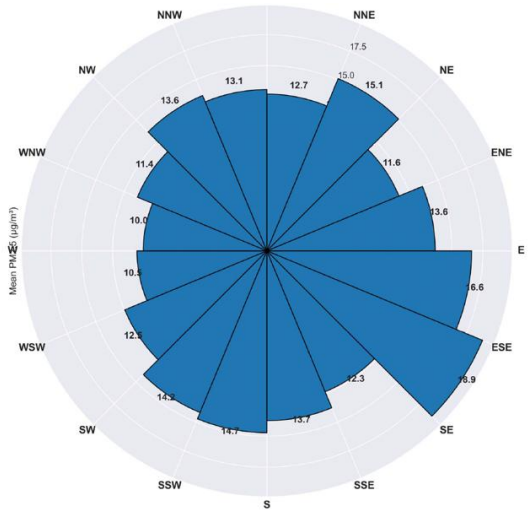
Label	Value
Observations	80,302
Park < Street	53.3%
Relative reduction	6.68%
Absolute reduction	1.33 μg m^{-3}

Across the full monitoring period, the reduction effect remained modest but occurred more frequently than concentration increases, demonstrating that the moss-covered surface contributed to local particulate attenuation under real environmental exposure. The standard deviation reported in the dataset indicates considerable temporal variability, suggesting that barrier performance changed continuously according to meteorological conditions and local emission dynamics. Although the observed reduction values (6.68% and 1.33 μg m^{-3}) may appear modest, they are environmentally relevant at the micro-scale level, particularly in pedestrian zones where even small reductions in $PM_{2.5}$ exposure can contribute to improved air quality and reduced health risks. Compared to controlled laboratory experiments, the lower efficiency observed in this study reflects the complexity of real urban environments, where turbulence, variable emission sources, and meteorological conditions continuously influence pollutant dispersion and deposition processes. Similar variability in vegetation-based mitigation performance under outdoor conditions has been reported in previous studies (Hewitt et al., 2019; Kumar et al., 2019), confirming that nature-based solutions function as complementary rather than primary filtration systems.

Mean $PM_{2.5}$ concentrations varied considerably according to wind direction during the study period (Figure 4). The highest concentrations were recorded under southeastern and eastern airflows, with maximum values observed for SE (18.9 μg m^{-3}), ESE (16.6 μg m^{-3}), and NE (15.1 μg m^{-3}) directions. In contrast, lower $PM_{2.5}$ concentrations were associated with western sectors, particularly W (10.0 μg m^{-3}) and WNW (11.4 μg m^{-3}). Overall, winds from the east to southeast sector were associated with higher particulate matter loads than winds from the west, indicating a clear directional influence on local $PM_{2.5}$ distribution. For the dominant wind sectors during the monitoring period, concentrations generally ranged between 12.5 and 15 μg/m^3, reflecting a persistent background influence of surrounding urban emission sources. These results suggest that air masses arriving

from eastern sectors transport higher pollutant loads to the site, whereas westerly winds favour stronger atmospheric dispersion and lower $PM_{2.5}$ accumulation.

Figure 4
Distribution of $PM_{2.5}$ pollution depending on wind direction



Furthermore, wind direction had a clear influence on barrier behaviour. Under westerly winds (250°–290°), when polluted air moved from the street towards the park through the barrier, 5,236 valid observations were recorded. In this configuration, the average reduction reached 1.10%, corresponding to an absolute difference of 0.14 µg m^{-3}. Under easterly winds (70°–110°), 7,598 observations were analysed, and the average reduction increased to 2.65%, with an absolute reduction of 0.78 µg m^{-3}. The stronger attenuation observed during easterly flows may be associated with lower wind velocity and reduced atmospheric dilution, which increases particle residence time near the moss surface. The observed influence of wind direction highlights the importance of airflow alignment relative to barrier orientation. Under favourable transport conditions, the moss surface acts as a passive deposition interface, whereas under opposing or turbulent flow conditions, the mitigation effect is reduced or reversed. The measured reduction values are lower than efficiencies reported in some controlled laboratory experiments, which is expected because outdoor urban conditions introduce strong variability through turbulence, precipitation, humidity fluctuations, and changing emission sources. In real environments, moss barriers act not as closed filtration systems but as passive deposition surfaces that locally modify air movement and increase particle capture potential. Data from the second installation (large display) were excluded from quantitative interpretation due to almost all observations showing unrealistically high $PM_{2.5}$ concentrations on the park side, with an average calculated efficiency exceeding 250%, indicating probable sensor contamination or obstruction. This confirms that sensor maintenance and quality control remain critical when green infrastructures are used for continuous environmental monitoring. Overall, the validated results indicate that moss-based vertical barriers can provide modest but measurable local $PM_{2.5}$ attenuation while simultaneously functioning as decentralised monitoring elements within urban green infrastructure systems.

Conclusions

1. The validated moss-based vertical barrier installation showed measurable $PM_{2.5}$ attenuation under outdoor winter urban conditions, with lower concentrations behind the barrier recorded in 53.3% of observations.
2. The average relative reduction reached 6.68%, corresponding to an absolute reduction of 1.33 µg m^{-3}, indicating a modest but consistent local mitigation effect.
3. Wind direction influenced barrier performance, with measurable differences observed under both westerly and easterly atmospheric flow conditions.
4. The results confirm that moss-based vertical barriers can function as passive local biofiltration surfaces while simultaneously serving as decentralised air-quality monitoring elements.
5. Sensor reliability remains a critical factor for green infrastructure, as anomalous measurements from the second installation required exclusion from quantitative interpretation.

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VEGETATIVE PROPAGATION OF BRYOPHYTES FOR URBAN DEPLOYMENT AND ECOSYSTEM SERVICES PROVISION

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Abstract
Bryophytes, especially mosses, are increasingly recognised as multifunctional components of urban green infrastructure due to their capacity to contribute to ecosystem services such as air quality regulation, noise attenuation, microclimate stabilisation, and mitigation of urban heat island effects. The large-scale application of moss-based solutions, however, is constrained by the limited availability of sustainably produced moss biomass and by species-specific differences in cultivation requirements. This study presents a controlled, non-sterile vegetative propagation approach for selected moss species commonly associated with ecosystem service provision in urban environments. Four species—*Hypnum cupressiforme, Pleurozium schreberi, Plagiomnium affine,* and *Dicranum scoparium*—were propagated from vegetative fragments on hemp fibre substrates under controlled temperature (15–21 °C), relative humidity (60–80%), and light intensity (1000–2000 lux). Surface coverage, species vitality, and susceptibility to microbial contamination were monitored over a four-month cultivation period. The results demonstrate clear interspecific differences in growth strategies and resilience under controlled conditions. *Plagiomnium affine* exhibited rapid initial growth but limited long-term stability, while *Hypnum cupressiforme* showed slower establishment combined with high robustness and regenerative capacity. *Pleurozium schreberi* and *Dicranum scoparium* required higher initial planting densities to achieve stable coverage and were more sensitive to cultivation stress. These findings highlight the importance of species-specific propagation strategies when cultivating mosses intended for ecosystem service provision in urban environments. The study provides a practical knowledge base for sustainable moss biomass production as a prerequisite for future ecological and functional applications.
Keywords: bryophytes, moss cultivation, moss propagation, ecosystem services, biomass production.

Introduction

Ecosystem services refer to the benefits that humans derive from ecosystems and are commonly classified into four categories: provisioning, supporting, cultural, and regulating (Reid, 2005; Gómez-Baggethun et al., 2013). Regulating ecosystem services include ecological functions that moderate environmental conditions, such as air purification, temperature regulation, stormwater control, and noise attenuation, which are particularly important in densely urbanised areas where natural buffering capacity is reduced (Bolund & Hunhammar, 1999; Zulian et al., 2017).

Bryophytes and mosses in particular are increasingly recognised as functional components of urban green infrastructure due to their capacity to provide regulating ecosystem services under limited substrate conditions (Glime, 2021; Perini et al., 2020). Their poikilohydric physiology, lack of cuticle, and high surface-to-volume ratio allow direct exchange with atmospheric moisture and pollutants, making them particularly suitable for urban environmental applications (Perini et al., 2020; Chaudhuri & Roy, 2024; Garabito et al., 2017). The role of mosses in urban air pollution mitigation has gained increasing attention in recent years. For example, moss-based filtration systems have demonstrated the ability to capture PM and improve local environmental quality in engineered urban installations (Biloshchytskyi et al., 2023; Kārkliņa et al., 2024; Perini et al., 2025). Mosses are also widely recognised as atmospheric bioindicators because they accumulate airborne pollutants directly through their surface tissues and reflect local deposition patterns over time (Rühling & Tyler, 1968; Lazo et al., 2022; Chaudhuri & Roy, 2024). Urban deployment of mosses requires reliable biomass production since direct harvesting from natural habitats cannot support large-scale implementation and creates ecological pressure on natural ecosystems. Therefore, controlled cultivation becomes essential and can be achieved using several propagation approaches depending on the intended application and available infrastructure. In laboratory conditions, sterile in vitro propagation is frequently employed, enabling precise control over growth media, nutrient supply, and contamination levels. This method enables the rapid multiplication of moss biomass but requires specialised laboratory facilities and species-specific optimisation of culture media (Ćosić et al., 2025; Heck et al., 2021). Alternatively, non-sterile vegetative propagation represents a more practical approach for large-scale biomass production. In this method, moss fragments are cultivated on suitable substrates under controlled environmental conditions, including regulated temperature, humidity, and light intensity. Vegetative propagation utilises the natural regenerative capacity of bryophyte tissues, allowing new shoots to develop from fragmented plant material (Liu et al., 2021; Zechmeister et al., 2023).

Previous studies have demonstrated that the regeneration capacity of bryophyte species differs substantially, influencing cultivation efficiency and the long-term stability of propagated biomass. Therefore, selecting the appropriate species and cultivating under suitable conditions is essential for the successful application of moss in environmental settings (Morales-Sánchez et al., 2022; Haughian & Lundholm, 2024). Mosses possess a high regenerative ability due to the presence of meristematic cells distributed along their gametophyte tissues, allowing regeneration even from small shoot fragments, which makes vegetative propagation particularly effective compared to many vascular plant systems (Glime, 2021). Non-sterile

controlled propagation offers a more accessible alternative for producing moss biomass for urban green infrastructure applications (Zechmeister et al., 2023; Liu et al., 2021). Species differ substantially in regeneration speed, tolerance to moisture fluctuations, and resistance to microbial contamination. These interspecific differences directly influence cultivation success and later performance under urban environmental stress, particularly when mosses are intended for vertical systems, roofs, or linear barriers exposed to fluctuating temperature and hydration cycles (Haughian & Lundholm, 2024; Morales-Sánchez et al., 2022). This study aimed to evaluate vegetative propagation performance of four moss species under controlled non-sterile conditions and to identify cultivation parameters relevant for future ecosystem service applications in urban environments.

Materials and Methods

Four moss species were selected for vegetative propagation: *Hypnum cupressiforme, Pleurozium schreberi, Plagiomnium affine,* and *Dicranum scoparium.* Species selection was based on previous experimental observations showing their suitability for urban ecological applications, their morphological diversity, and their resilience under controlled cultivation conditions (Kārkliņa et al., 2024; Perini et al., 2020). Moss material was collected manually from forest habitats in accordance with sustainable biomass collection principles. Only green photosynthetically active segments were retained, while brown basal tissue and organic impurities were removed manually before cultivation. The prepared material was distributed manually onto pre-wetted hemp fibre mats (60 × 60 × 0.4 cm), ensuring near-complete (90%) initial substrate coverage. Lower initial densities had previously resulted in desiccation and reduced vitality. Mosses were placed on the substrate as monocultures – one species per hemp mat. This substrate was selected because of its water retention properties and biodegradability, which support moss establishment under controlled humidity conditions (Addo-Bankas et al., 2024). Cultivation took place in a climate-controlled indoor facility under non-sterile conditions (Figure 1). Environmental parameters were maintained as follows: temperature, 15–21 °C; relative humidity, 60–80%; light intensity, 1102–2573 lux; and photoperiod, 8 h light/16 h dark. These conditions were selected based on previous studies demonstrating that temperature, humidity, and irrigation regime strongly influence moss viability in indoor systems (Zechmeister et al., 2023; Perini et al., 2025). Mosses were irrigated three times daily using reverse osmosis water. Once per week, a modified Knop nutrient solution was applied at ¼ strength, consisting of calcium nitrate (0.25 g L^{-1}), potassium nitrate (0.06 g L^{-1}), potassium phosphate (0.06 g L^{-1}), and magnesium sulfate (0.06 g L^{-1}), supplemented with ammonium nitrate at a concentration of 0.04–0.08 g L^{-1} (equivalent to 0.5–1 mM). Approximately 100 mL of solution was applied per cultivation unit following nutrient recommendations developed for bryophyte cultivation (Heck et al., 2021; Ćosić et al., 2025). Growth was monitored visually over four months by assessing surface coverage, color stability, new shoot formation, and symptoms of contamination. Surface coverage was visually assessed at regular intervals during the cultivation period through repeated comparative observations of each cultivation unit. Surface coverage was expressed as the percentage of substrate area occupied by living moss biomass, based on repeated visual estimation under standardised lighting conditions. In addition to coverage, qualitative indicators of vitality were assessed, including colour intensity and shoot density. Colour intensity was evaluated using a three-level visual scale (green – indicating high vitality; pale green – indicating moderate vitality; yellow/brown – indicating reduced vitality or stress). Shoot density was assessed comparatively by observing the relative compactness of regenerated shoots across the substrate surface (low, medium, high density). All visual assessments were conducted by the same observer at regular intervals throughout the four-month cultivation period to ensure consistency. Observations were performed after irrigation cycles, when surface moisture conditions were stable, in order to minimise variability caused by temporary desiccation. To ensure comparability between species, all observations were performed under identical lighting conditions and after irrigation cycles had stabilised surface moisture conditions. The obtained coverage values were subsequently used for descriptive statistical analysis and interspecific comparison.

During cultivation, fungal contamination was treated using Hydrogen peroxide, which slowed the spread of fungi, but concentrations above 1.25% caused visible chlorosis, indicating the limited applicability of chemical suppression under long-term cultivation.

After completion of the four-month controlled indoor cultivation phase, the moss mats were relocated to outdoor conditions to undergo winter exposure. The cultivated material remained outdoors for six months before subsequent visual assessment.

Statistical analysis of surface coverage data was performed using R statistical software. Analysis of variance (ANOVA) and Tukey HSD post hoc comparisons were applied to evaluate interspecific differences in coverage values. Descriptive statistics were calculated to determine mean values, standard deviation, minimum, and maximum coverage. Graphical visualisation of results was prepared using boxplot and barplot functions in RStudio.

Results and Discussion

The four species showed clear differences in establishment dynamics under identical cultivation conditions. *Plagiomnium affine* exhibited the most rapid early development, reaching approximately 2 cm shoot elongation within two to three months. However, vitality declined after the third month, particularly under monoculture conditions, while a mix of all moss

species was stronger. This suggests a high colonisation potential, combined with limited long-term stability under continuous high humidity, which corresponds with the fast colonisation strategies described for bryophyte growth under favourable moisture conditions (Glime, 2021; Liu et al., 2021). By contrast, *Hypnum cupressiforme* showed slower initial growth but the highest resilience during the full cultivation period. It regenerated effectively in low-density areas and in zones affected by microbial contamination, indicating strong tolerance to cultivation stress and stable persistence under fluctuating humidity conditions (Morales-Sánchez et al., 2022). *Pleurozium schreberi* required higher planting density to achieve stable coverage, while *Dicranum scoparium* showed the greatest sensitivity to low density and contamination. Low-density cultures of *D. scoparium* frequently developed chlorosis and tissue loss. After four months, most cultivation units exceeded 80% surface coverage, confirming the practical suitability of non-sterile vegetative propagation for biomass production.

Figure 1
Moss cultivation within a controlled environment after four months

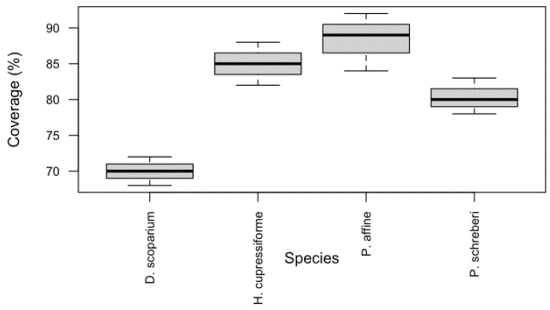


Analysis of variance (ANOVA) was applied to determine whether the observed differences in surface coverage among cultivated moss species were statistically significant, since species-specific variation was expected to influence cultivation performance under identical environmental conditions.

ANOVA revealed statistically significant differences in surface coverage among the cultivated moss species ($F = 21.44$, $p = 0.000352$), indicating species-specific variation in establishment performance under controlled cultivation conditions.

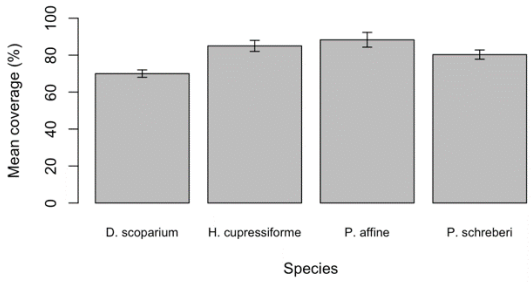
Plagiomnium affine demonstrated the highest median coverage, whereas *Dicranum scoparium* had the lowest (Figure 2). Post hoc Tukey HSD analysis further demonstrated that *Dicranum scoparium* differed significantly from all other species in surface coverage. Significant differences were observed between Dicranum scoparium and *Hypnum cupressiforme* ($p = 0.0012$), *Plagiomnium affine* ($p = 0.0003$), and *Pleurozium schreberi* ($p = 0.0121$). In addition, *Pleurozium schreberi* differed significantly from *Plagiomnium affine* ($p = 0.0448$).

Figure 2
Surface coverage differences among cultivated moss species under controlled propagation conditions



The mean surface coverage values with standard deviations for the cultivated moss species after four months of controlled propagation (Figure 3) indicate that *Plagiomnium affine* achieved the highest mean coverage (88.3 ± 4.0%), followed by *Hypnum cupressiforme* (85.0 ± 3.0%). In contrast, *Dicranum scoparium* showed the lowest mean coverage (70.0 ± 2.0%).

Figure 3
Mean surface coverage and standard deviation among cultivated moss species under controlled propagation conditions



The statistical differences observed in surface coverage corresponded closely with visual cultivation dynamics recorded during the monitoring period. Species showing higher mean coverage values also demonstrated more homogeneous shoot expansion and lower susceptibility to local tissue degradation. In contrast, lower coverage values were associated with delayed lateral expansion, reduced density of regenerated shoots, and greater sensitivity to contamination episodes. Similar growth performance has been reported in other controlled moss cultivation studies where vegetative fragments were used for biomass multiplication (Liu et al., 2021; Zechmeister et al., 2023).

During the cultivation span, microbial contamination remained the primary limitation to cultivation. Comparable contamination challenges are described in non-axenic bryophyte production systems (Ćosić et al., 2025). The observed differences correspond to ecological growth strategies described by Grime (2001), where rapidly colonising species show weaker stress tolerance, while slower-growing species provide greater cultivation stability.

After four months of controlled indoor cultivation, the moss mats were transferred to outdoor conditions to assess their ability to maintain vitality beyond the controlled propagation phase during winter exposure. Following six months under external environmental conditions, the cultivated moss biomass still showed visible signs of viability, including preserved green pigmentation and structural integrity in most cultivation units (Figure 4).

Finally, findings confirm that reliable biomass production remains a necessary precondition for broader investigation of moss-based ecosystem service applications in urban environments.

Since bryophytes are increasingly considered as functional elements of green infrastructure, the availability of stable cultivated material is essential for subsequent experimental studies addressing PM retention, microclimate regulation, moisture buffering, and other regulating ecosystem services.

Figure 4

Cultivated mosses in an outdoor environment



The present cultivation experiment, therefore, represents an initial practical stage within a broader research direction focused on evaluating moss species not only for propagation efficiency but also for their environmental performance under urban conditions.

Conclusions

1. Non-sterile vegetative propagation under controlled indoor conditions enabled the successful establishment of all four cultivated moss species on hemp fibre substrate.
2. Significant interspecific differences in surface coverage were identified, confirming that moss species differ in regeneration performance under identical cultivation conditions.
3. *Plagiomnium affine* and *Hypnum cupressiforme* demonstrated the highest surface coverage and the most stable establishment during the four-month cultivation period. *Dicranum scoparium* showed the lowest surface coverage and the highest sensitivity to cultivation conditions, indicating lower suitability for rapid biomass production.
4. Outdoor exposure after indoor cultivation confirmed that propagated moss mats retained viability under winter conditions, supporting their potential for further application in urban green infrastructure systems.

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IRRIGATION PRIORITIZATION MODEL FOR DROUGHT RESILIENCE: CROP RANKING AND WATER SAVING SCENARIOS

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Abstract
Drought-induced water scarcity increasingly constrains irrigation planning and is expected to intensify under climate change. Under limited water availability, efficient allocation of irrigation water is essential to minimize yield losses and improve water-use efficiency. This study develops a decision-support model that ranks crops during drought conditions by integrating crop water requirements, yield response to deficit irrigation, and economic valuation of production. The model is applied to the Ararat region (Armenia), a drought-prone area with irrigation-dependent agriculture. Results indicate that moderate irrigation restriction can reduce seasonal water use by 28–45% while maintaining a substantial share of crop yield. Under severe drought conditions, reallocating water from low-priority crops to higher-value crops reduces total economic losses. The proposed prioritization index (EUR m^{-3}) provides a transparent basis for ranking crops according to the economic value of irrigation water. Results further show that tomato generates the highest economic return per unit of irrigation water, while potato exhibits the lowest priority. This index-based approach is applicable to other water-scarce agricultural regions seeking transparent allocation tools. The framework is designed as a simplified, scenario-based tool intended for comparative analysis under data-limited conditions. It supports regional drought management by enabling systematic evaluation of irrigation allocation strategies.
Keywords: irrigation, droughts, crop water requirements, water allocation strategies.

Introduction

Drought frequency and intensity have increased in many semi-arid and continental regions, intensifying seasonal water shortages and placing irrigation-dependent agriculture under increasing pressure. Global climate assessments indicate that rising temperatures, increased evapotranspiration and higher precipitation variability are expected to aggravate water scarcity in many agricultural regions (Intergovernmental Panel on Climate Change, 2021).

Climate projections for the South Caucasus region suggest a continued warming trend and increasing hydrological variability, which may significantly intensify agricultural water deficits and irrigation demand (United Nations Development Programme, 2011). Under such conditions, irrigation management gradually shifts from maximizing crop production under sufficient water supply to optimizing allocation under water scarcity.

Agriculture in Armenia remains strongly dependent on irrigation, particularly in lowland agricultural zones such as the Ararat Valley. Approximately one quarter of the country's arable land is irrigated, and crop productivity in these areas relies heavily on stable seasonal irrigation supply (Food and Agriculture Organization, 2016; World Bank, 2018; Yu et al., 2014). During drought years, available irrigation water often becomes insufficient to meet full crop water requirements. In many irrigation systems, water reductions are applied uniformly across crops in order to distribute shortages. However, such approaches may lead to inefficient allocation of scarce water resources and disproportionate economic losses.

Several regional studies highlight the vulnerability of Armenia's irrigated agriculture to climate-driven water scarcity and increasing irrigation demand. For example, Aram Melkonyan and co-authors show that Armenia's agricultural sector is highly sensitive to climate change due to increasing temperatures, declining precipitation and rising evapotranspiration, which together intensify irrigation water shortages and threaten crop productivity (Melkonyan et al., 2015). Their modelling results indicate that irrigation demand may increase substantially in major agricultural regions under future climate scenarios.

Complementary hydrogeological research conducted in the Ararat Valley demonstrates that groundwater resources supporting irrigation systems are under increasing pressure from agricultural water withdrawals and reduced recharge rates. Environmental tracer analysis confirms that the valley's aquifers still receive modern recharge but remain vulnerable to over-exploitation due to intensive irrigation and expanding agricultural water demand (Schubert et al., 2021). Together, these studies emphasize that improving irrigation efficiency and developing economically informed water allocation mechanisms are critical for maintaining agricultural productivity under increasing water scarcity in Armenia.

Economic theory suggests that scarce water resources should be allocated according to their marginal productivity, prioritizing uses that generate the highest economic return per unit of water (Young, 2005; Ward & Michelsen, 2002). In irrigated agriculture, the economic value of irrigation water can be expressed as the change in agricultural output resulting from incremental changes in water supply. When water availability declines, crops generating lower economic return per cubic metre of water should be reduced first in order to minimize total economic losses.

Agronomic research provides the methodological basis for linking irrigation water deficits with crop yield response. A widely used framework is the FAO yield–water production function, which describes the

relationship between relative yield reduction and relative evapotranspiration deficit (Doorenbos & Kassam, 1979). The model assumes that yield losses are proportional to evapotranspiration deficits, enabling estimation of crop productivity under different irrigation regimes.

Later developments expanded this framework and produced practical tools for estimating crop yield under deficit irrigation conditions (Steduto et al., 2012). These models form the basis of modern crop–water productivity analysis and irrigation planning tools such as AquaCrop.

Deficit irrigation strategies demonstrate that controlled reductions in irrigation can significantly reduce water consumption while preserving a substantial share of crop yield, depending on crop sensitivity and the timing of water stress during the growing season (Fereres & Soriano, 2007). In water – limited environments, irrigation management, therefore, increasingly focuses on maximizing crop production per unit of water rather than per unit of land (Molden et al., 2010).

Despite the availability of hydrological and agronomic models capable of estimating crop water requirements and yield response, practical decision-support frameworks that translate irrigation shortages into crop-level prioritization remain limited at regional scale. Existing drought management strategies in Armenia mainly focus on infrastructure development and water supply stabilization rather than on operational allocation tools capable of guiding crop prioritization during seasonal shortages (United Nations Development Programme, 2015; World Bank, 2018).

Therefore, a transparent and economically grounded framework is needed to support irrigation allocation decisions during drought conditions. By integrating irrigation volumes, crop yield response functions and market valuation of agricultural production, such a framework can enable systematic ranking of crops under progressive irrigation restrictions and support economically efficient water allocation during water scarcity events.

The objective of this study is to develop and apply an irrigation prioritization index that combines agronomic yield response with economic valuation of crop production. The proposed framework is designed to support crop-level ranking under different irrigation reduction scenarios and to minimize total economic losses associated with drought-induced irrigation shortages.

Materials and Methods

Study area

The model is applied to the Ararat region of Armenia, a major lowland agricultural area where irrigation is essential due to limited summer precipitation and high evapotranspiration rates (Food and Agriculture Organization, 2016). Crop production in the region depends on multiple irrigation cycles during the growing season. During drought years, available irrigation volumes decline, requiring progressive irrigation restriction measures in order to distribute limited water resources among crops.

Data sources and analytical framework

The prioritization framework is constructed at the crop level using regional agricultural statistics, irrigation schedules and average market prices of agricultural products. The analysis was based on representative regional agricultural, irrigation and economic data for the period 2020–2024. Crop water use, irrigation schedules and yield response assumptions were derived from regional irrigation practices and literature sources relevant to current agricultural conditions in the Ararat region of Armenia.

The analysis is conducted on a per-hectare basis to ensure comparability across different crops and production systems. This approach allows the estimation of irrigation water use, yield changes and economic outcomes under different irrigation scenarios.

Irrigation scenarios

For each crop, three irrigation regimes are defined to represent increasing levels of water scarcity:

Optimal irrigation – full irrigation according to the standard regional irrigation schedule.

Limited irrigation – reduced number of irrigation cycles representing deficit irrigation conditions.

No irrigation – complete withdrawal of irrigation supply.

Seasonal irrigation water use is calculated as:

$$W = n \times V \quad (1)$$

where

n – number of irrigation cycles,

V – water volume per cycle ($m^3\ ha^{-1}$).

The limited irrigation regime reflects a deficit irrigation approach, where water supply is intentionally reduced below full crop evapotranspiration (ETc) while maintaining partial crop productivity (Food and Agriculture Organization, 2002; Fereres & Soriano, 2007).

Yield and economic losses

Crop yield under limited irrigation is estimated using regional production data and agronomic relationships between water deficit and yield reduction. The estimation follows the FAO yield–water production framework, which links relative yield reduction to relative evapotranspiration deficit (Doorenbos & Kassam, 1979; Fereres & Soriano, 2007).

Economic loss resulting from irrigation restriction is calculated as:

$$EL = (Yo - Yr) \times P \quad (2)$$

where

EL – economic loss (EUR ha^{-1}),

Yo – crop yield under optimal irrigation (quintal ha^{-1}),

Yr – crop yield under reduced irrigation (quintal ha^{-1}),

P – crop market price (EUR per quintal).

Water savings

Water savings resulting from irrigation restriction are calculated as:

$$WS = Wo - Wr \quad (3)$$

where

WS – irrigation water saved (m³ ha⁻¹),
Wo – water use under optimal irrigation (m³ ha⁻¹),
Wr – water use under reduced irrigation (m³ ha⁻¹).

Irrigation prioritization index

To rank crops under drought conditions, an irrigation prioritization index is defined as:

$$PI = EL/WS \quad (4)$$

where

PI – prioritization index (EUR m⁻³),
EL– economic loss resulting from irrigation restriction (EUR ha⁻¹),
WS – irrigation water saved (m³ ha⁻¹).

The index represents economic loss per cubic metre of water not applied. Crops with lower index values generate smaller economic losses per unit of water saved and are therefore assigned lower irrigation priority. Crops with higher index values are prioritised for irrigation water allocation during drought conditions.

Progressive restriction logic

The model allows implementation of staged drought response strategies:

Phase 1 – moderate drought

Transition from optimal to limited irrigation, starting with crops that have the lowest prioritization index.

Phase 2 – severe drought

Complete irrigation withdrawal is applied progressively to crops with the lowest economic return per unit of water.

The framework is implemented as a spreadsheet-based decision-support tool that allows recalculation of crop prioritization under different drought severities, irrigation reductions and agricultural price scenarios. This structure enables rapid evaluation of alternative water allocation strategies and supports practical drought management decisions at regional level.

Results and Discussion

Irrigation water use under restriction scenarios

Application of the proposed prioritization framework to irrigated crops in the Ararat region illustrates how irrigation water demand changes under progressive restriction scenarios. Based on the irrigation schedules described in the methodological framework, seasonal water use varies substantially between optimal, limited and no-irrigation regimes.

Under optimal irrigation conditions, crops receive the full number of irrigation cycles required to maintain maximum productivity. When irrigation is partially restricted, the number of irrigation cycles decreases, leading to a corresponding reduction in seasonal water use. Under severe drought conditions, irrigation can be fully withdrawn, resulting in the maximum possible water savings.

Across the analysed crops, moderate irrigation restriction reduces seasonal irrigation water use by approximately 28–45%, depending on crop irrigation requirements and production characteristics. This reduction represents the first stage of drought management, where irrigation is reduced but crop production is partially maintained through deficit irrigation practices.

The irrigation regimes and associated seasonal water use used in the analysis are summarized in Table 1.

Table 1

Irrigation regimes and water use (Ararat example)

Irrigation regime	Irrigation cycles	Seasonal water use (m³ ha⁻¹)	Water saved (m³ ha⁻¹)
Optimal	7	5600	-
Limited	5	4000	1600
No Irrigation	0	0	5600

Economic losses and prioritization index

Under optimal irrigation conditions, the analysed crop produced an average yield of approximately 100 quintals ha⁻¹. When irrigation was reduced, yield declined to about 50 quintals ha⁻¹, while complete withdrawal of irrigation resulted in total crop failure.

Using an average market price of 46.5 EUR per quintal, the estimated economic losses differed substantially between irrigation restriction levels. The transition from optimal to limited irrigation resulted in moderate economic losses associated with partial yield reduction, whereas complete irrigation withdrawal generated significantly higher production losses due to total yield elimination.

These results illustrate the economic trade-off between water savings and agricultural production losses. Moderate irrigation restriction reduces water consumption while maintaining part of the crop yield, whereas complete irrigation withdrawal maximizes water savings but leads to substantially higher economic losses.

The calculated economic losses, associated water savings and resulting prioritization index values are presented in Table 2.

Table 2

Economic losses and irrigation prioritization index under restriction scenarios

Restriction scenario	Economic loss (EUR ha⁻¹)	Water saved (m³ ha⁻¹)	Index (EUR m⁻³)
Optimal → Limited	2 326	1 600	1.45
Optimal → No irrigation	4651	5600	0.83

Interpretation of the prioritization index

The prioritization index expresses the economic loss associated with each cubic metre of irrigation water not applied. Higher index values, therefore, indicate greater marginal economic productivity of irrigation water and, consequently, higher priority for irrigation allocation during water scarcity.

The results demonstrate that irrigation water has substantially higher marginal economic value under moderate irrigation restriction than under complete irrigation withdrawal. Under limited irrigation conditions, each cubic metre of water not applied results in an economic loss of approximately 1.45 EUR m^{-3}, reflecting the relatively high productivity of irrigation water when crop production is partially maintained.

In contrast, under complete irrigation withdrawal the average economic loss per cubic metre decreases to approximately 0.83 EUR m^{-3}. This occurs because total yield loss is distributed across a larger volume of water savings, reducing the average economic value per unit of water.

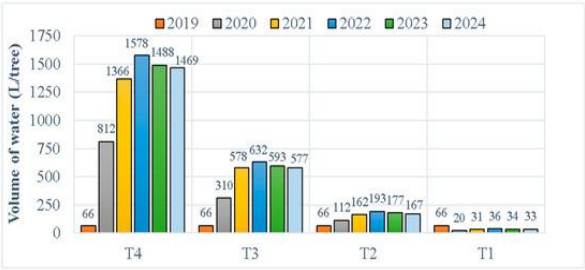
This occurs because total yield loss is distributed across a larger volume of water savings, reducing the average economic value per unit of water.

This implies that irrigation water allocation decisions based solely on total water savings may lead to economically inefficient outcomes if differences in marginal productivity are not considered.

These results illustrate the economic rationale for staged irrigation restriction strategies, where partial irrigation reductions are implemented before complete irrigation withdrawal. The comparison of prioritization index values across restriction scenarios is illustrated in Figure 1.

Figure 1

Prioritization index comparison



Crop prioritization under drought conditions

While the prioritization index quantifies the economic value of irrigation water under different restriction scenarios, its practical application lies in ranking crops according to their marginal economic productivity of water. Crops generating higher economic return per cubic metre of irrigation water should receive higher priority during water allocation under drought conditions.

Application of the proposed index to representative irrigated crops in the Ararat region illustrates clear differences in irrigation priority among crop types. The presented irrigation scenarios and economic calculations reflect representative conditions for the 2020–2024 agricultural seasons.

Crops with higher market value and higher sensitivity to irrigation shortages tend to generate greater economic loss per unit of water saved, which results in higher prioritization index values.

Conversely, crops with lower economic return per unit of irrigation water show lower prioritization index values and may be considered for earlier irrigation reduction during drought events. This ranking approach allows irrigation managers to implement staged restriction strategies while minimizing total economic losses in agricultural production systems.

Importantly, the results indicate that crop prioritization should be dynamic and responsive to both economic conditions and water availability, rather than based on fixed allocation rules.

The resulting crop prioritization based on the economic-loss-per-unit-water principle is illustrated in Figure 2.

Figure 2

Crop prioritization ranking based on economic loss per unit of irrigation water

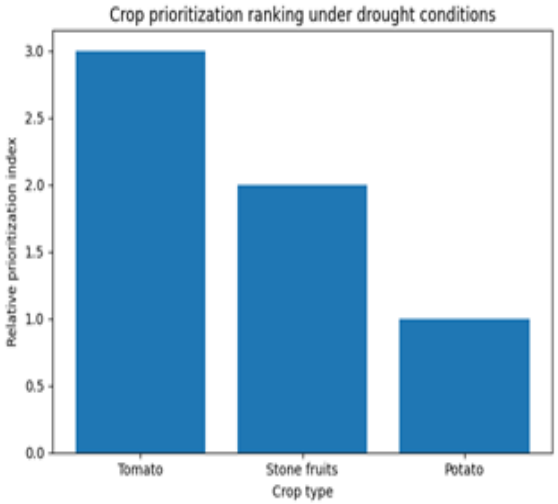


Figure 2 presents the crop prioritization ranking derived from the proposed economic-loss-per-unit-water approach. The results indicate clear differences in the marginal economic productivity of irrigation water among the analysed crops.

Tomato shows the highest prioritization index, reflecting its relatively high economic return per unit of irrigation water. Stone fruits occupy an intermediate position, while potato demonstrates the lowest prioritization index due to its lower economic productivity per cubic metre of irrigation water.

This ranking provides a practical basis for staged irrigation restriction during drought conditions. Crops with lower prioritization index values can be subjected to irrigation reductions earlier, while crops with higher economic value of irrigation water should be maintained under irrigation for as long as possible.

The results demonstrate that irrigation allocation based on economic loss per unit of water can provide a transparent and operational basis for drought

management in irrigated agricultural systems. The prioritization index developed in this study quantifies the marginal economic productivity of irrigation water and allows crops to be ranked according to the economic consequences of irrigation reduction.

The findings indicate that moderate irrigation restriction can significantly reduce water consumption while preserving a substantial share of crop production. This result is consistent with previous research on deficit irrigation, which shows that controlled reductions in irrigation water can maintain acceptable yield levels depending on crop sensitivity and timing of water stress (Fereres & Soriano, 2007; Steduto et al., 2012). In such situations, partial irrigation reductions represent an efficient first response to water scarcity, allowing water savings without immediate full production losses.

The results also highlight that the economic value of irrigation water differs considerably between crops. Crops generating higher economic return per unit of irrigation water require greater protection during drought periods, while crops with lower marginal economic productivity may be subjected to earlier irrigation reductions. Similar economic allocation principles have been widely discussed in water resource economics, where water scarcity requires prioritizing uses that generate the highest economic benefits (Young, 2005; Ward & Michelsen, 2002).

The proposed prioritization framework therefore provides a practical tool for implementing staged irrigation restriction strategies during drought events. By integrating irrigation volumes, crop yield response and market valuation, the model translates water scarcity into operational crop ranking decisions. Such tools are particularly relevant in regions like the Ararat Valley, where irrigation-dependent agriculture faces increasing pressure from climate variability and growing water demand.

Nevertheless, several limitations should be acknowledged. The model relies on representative yield values, average market prices and simplified irrigation regimes, which may vary across farms and seasons. In addition, the framework does not explicitly account for crop growth stage sensitivity, long-term soil effects or social and food security considerations that may influence water allocation decisions. In addition to the presented results, the findings can be interpreted within a broader context of recent advances in water resource management under climate change. Increasing evidence suggests that water scarcity is not only a function of physical water availability but also of allocation efficiency and governance structures. Global assessments indicate that climate change is expected to intensify water scarcity in many agricultural regions, increasing the need for adaptive and economically efficient allocation mechanisms (Schewe et al., 2014).

From an economic perspective, recent studies emphasize that efficient water allocation requires moving beyond uniform distribution practices toward mechanisms that reflect the marginal value of water across competing uses (Grafton et al., 2018). The results of this study support this view by demonstrating that the economic productivity of irrigation water varies substantially between crops and across irrigation regimes.

Furthermore, research on agricultural water productivity highlights that significant improvements in water-use efficiency can be achieved through targeted allocation strategies and deficit irrigation practices, particularly in water-limited environments (Zwart & Bastiaanssen, 2004). The prioritization index proposed in this study provides a practical tool for implementing such strategies by linking agronomic yield response with economic valuation.

While the framework is simplified, it contributes to bridging the gap between theoretical economic principles and operational irrigation management by providing a transparent and easily applicable decision-support approach. This is particularly relevant in data-limited regions, where complex modelling approaches may not be feasible but where efficient water allocation remains critical for sustaining agricultural productivity.

Future research could therefore integrate more detailed agronomic modelling and regional economic data to improve the robustness of irrigation prioritization tools.

Conclusions

1. The case study of the Ararat region demonstrates the applicability of an economic-loss-based prioritization framework for irrigation management under drought conditions.
2. The results show that moderate irrigation restriction can reduce seasonal irrigation water use by approximately 28–45%, depending on crop irrigation requirements. Under such conditions, partial irrigation reductions allow substantial water savings while maintaining a significant share of crop yield.
3. Complete irrigation withdrawal provides the largest potential water savings but results in significantly higher economic losses due to total production failure. The calculated prioritization index shows that the economic loss per cubic metre of water saved varies considerably between irrigation restriction levels and crop types.
4. The proposed prioritization index therefore provides a transparent indicator of the marginal economic productivity of irrigation water and enables ranking of crops according to their economic sensitivity to irrigation reduction. This approach supports staged drought response strategies, where irrigation reductions are first applied to crops generating lower economic return per unit of water.
5. Overall, the developed framework represents a simple and operational decision-support tool that can assist irrigation managers and regional planners in allocating limited water resources during drought events while minimizing total economic losses in

irrigated agricultural systems. The results should be interpreted as indicative rather than statistically generalizable, as the model is based on representative values and simplified assumptions.

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A COMPARATIVE ASSESSMENT OF FARM-LEVEL GREENHOUSE GAS EMISSION ESTIMATES USING DECARBFARM AND ESTABLISHED GHG TOOLS

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Abstract
The foundation of effective agriculture decarbonisation at farm level is the establishment of a comprehensive understanding of the farm's current greenhouse gas (GHG) emission baseline. The establishment of effective baselines and the monitoring of GHG emissions over time are ensured through the provision of farm-level GHG emission calculators available for farmers. As of the present moment there are number of GHG emission calculation tools available for farmers. In addition to these, a new decarbonisation decision support tool (DST), DecarbFarm, is currently under the development. Although the developed DecarbFarm tool is not yet widely available for famers, it is crucial to evaluate DSTs comparability with other, already available GHG DSTs. This research paper aims to evaluate the comparability of GHG emission estimates generated by the DecarbFarm DST by three already established agriculture GHG emission calculators – the Estonian Carbon Footprint assessment tool, the Latvian GHG and Ammonia Emission Calculation tool, and Cool Farm Tool – using harmonised input data. The findings of the study suggest general consistency in total GHG emission estimates across tools, alongside notable variability in source-specific emissions. These differences highlight the influence of methodological choices on estimated emission baselines and have direct implications for farm-level decarbonisation planning. Furthermore, the results underline the importance of region-specific GHG emission calculation tool in more accurately reflecting local emission factors within farm-level GHG baselines.
Keywords: farm GHG emissions, agricultural decarbonization, decision support tools, regional emission factor.

Introduction

Latest Latvian national greenhouse gas (GHG) inventory report indicates, that Latvia's GHG emissions, including land use, land use change, and forestry emissions, have been increasing throughout years 2000 and 2023 (Skrebele et al., 2025). Similar observations can be made regarding the sector of agriculture, however the GHG emission increase in agriculture is more gradual (Skrebele et al., 2025). Within Latvia's national energy and climate action plan for the sector of agriculture the target is set to achieve GHG emission amount of 2,176.33 kt CO_2 eq. in 2030, contributing to the target of reducing 17% of GHG emissions stemming from sectors not included in European Union Emission Trading System (ETS) (Latvijas Republikas Ekonomikas Ministrija, 2024). The plan also acknowledges the difficulties achieving the set target, however it also emphasises the role of non-ETS sector including agriculture's role in achieving Latvia's decarbonisation targets (Latvijas Republikas Ekonomikas Ministrija, 2024).

The foundation of effective agriculture decarbonisation begins at the farm level, specifically with the understanding of farm's GHG emission baseline. This understanding can be established by utilising an effective GHG emission accounting tool suitable for application at farm level. Throughout past couple of decades, several GHG emission accounting tools have been developed, ranging in geographies, methodologies, utilised calculation solutions, focus of the calculator (Colomb et al., 2012; Dzalbs et al., 2023; Jabbour et al., 2021). In Denef et al. (2012) report the earliest developed tool has been identified as developed in 2002. Since then, several more GHG emission accounting tools for agriculture have been developed, allowing farm-level GHG emission accounting to become more accessible all over the world. In case the calculator is easy to use and it's use is not time consuming, the calculator can act also as a tool for awareness raising as an equal goal (Peter et al., 2017).

In the Baltic countries over the past ten years agriculture GHG emission accounting tools have gained increasing attention, driving the development of new tools. Currently there are GHG emission accounting tools available developed by scientific institutions, such as GHG and ammonium emission calculator developed by scientists of Latvia University of Life Sciences and Technology (Grinfelde et al., 2018b), as well as tools developed by the request of governments, such as Carbon Footprint Assessment Tool (CFAT) (Ministry of Regional Affairs and Agriculture of Estonia & Sustinere OÜ, 2024). There is also a GHG emission accounting tool developed by Deloitte after the request of the Baltic banking associations (Deloitte, 2024), however the scope of agriculture production-related accounting options within the tool are significantly smaller than within the other Baltic tools mentioned. The presence of various accounting tools raises the question of whether there are differences among them, and if so, whether those differences in the resulting GHG emission estimates are significant.

In scientific literature there are studies available comparing the available GHG emission accounting tools (Dzalbs et al., 2023; Keller et al., 2014; Sykes et al., 2017), including region-specific agriculture GHG emission accounting tool evaluations (Whittaker et al., 2013). However, the analysis of the Baltic tools is limited. This raises questions, if the tools developed specifically for the Baltic region are comparable with those agriculture GHG emission accounting tools recognised worldwide. Furthermore, given the authors of the study have developed a new GHG emission

accounting tool for farm-level decarbonisation decision-making support in Latvia (Muižniece, 2025), it is important to evaluate how the results generated by this tool compare with those produced by other established agricultural GHG emission accounting tools both locally and internationally.

To find the answers to the abovementioned questions, this research is aimed to evaluate the comparability of GHG emission estimates generated by the DecarbFarm DST by three already established agriculture GHG emission calculators – the Estonian Carbon Footprint Assessment Tool, the Latvian GHG and Ammonia Emission Calculation tool, and Cool Farm Tool – using harmonised input data.

Materials and Methods

The study evaluates four different GHG emission accounting tools for the agriculture (see Table 1). Besides the DecarbFarm tool developed by the authors of this study, the tools for the study were selected primarily focusing on the Baltic region. Based on this criteria, GHG and Ammonium Emission Calculator (Grinfelde et al., 2018b) developed in Latvia and CFAT (Ministry of Regional Affairs and Agriculture of Estonia & Sustinere OÜ, 2024) developed in Estonia were selected. To provide an internationally recognized benchmark within the analysis, a Cool Farm Tool (Cool Farm Alliance, 2026) was selected, due to its applicability to Europe, including the Baltics.

Table 1

Comparison between the tools used in this study

Tool name	Country	Language	Technical solution	Tool focus	Number of input data points	Reference
DecarbFarm	Latvia	Latvian	Excel	Integrated livestock-crop farms	99	(Muižniece, 2025)
Carbon Footprint Assessment Tool	Estonia	Estonian	Excel	Crop farming	1385	(Ministry of Regional Affairs and Agriculture of Estonia & Sustinere OÜ, 2024)
				Livestock	1907	
				Buildings and administration	191	
GHG and Ammonium Emission Calculator	Latvia	Latvian	Web-based	Integrated livestock-crop farms	111	(Grinfelde et al., 2018b)
CoolFarm	United Kingdom	English, Latvian	Web-based	Crop farming	66	(Cool Farm Alliance, 2026)
				Livestock	70	

The tools were screened as of 23rd of February 2026 until 1st of March 2026. For each tool input data points were manually counted, considering, that one data point is one entry field for information, including fields where information from dropdowns is selected. Selections within a dropdown are not counted separately. As within CFAT (Ministry of Regional Affairs and Agriculture of Estonia & Sustinere OÜ, 2024) it was possible to change the tools structure, for the purpose of this study the structure of the tool was not adjusted. For the Cool Farm Tool it is possible to add additional sources of GHG emissions about whom GHG emissions could be provided (Cool Farm Alliance, 2026). In these instances, the input data points were counted only for the first entry. Units, that are directly linked with the input numbers, are not counted as separate input data points.

Given the different parameter scopes of each parameter, five common parameters across the four tools were chosen for which data is collected. The chosen parameters are:

- Dairy cows;
- Swine;
- Wheat;
- Pasture/grassland;
- Natural gas.

For each parameter a randomised input data string consisting of ten data points was developed. These data strings (see Table 2) were after used as inputs in each of the four GHG emission accounting tools. These input data strings were developed to approximate realistic farm ranges. For each input data point the respective output of calculated GHG emission was recorded.

During the data collection process, it was observed that the Cool Farm Tool differed in the chosen parameter's calculation approach, for example, calculating the GHG emissions from wheat as residue management only. In addition, this tool did not provide the option to evaluate the GHG emissions from pasture/grasslands. To maintain the comparability between the tools, the Cool Farm Tool was further excluded from the assessment. In addition, parameter Natural gas was excluded from the assessment due to visibly higher obtained output values from GHG and Ammonium Emission Calculator (see Figure 1).

All data obtained from the tools and included in this study were evaluated to ensure compliance with the assumptions required for parametric statistical analyses. Normality of data distribution was assessed prior to selecting the appropriate statistical test. In case data is normally distributed, a parametric data can be used. Otherwise, the nonparametric Friedman test was used.

Normality was examined using the Shapiro–Wilk test in statistics software RStudio (version 2026.01.0+392) with α = 95% confidence interval. If the recorder p-value is above 0.05, the null hypothesis of normal distribution of data cannot be rejected.

Table 2
Input data used in the tool screening process

Number of input data point	Dairy cows, number of animals	Swine, number of animals	Wheat, t	Pasture/Grassland, ha	Natural Gas, m^3
1	80	500	200	10	1,000
2	102	634	248	12	1,259
3	118	729	292	17	1,695
4	136	851	383	18	1,906
5	142	1,034	437	20	1,993
6	156	1,382	481	21	2,041
7	169	1,544	524	24	2,428
8	172	1,634	561	27	2,682
9	189	1,853	601	29	2,847
10	205	2,000	650	30	3,000

To evaluate differences among GHG accounting tools within each agricultural parameter, the nonparametric Friedman rank-sum test was applied. This test was selected as the dataset represents a repeated-measures design in which identical input levels were evaluated using multiple tools. In this study, the agricultural parameter was considered the block, and the GHG accounting tools were treated as related groups. The test evaluates whether the median rankings of GHG emission estimates differ significantly among tools while controlling for variability attributable to input magnitude.

The Friedman test was performed in RStudio (version 2026.01.0+392) using a significance threshold corresponding to a 95% confidence level. When statistically significant differences were detected at this level, post hoc pairwise comparisons were performed using Wilcoxon signed-rank tests, with Bonferroni-adjusted p-values applied to control the family-wise error rate at α = 0.05. Kendall's coefficient of concordance (W) was used to quantify the magnitude of differences among tools. Kendall's coefficient value provides a standardized measure of agreement among ranks across parameters, with values ranging from 0 indicating no effect to 1, indicating perfect agreement. This test allows interpretation of the practical relevance of the observed differences independently of statistical significance.

The findings of the analysis facilitate the identification of key differences among GHG accounting tools and provide a solid foundation for subsequent research.

Results and Discussion

The Figure 1 presents the registered tool output GHG emissions per parameter. Based on the recorded data it can be seen that obtained GHG emissions from Natural Gas in GHG and Ammonia calculator (Grinfelde et al., 2018b) is visibly higher than other registered GHG emissions both for the same parameter as well as other parameters among the tools, indicating a potential inconsistency for Natural Gas GHG emission calculation. Therefore, Natural Gas as a parameter was excluded from further statistical analysis in order to avoid potential bias resulting from methodological differences in emission calculation approaches among the tools (see Figure 2).

The Shapiro-Wilk normality test revealed the data used in the study are not normally distributed (p = 6.808e - 12). Therefore, nonparametric Friedman test was used to assess the GHG emission estimates provided by the utilised GHG assessment tools.

Comparing the parameter registered output GHG emissions form three different tools, the Friedman test suggest that there are no statistically significant differences (p = 0.082) between the analysed tools. When analysing the GHG emissions between tool pairs applying Wilcoxon signed rank pairwise tests, the results indicate that between DecarbFarm and CFAT there are no differences (p = 1.000), while GHG and Ammonium Emission Calculator was statistically significantly different from both DecarbFarm (p = 0.019) and CFAT (p = 0.021). From a practical perspective, the observed similarity between DecarbFarm and CFAT suggests that the newly developed tool can provide comparable GHG emission estimates for farm-level baseline assessments. These differences in the tools are mainly related with the underlying IPCC methodology version used in the methodology of the tool, as both DecarbFarm and CFAT applies 2019 revision of the guidelines , while the GHG and Ammonium Emission Calculator was mainly based on the 2006 revision of the IPCC guidelines (Grinfelde et al., 2018a).

In addition, Friedman Kendall's W value was calculated. The value of 0.0625 indicate that the differences between tools are statistically small, and the tools produce very similar GHG profiles relative to one another. This indicates weak agreement in rank ordering of GHG values across tools, suggesting that differences between tools are minimal in practical terms. Given that the tools rely on different region-specific GHG emission factors, such minimal

differences, particularly regarding DecarbFarm and CFAT tools, are likely driven more by variations in the underlying emission factor assumptions than by any substantive methodological divergence. Given that assessed tools are developed in the Baltic region, the emission factor impact does not yield significant differences.

Figure 1
GHG emission results obtained from different tools per parameter. The abbreviations used in the figure are as follows: CFAT – Carbon Footprint Assessment Tool, GHGAmmonia – GHG and Ammonium Emission Calculator, NatGas – Natural Gas

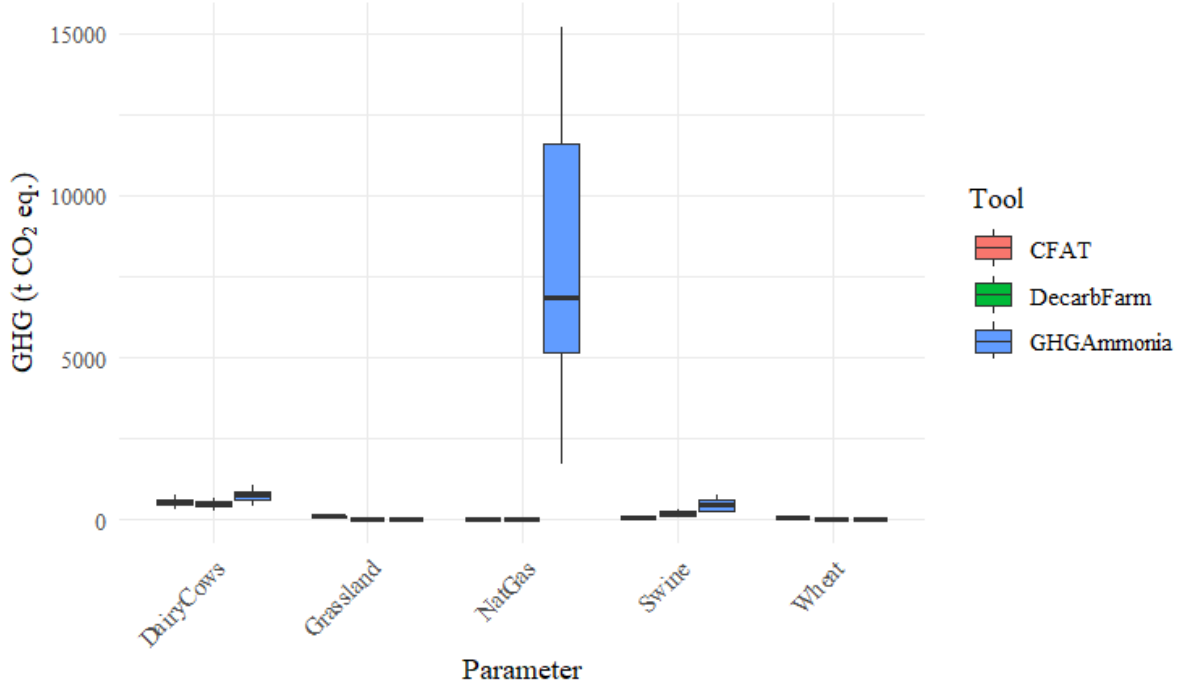
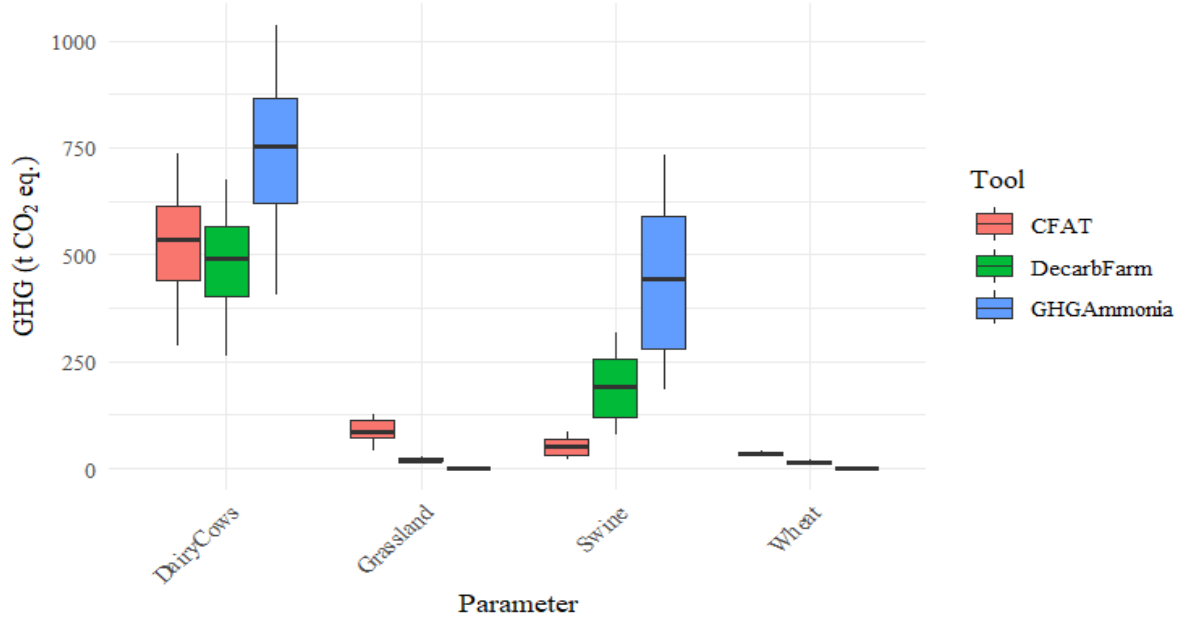


Figure 2
GHG emission results per parameter per tool used in analysis. The abbreviations used in the figure are as follows: CFAT – Carbon Footprint Assessment Tool, GHGAmmonia – GHG and Ammonium Emission Calculator



Whittaker et al. (2013) study evaluated carbon accounting tools for the application in the United Kingdom, analysing also each parameter emissions among the tools, evaluating the differences stemming

from emission factors used in parameter GHG emission estimations. In further research, the data obtained within this study can be further evaluated also considering the statistical differences between the chosen parameters separately.

While the results of the analysed tools indicate that these tools statistically are not significantly different and can be used by farmers in the Baltic region without notable restrictions against the use of tool. Besides the underlying methodology and regional aspects of the tool, Dzalbs et al. (2023) in their study evaluated other aspects crucial for farmers for successful adaptation in everyday aspects. Those cover several characteristics, such as usability, assessment simplicity, and recognition among peers (Dzalbs et al., 2023). The authors suggest in further research to assess these aspects of the tools used within this study.

Additionally, the applicability of these analysed calculators could depend on the level of details required to be provided for GHG emission estimations. Peter et al. (2017) study evaluated GHG emission calculators for the energy crop production. They concluded that the analysed tools either provided ease of use leading to reporting driven results, or required more detailed and time-consuming data inputs, therefore allowing farmers to gain insights on more granular calculated output level (Peter et al., 2017). All four tools initially included in this study exhibit potential for application not only for reporting purposes, but also for more detailed analysis of key GHG emission sources. However, due to the limitation of one-year GHG emission calculation, more detailed and continuous analysis would be difficult.

Given the limitations in obtaining comparable data for the Cool Farm Tool, the comparability of Baltic GHG emission accounting tools with other internationally recognised tools remains limited. Therefore, the authors suggest further evaluation of established GHG emission accounting tools by expanding the range of tools included in the analysis, which would enable a statistical comparison of Baltic tools with a broader set of internationally used calculators.

Conclusions

1. The tools assessed generate comparable GHG emission results, with differences stemming from underlying methodology and region-specific emission factors.
2. The analysed tool practical use may vary depending on usability, data requirements, and the level of detail required for GHG emission assessment.
3. To understand the effects of regional emission factors, the selected tools should be statistically compared on a parameter level.
4. Further analysis can be conducted to evaluate factors influencing the practical adoption of these tools in real-world factors.
5. Future research should include a broader range of GHG emission accounting tools to enable statistical comparison between the Baltic and internationally recognised calculators.

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SPATIAL OCCURRENCE OF PFOS AND PFOA IN THE DAUGAVA AND LIELUPE RIVER BASINS (LATVIA)

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Abstract
Persistent synthetic chemicals known as per- and polyfluoroalkyl substances (PFAS) are widely detected in aquatic environments and are recognized as contaminants of concern in surface waters worldwide. Although agricultural areas are not typically considered primary PFAS sources, rural catchments may act as transport pathways where hydrological processes and surface runoff influence PFAS mobility and distribution. This study presents a comparative assessment of PFAS occurrence in river basins in Latvia: the Daugava River Basin, representing a mixed urban–rural catchment, and the Lielupe River Basin, characterised by intensive agricultural land use. The analysis focuses on perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), two indicator PFAS compounds included in national monitoring programs. Monitoring data from multiple stations were evaluated for the period 2017–2025 in the Daugava River Basin and 2018–2024 in the Lielupe River Basin using descriptive statistics and non-parametric statistical analysis. No statistically significant differences in PFOS and PFOA concentrations were observed between the Daugava and Lielupe river basins (Kruskal–Wallis test, $p > 0.05$). In contrast, concentrations differed significantly between PFOS and PFOA ($p < 0.001$) and among individual monitoring stations, suggesting the influence of local contamination sources and localised spatial differences. These findings indicate that PFAS occurrence in rural surface waters is influenced by local environmental conditions and catchment characteristics. The study highlights the importance of river basin monitoring for understanding PFAS distribution and supports the need for more systematic PFAS monitoring in agricultural regions of the Baltic area.
Keywords: PFAS, PFOS, PFOA, surface water, river basins.

Introduction

Per- and polyfluoroalkyl substances (PFAS) represent a large group of synthetic chemicals widely used in industrial processes and consumer products due to their unique physicochemical properties, including high thermal stability and surfactant behaviour. According to Buck et al. (2011), PFAS comprise a diverse class of fluorinated compounds characterised by strong carbon–fluorine bonds, which contribute to their exceptional environmental persistence (Buck et al., 2011). Because of their resistance to degradation and extensive historical use, PFAS are now recognised as globally distributed contaminants detected in various environmental compartments, including surface waters, groundwater, sediments, and biota (Brusseau, 2023; Gomis et al., 2015; Ackerman Grunfeld et al., 2024; Alam et al., 2024). Numerous monitoring studies have demonstrated their widespread occurrence in aquatic environments across different regions of the world, indicating that PFAS contamination has become a global environmental concern (Ahrens, 2010; McMahon et al., 2022; Calore et al., 2023; Miladinova et al., 2024).

Among the numerous PFAS compounds, perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA) are among the most widely studied substances due to their persistence, mobility, and environmental relevance. These compounds are frequently detected in rivers and other surface water bodies worldwide, where they may originate from multiple anthropogenic sources such as industrial discharges, wastewater treatment plant effluents, landfill leachates, and diffuse emissions from urban and rural areas (Sun & Li, 2025; Tang et al., 2023). Urban environments and wastewater systems have been identified as important contributors to PFAS contamination in aquatic ecosystems, as demonstrated by Yang et al. (2025).

Rivers play an important role in the environmental transport and redistribution of PFAS, acting as pathways that connect terrestrial emission sources with downstream aquatic ecosystems and marine environments (Cai et al., 2018; Byrne et al., 2024). The occurrence and distribution of PFAS in river basins are influenced by various environmental processes, including hydrological transport, catchment characteristics, and interactions with environmental matrices such as dissolved organic matter and suspended particles. Previous studies have shown that organic carbon and particulate matter can influence the mobility and distribution of PFAS in aquatic systems (Li et al., 2022).

Although PFAS contamination is often associated with industrialised or highly urbanised regions, rural catchments may also act as important pathways for PFAS transport. Diffuse pollution processes, surface runoff, and soil–water interactions may contribute to the mobilisation of PFAS in agricultural landscapes. In addition, the application of sewage sludge and biosolids to agricultural soils has been recognised as a potential secondary source of PFAS in the environment (Zhou et al., 2024).

Studies conducted in Nordic and Baltic regions have increasingly reported the presence of PFAS in surface waters, indicating that these contaminants are also widespread in northern European aquatic environments. For example, Kärrman et al. (2019) and Soerensen et al. (2024) reported detectable PFAS concentrations in Nordic and Baltic surface waters, highlighting the importance of regional monitoring and improved understanding of PFAS transport processes in these catchments (Kärrman et al., 2019;

Soerensen et al., 2024).

In addition to growing scientific attention, PFAS contamination has also become an important regulatory concern. Within the European Union, several PFAS compounds are subject to environmental monitoring and regulatory control due to their persistence and potential risks to ecosystems and human health (European Parliament and Council, 2008; EC, 2022). However, PFAS monitoring data in Latvian river basins remain limited, and studies addressing spatial and temporal variability of PFAS in surface waters are still scarce.

The present study provides a comparative assessment of PFOS and PFOA occurrence in two major Latvian river basins with contrasting land-use characteristics: the Daugava River Basin, representing a mixed urban–rural system, and the Lielupe River Basin, which is strongly influenced by agricultural activities. Despite the existence of national environmental monitoring data, studies interpreting PFAS distribution patterns and variability in Latvian river systems remain limited. Using national monitoring data, this study evaluates the spatial and temporal variability of PFOS and PFOA occurrence in surface waters and examines potential differences in PFAS distribution between river basins and individual monitoring stations. Spatial variability between monitoring stations may reflect differences in land use, urban influence, wastewater inputs, and hydrological conditions within river catchments. Therefore, analysing PFAS occurrence at both river basin and monitoring station level is important for understanding local contamination patterns and potential PFAS sources under Latvian conditions. This study provides new evidence on the spatial and temporal distribution of PFOS and PFOA in Latvian surface waters at the river-basin scale.

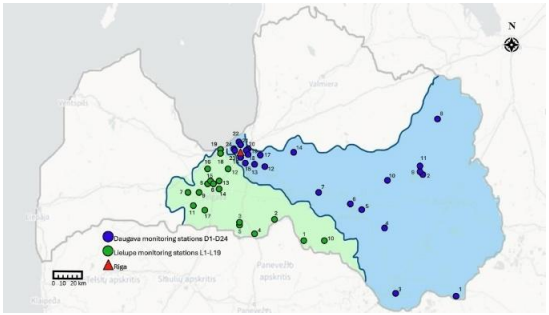
Materials and Methods

This study focuses on two major river basins in Latvia: the Daugava River Basin and the Lielupe River Basin, which represent catchments with contrasting land-use characteristics. The Daugava River Basin is characterised by a mixed urban–rural landscape including major urban areas and diverse land-use patterns, whereas the Lielupe River Basin is strongly influenced by agricultural activities and intensive land use. Catchment characteristics and land-use patterns were interpreted descriptively based on the general characteristics of the river basins reported in previous studies and regional environmental information.

PFAS occurrence was assessed using available surface water monitoring data obtained from the Latvian Environment, Geology and Meteorology Centre (LVĢMC) (LVĢMC, 2026). Monitoring stations included in this study represent official surface water monitoring sites located within the Daugava and Lielupe river basins. The spatial distribution of monitoring stations included in the analysis is presented in Figure 1. A total of 43 surface water monitoring stations included in the study were located throughout the Daugava (24) and Lielupe (19) river basins. Stations in the Daugava River Basin included: *Daugava (further – DA) Piedruja-Latvijas-Baltkrievijas-robeža (D1), Rēzeknes grīva (D2), DA 1.5 km lejpus Daugavpils (D3), Dubnas 2.5 km augšpus Līvāniem (D4), DA 1.0km-augšpus Jēkabpils (D5), DA 1.5km lejpus Jēkabpils (Zeļķu tilts) (D6), Pļaviņu ūdenskrātuve 1.0km augšpus Aizkraukles (D7), Balvu ezers vidusdaļa (D8), Lubāna ezers vidusdaļa (D9), Kujas grīva (D10), Aiviekste augšpus Ičas (D11), DA augšpus Ogres (D12), Rīgas ūdenskrātuve 1.0 km lejpus Lipšiem (D13), Mergupes grīva (D14), Ķekavas grīva (D15), DA pie Rumbulas (D16), Lielā Jugla 0.2 km augšpus Zaķiem hidroprofils (D17), Juglas ezers vidusdaļa (D18), Lielais Baltezers vidusdaļa (D19), Mazais Baltezers pie sūkņu stacijas (D20), Ķīšezers pretī Mežaparkam (D21), Mārupītes grīva (D23), Ķīšezers pretī Mīlgrāvja caurtekai (D22) and DA Andrejosta (D24). Stations in the Lielupe River Basin included: Mēmele Latvijas–Lietuvas robeža Rises (L1), Mēmele 0.5 km lejpus Skaistkalnes (L2), Mēmeles grīva (L3), Mūsa Latvijas–Lietuvas robeža (L4), Mūsas grīva (L5), Iecavas grīva (L6), Bērze 1.0 km lejpus Dobeles (L7), Bērzes grīva (L8), Auce lejpus Nākotnes (L9), Saukas ezers vidusdaļa (L10), Tērvete augšpus Tērvetes ciema (L11), Misa 1.5 km lejpus Olaines (L12), Misas grīva (L13), Lielupe 1.0 km augšpus Jelgavas (L14), Lielupe 2.5 km lejpus Jelgavas (L15), Lielupe 0.5 km lejpus Kalnciema (L16), Vilces grīva (L17), Babītes ezers vidusdaļa (L18) and Lielupe Majori (L19).*

Figure 1

Map of monitoring stations in the Daugava and Lielupe river basins



The analysis focused on two widely monitored indicator compounds: perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA). PFOS and PFOA concentrations from the Daugava River Basin were analysed for the period 2017–2025, while data from the Lielupe River Basin covered the period 2018–2024. The monitoring data represent episodic sampling events conducted within the national surface water monitoring programme.

Water samples collected within this period in each basin were tested in accredited laboratories using liquid chromatography coupled with tandem mass spectrometry (LC–MS/MS), which is a widely used

analytical technique for PFAS determination in environmental samples. PFOS and PFOA concentrations were originally reported in micrograms in the available monitoring datasets. However, in this study, results were converted to nanograms per litre (ng L^{-1}) in order to compare with other studies and regulatory norms.

In total, 892 surface water samples were analysed for both PFOS and PFOA, including 504 samples from the Daugava River Basin and 388 samples from the Lielupe River Basin.

To evaluate the occurrence of both compounds in the two river basins, descriptive statistical analysis was performed. The calculated statistical parameters included minimum, maximum, mean, median, standard deviation, skewness and kurtosis (Table 1).

Spatial variability of PFAS concentrations between the two river basins was explored using graphical visualization techniques. Differences in PFOS and PFOA concentrations between the Daugava and Lielupe river basins were illustrated using boxplot diagrams, which allow comparison of data distribution, median values, and potential outliers between datasets (Figure 3).

Temporal variability of PFOS and PFOA concentrations was analyzed by evaluating annual patterns of PFOS and PFOA concentrations over the monitoring period. Temporal trends were illustrated using annual concentration plots showing changes in PFOS and PFOA levels during the study period (Figure 5).

Because environmental monitoring data showed non-normal distribution, differences between groups were evaluated using non-parametric statistical tests. The Kruskal–Wallis test was applied to assess differences between river basins, compounds, monitoring stations, and years. When statistically significant differences were detected, Dunn's post-hoc test with Bonferroni correction was used to identify pairwise differences between groups.

All data processing, graphical visualisation, and statistical analyses were performed using R statistical software.

Table 1

Descriptive statistics of PFOS and PFOA concentrations (ng L^{-1}) in the Daugava and Lielupe river basins during the monitoring period

Basin	Compound	n	mean	median	sd	min	max	skewness	kurtosis
Daugava	PFOA	252	0.5605	0.203	1.3290	0.039	13.221	7.15	61.32
Daugava	PFOS	252	0.1282	0.052	0.7162	0.039	11.106	14.48	216.71
Lielupe	PFOA	194	0.5366	0.194	0.9754	0.039	9.202	4.69	32.48
Lielupe	PFOS	194	0.0829	0.040	0.1494	0.039	1.928	10.01	117.65

Results and Discussion

The results are presented in three main analytical steps. First, the overall concentration levels and detection frequencies of PFOS and PFOA in the studied river basins are summarized. Second, differences between the Daugava and Lielupe river basins are analysed. Finally, temporal variability of PFOS and PFOA concentrations during the study period is examined.

Spatial variability of PFOS and PFOA

The occurrence of PFOS and PFOA in the two river basins was evaluated in order to identify spatial differences associated with catchment characteristics and land-use patterns. Descriptive statistical analysis of the monitoring dataset is presented in Table 1. Overall, PFOS and PFOA concentrations were relatively low in both river basins and exhibited comparable concentration ranges. In most samples, PFOS concentrations remained below the PFOS AA-EQS threshold (0.65 ng L^{-1}), while PFOA concentrations were also observed within relatively low concentration ranges, suggesting relatively low background contamination levels in the Daugava and Lielupe river systems.

Across the monitoring period, PFOS concentrations were typically observed within the range of approximately 0.04–0.1 ng L^{-1}, whereas PFOA concentrations were generally higher, most frequently ranging between 0.1 and 0.5 ng L^{-1}. This pattern is consistent with observations from other European monitoring studies, where PFOA is often detected at slightly higher concentrations due to its higher environmental mobility and lower sorption affinity compared with PFOS (Tang et al., 2023; Cai et al., 2018).

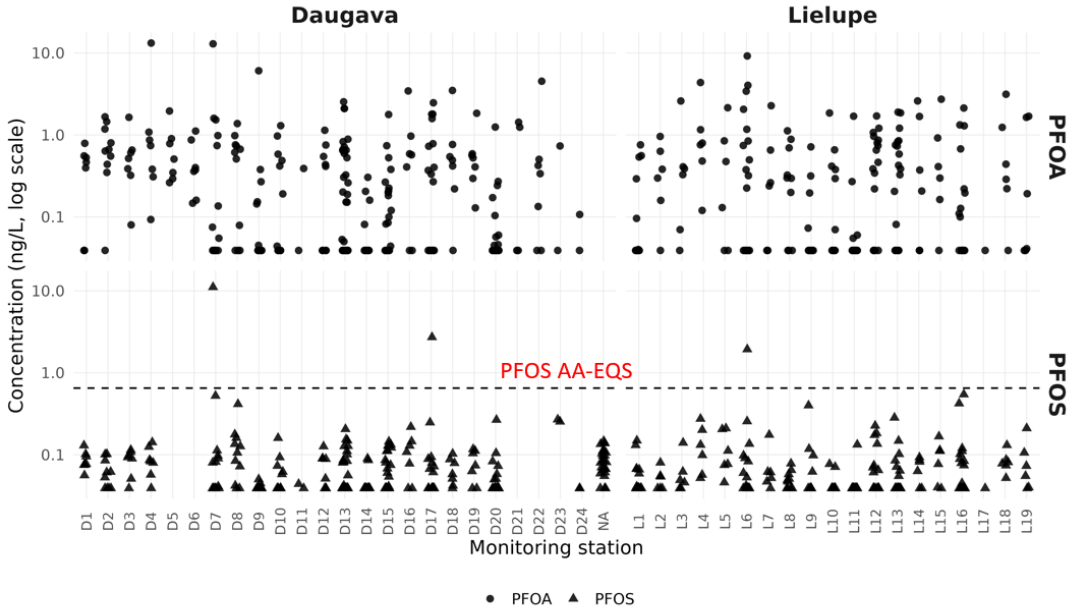
Descriptive statistical analysis indicates that overall concentration patterns in the two river basins are relatively similar. Median concentrations of both compounds differed only slightly between the Daugava and Lielupe river basins. This observation is supported by the results of the Kruskal–Wallis statistical test, which did not reveal statistically significant differences between PFAS concentrations in the two river basins ($p > 0.05$). The descriptive statistical parameters presented in Table 1 also provide additional insight into the distribution characteristics of PFOS and PFOA concentrations in the studied river basins. The calculated skewness values indicate a strongly right-skewed distribution for both compounds, particularly for PFOS in the Daugava River Basin. This suggests that most observations are

concentrated at relatively low concentrations, while a limited number of measurements represent substantially higher values.

Similarly, the high kurtosis values observed in several datasets indicate the presence of extreme observations compared with a normal distribution. Such statistical patterns are typical for environmental contaminant datasets, where concentrations often exhibit strong variability due to episodic inputs or localised emission sources. In the present study, the observed skewness and kurtosis values confirm that PFAS concentrations are dominated by background levels with occasional elevated measurements, which appear as outliers in the graphical analysis. These statistical characteristics further support the use of non-parametric methods such as the Kruskal–Wallis test for analysing differences between groups. In contrast, statistically significant differences were observed between the two analyzed compoundsWhen PFOS and PFOA concentrations were compared across all monitoring data, the Kruskal–Wallis test indicated a significant difference between the compounds ($p < 0.001$), confirming that PFOA concentrations were generally higher than PFOS concentrations in both river basins. The distribution of PFOS and PFOA concentrations across individual monitoring stations is illustrated in Figure 2, where each point represents a single monitoring observation.

Figure 2

Distribution of PFOS and PFOA concentrations across monitoring stations in the Daugava and Lielupe river basins. The dashed line indicates the PFOS AA-EQS value (0.65 ng L⁻¹)



The graphical representation shows that the majority of measurements cluster within a relatively narrow concentration range corresponding to background levels, while several monitoring stations exhibit elevated values that may indicate localised contamination sources. Additionally, the dashed line in the PFOS panel indicates the Annual Average Environmental Quality Standard for PFOS in surface waters (AA–EQS = 0.65 ng L^{-1}). The results show that the majority of PFOS measurements were well below this regulatory threshold.

Although statistically significant spatial differences among monitoring stations were detected within both river basins (Kruskal–Wallis test, $p < 0.001$), the post-hoc Dunn test with Bonferroni correction showed that only a limited number of station pairs differed significantly. Some monitoring stations exhibited more distinct concentration patterns compared with other sites, particularly D20 in the Daugava River Basin and L4 in the Lielupe River Basin. Nevertheless, the limited number of statistically significant pairwise differences suggests that PFOS and PFOA occurrence was influenced mainly by localised conditions or episodic inputs rather than consistent basin-wide spatial gradients.

The spatial variability observed between monitoring stations may reflect differences in land use, population density, and wastewater management within the river catchments. In the Daugava River Basin, several monitoring stations with elevated concentration variability are located in areas influenced by urban development, particularly in the vicinity of the Riga metropolitan region. Urban areas are frequently associated with PFAS emissions originating from wastewater treatment plants, stormwater runoff, and industrial activities.

In contrast, the Lielupe River Basin is characterised by extensive agricultural land use. Although agricultural areas are not typically considered primary sources of PFAS contamination, diffuse pollution processes may

contribute to the transport of these substances through surface runoff and soil–water interactions. In addition, the application of sewage sludge or biosolids to agricultural soils has been identified as a potential pathway for PFAS introduction into rural environments.

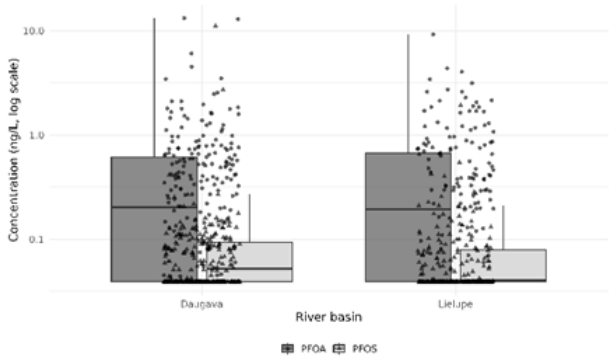
These contrasting catchment characteristics may partly explain the localised concentration differences observed between monitoring stations, indicating that both urban and agricultural processes may contribute to PFAS transport within river systems. A notable feature of the dataset is the presence of several elevated concentration values compared with the overall concentration range. These higher values appear as outliers in the graphical analysis and may reflect episodic PFAS inputs or localised contamination sources, such as wastewater discharges, stormwater runoff, industrial releases, or other temporary emission events.

Rivers are known to act as effective transport pathways for PFAS, redistributing contaminants from terrestrial environments to aquatic systems (Brusseau, 2023). The comparative distribution of PFOS and PFOA concentrations between the two river basins is further illustrated in Figure 3, which presents boxplot diagrams showing median values, interquartile ranges, and outliers. The results demonstrate that most PFOS concentrations were substantially lower than PFOA concentrations in both river basins.

The observed spatial variability and episodic elevated concentrations demonstrate the complexity of PFAS occurrence in surface waters and underline the need for continued monitoring at both river basin and local scales.

Figure 3

Comparison of PFOS and PFOA concentration distributions between the Daugava and Lielupe river basins



A large proportion of PFOS concentrations were observed close to approximately 0.039–0.04 ng L^{-1}. This clustering likely reflects the analytical quantification limit (LOQ) of the applied laboratory method rather than a uniform environmental background concentration. Similar patterns have been reported in other PFAS monitoring datasets where concentrations frequently approach analytical detection limits due to the trace-level occurrence of PFAS in surface waters.

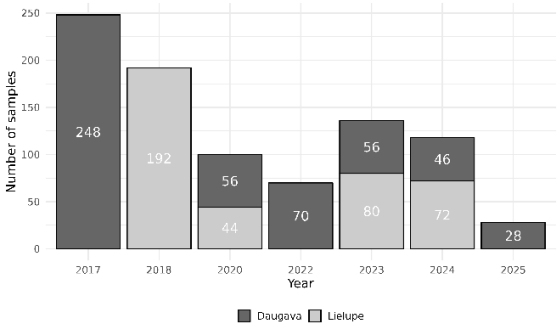
Temporal variability of PFAS occurrence

Temporal patterns of PFAS monitoring were evaluated by analyzing annual distributions of PFOS and PFOA concentrations across the study period. The number of collected samples varied substantially between years and river basins, reflecting the episodic nature of monitoring (Figure 4).

The sampling frequency was highest in 2017 in the Daugava River Basin and 2018 in the Lielupe River Basin, particularly, while fewer observations were recorded in several later years. Differences in monitoring intensity between years should therefore be considered when interpreting temporal patterns.

Figure 4

Number of PFOS and PFOA samples collected per year in the Daugava and Lielupe river basins during the monitoring period



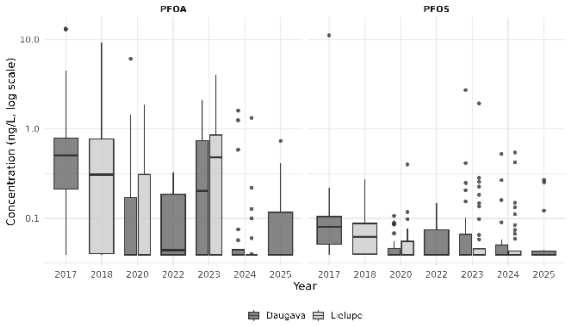
Annual concentration patterns of PFOS and PFOA are illustrated in Figure 5, which presents boxplots of concentration distributions for each year and river basin. Statistical analysis indicated significant temporal variability in PFAS concentrations during the monitoring period ($p < 0.05$). When analyzed separately, both PFOS and PFOA showed significant differences between years ($p < 0.05$), indicating that PFAS occurrence in the studied river basins varies over time. Such temporal variability may be influenced by changes in hydrological conditions, seasonal runoff dynamics, and variability in local emission sources.

Hydrological processes can play a significant role in the temporal dynamics of PFAS concentrations in surface waters. Variations in precipitation, river discharge, and seasonal runoff may influence the mobilization and transport of contaminants within river catchments. During periods of increased runoff, contaminants accumulated in soils or sediments may be transported into river systems, resulting in temporarily elevated concentrations.

In addition to hydrological variability, differences in monitoring intensity between years may also influence the observed temporal patterns. As shown in Figure 4, the number of collected samples varied considerably throughout the monitoring period, with higher sampling frequency during certain years. Such variations in monitoring coverage may affect the interpretation of long-term trends and highlight the importance of consistent and systematic monitoring

programmes for evaluating PFAS dynamics in aquatic environments.

Figure 5
Annual variability of PFOS and PFOA concentrations during the monitoring period



Overall, the spatial and temporal patterns observed in this study are consistent with previously reported patterns of PFAS distribution in European river systems, where contamination is typically characterized by relatively low background concentrations combined with occasional elevated values linked to local emission sources (Li et al., 2023; Byrne et al., 2024; Soerensen et al., 2024).

These findings suggest that PFOS and PFOA occurrence in the studied Latvian river basins is largely influenced by diffuse pollution sources and regional contamination patterns rather than by a single dominant point source.

The results of this study contribute to the growing body of research on PFOS and PFOA occurrence in European river systems and provide new insights into distribution of both compounds in Latvian surface waters. Although PFOS and PFOA contamination is often associated with highly industrialized regions, the present findings demonstrate that both urban–rural and agricultural catchments may act as pathways for transport of both compounds in the environment.

In urbanized catchments, PFOS and PFOA contamination is frequently linked to wastewater treatment plant effluents, stormwater drainage systems, and industrial discharges. Rivers located downstream of large cities may therefore receive continuous inputs of PFAS compounds originating from various anthropogenic activities. The Daugava River Basin, which includes the largest urban area in Latvia, represents an example of such mixed urban–rural catchment conditions.

At the same time, agricultural catchments may also contribute to PFAS compound transport through diffuse pollution processes. Agricultural landscapes may receive those chemicals through atmospheric deposition, irrigation water, or the application of sludge-based fertilizers. Once present in soils, these compounds may be mobilized through surface runoff and transported into nearby rivers and streams.

Similar patterns have been reported in other Nordic and Baltic studies, where contamination of PFAS compounds is typically characterized by relatively low background concentrations combined with occasional elevated values associated with local emission sources (Kärrman et al., 2019; Soerensen et al., 2024). Comparable PFAS pollutants occurrence patterns have been documented in regional monitoring studies across Nordic and Baltic surface waters, highlighting the widespread distribution of these compounds in northern European aquatic environments (Filipovic et al., 2013; Junttila et al., 2019).

The findings of the present study are therefore consistent with broader regional observations and highlight the importance of continued PFAS compound monitoring in river basins across the Baltic region.

Conclusions

1. The study evaluated the occurrence of two indicator PFAS compounds, PFOS and PFOA, in surface waters of two major Latvian river basins with contrasting land-use characteristics. The results confirm that PFOA and PFOS are detectable in both the Daugava and Lielupe river basins, indicating the presence of these persistent contaminants in surface waters across the studied catchments.
2. Comparative statistical analysis revealed no statistically significant differences in PFOA and PFOS concentrations in the two river basins ($p > 0.05$), suggesting that overall PFOA and PFOS contamination levels are broadly comparable in the Daugava and Lielupe river systems.
3. In contrast, statistically significant differences were observed between the two analyzed compounds ($p < 0.001$). PFOA concentrations were generally higher than PFOS concentrations in both river basins, reflecting differences in environmental mobility and behavior of these compounds.
4. Significant spatial differences between monitoring stations were detected within both river basins ($p < 0.001$). However, post-hoc analysis indicated that only a limited number of station pairs differed significantly, suggesting that PFOS and PFOA occurrence was influenced mainly by localised conditions or episodic inputs rather than consistent basin-wide spatial gradients.
5. Temporal analysis demonstrated significant differences between monitoring years ($p < 0.001$), indicating that PFOS and PFOA concentrations in surface waters vary over time and may be influenced by hydrological conditions, episodic pollution events, or changes in emission patterns.
6. These results suggest that continued monitoring may help improve understanding of PFAS occurrence and temporal variability in Latvian surface waters. Improved long-term monitoring and integrated assessment approaches may further contribute to understanding the distribution and behaviour of PFAS compounds in river catchments of the Baltic region.

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WATER RESOURCES GOVERNANCE CAPACITIES ENHANCEMENT IMPERATIVE: BOTTOM-UP PARTICIPATION, CROSS-SECTORIALITY AND DELEGATION FOR CO-MANAGEMENT

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Abstract
Water resource governance in Latvia, particularly for surface waters as rivers and lakes, are facing local stakeholder participation and voluntary initiatives growth in some municipalities, but, in general, remains institutionally fragmented with limited governance capacities and insufficient cross-sectoral coordination, especially, within local river basins, being subject of this study - approaching water resource governance as necessarily and complementary multi-sectoral, multi-stakeholder and multi-instrumental (triple governance dimensions frame) governance processes within two characteristic surface-water case territories to identify preconditions for strengthening capacities and qualities of water resources management. The research applied a case study research methodology complementary including document analysis, field observations, local-regional stakeholder mapping, and in-depth semi-structured interviews with all governance stakeholder groups. Findings indicate that water resource governance in the country remains statutory not yet complete, vertically and horizontally fragmented; stakeholder involvement is not overall spread and often realised as formal consultation processes. Cross-sectoral integration between water resource management and related agriculture, fisheries, recreation and tourism, etc. local development sectors, remains not sufficiently developed. Meantime, local river basin case studies demonstrate that societal NGO-based bottom-up governance initiatives can to some extent compensate or even substitute limited national and local governmental capacities and instrumentation - NGOs can function as important co-management institutions for natural resources, providing communication and facilitating various stakeholders' engagement, multi-instrumental consultation and communication programs and processes, carrying out practical resources management activities. Administrative recognition and support for local inhabitants-based NGOs and community-based co-management practices are to be elaborated and integrated into water resources governance system.
Keywords: water governance, cross-sectoral, stakeholders, participation, bottom-up governance approaches.

Introduction

Since its adoption in 2000, the European Union's Water Framework Directive (WFD) (2000/60/EC) has fundamentally transformed water resource management across Europe by promoting an ecosystem-based and sustainability-oriented approach to water governance. The directive introduced river basin districts as the primary planning and management units, replacing fragmented administrative approaches with integrated governance based on hydrological boundaries (Hering et al., 2010). A central principle of the WFD is the active involvement of stakeholders and the public in water management processes, recognising that effective governance requires coordination across multiple sectors, administrative levels, and societal actors. Despite these policy advances, stakeholder participation and governance effectiveness remain uneven across Europe, particularly in smaller river basins and peripheral regions with limited institutional capacity (Neto et al., 2017).

Contemporary water challenges are increasingly viewed not merely as issues of physical water scarcity or environmental degradation but as governance challenges arising from fragmented decision-making, institutional complexity, and insufficient coordination among responsible actors (OECD, 2011). As a result, growing attention has been given to governance approaches that emphasise shared responsibility between governmental institutions, civil society, private stakeholders, and resource users. These approaches seek to improve policy coherence, strengthen institutional adaptability, and increase societal engagement in decision-making processes (Julio et al., 2021).

Effective water governance is widely recognised as a multi-level and multi-actor process involving both formal institutional arrangements and informal practices. Within this context, Integrated River Basin Management (IRBM) has emerged as a key framework promoting the holistic management of water resources, land use, and ecosystems across hydrological boundaries rather than administrative jurisdictions (Jaspers, 2003). The effectiveness of IRBM depends on the ability of governance systems to facilitate cooperation across sectors and scales while addressing the complexity of socio-ecological systems (SES), where ecological processes and human activities are closely interconnected (OECD, 2015; Huffy, 2011).

To address these challenges, several governance models have been developed, including co-governance, network and adaptive governance. These approaches emphasise collaboration among public authorities, non-governmental organisations (NGOs), private actors, local communities, and scientific institutions, thereby fostering social learning, institutional resilience, and adaptive capacity (Kooiman & Jentoft, 2009; Turton et al., 2007). Participatory governance approaches are particularly important in complex SES contexts, where multiple interests, knowledge systems, and management objectives intersect. By involving stakeholders directly in decision-making processes, governance systems can improve legitimacy, strengthen local ownership, and

enhance the long-term effectiveness of environmental management measures (Julio et al., 2021).

The Organisation for Economic Co-operation and Development (OECD) has further advanced the understanding of water governance through its Principles on Water Governance, which identify effectiveness, efficiency, and trust and engagement as the three core dimensions of successful governance systems (Akhmouch & Clavreul, 2016). These principles emphasise the importance of clearly defined institutional roles, policy coherence across sectors, stakeholder involvement, transparency, and adaptive management mechanisms. Although widely recognised in policy and academic discourse, their implementation remains uneven, particularly at local and regional levels with limited governance capacity, resources, and coordination (Jiménez et al., 2024).

To better address the complexity of water governance, this study draws upon the Triple governance dimensions framework (Ernsteins et al., 2017, 2025). The framework conceptualises governance through three complementary dimensions: governance content, governance instruments, and governance stakeholders. Governance content (esp. cross-sectorial applicability and water-nature-food nexus) is examined through a socio-ecological systems (SES) perspective, reflecting the interconnected nature of environmental, social, and economic processes. Governance instruments comprise policy, planning, institutional, economic, technological, and communication mechanisms that support governance implementation and development. Governance stakeholders represent various actors involved in governance processes, together with their interests, responsibilities, participation, and interactions. Combined, these dimensions provide a framework for analysing water governance challenges and opportunities across multiple sectors and administrative levels.

The two case study areas selected for this research were chosen not only for their relevance to water resource governance but also for their strong focus on nature conservation, particularly within Natura 2000 territories. This highlights the importance of the water–nature nexus and its broader potential to extend towards water–nature–food interactions through activities such as agriculture and fisheries. Furthermore, both territories demonstrate established examples of society-driven governance practices, including active NGO involvement and well-developed communication mechanisms. These areas have previously been subject to research and are currently being further examined within the Horizon-Widera project BETTER LIFE, which aims to advance transformative and socially engaged research approaches.

Emerging evidence from various river basin initiatives demonstrates the potential of place-based and participatory governance approaches. The Catchment-Based Approach (CaBA) in the United Kingdom illustrates how local stakeholder networks can contribute to improved environmental outcomes, stronger community engagement, and enhanced governance legitimacy (Neto et al., 2017). Similarly, experiences from the Ebro River Basin in Spain and the Tucson Basin in the United States indicate that structured stakeholder participation can strengthen institutional adaptability and governance capacity, although outcomes remain highly dependent on local political, social, and institutional contexts (Ballester & Mott Lacroix, 2016; Megdal et al., 2017).

Despite growing international experience, significant knowledge gaps remain regarding the practical implementation of participatory and delegated governance approaches in smaller river basins and protected nature areas operating within highly centralised governance systems. While substantial research has focused on national and regional water governance, less attention has been paid to how local actors can complement formal governance arrangements in areas with limited institutional capacity and complex water–nature interactions.

This challenge is particularly relevant in Latvia. Water governance under the WFD is largely centralised, with river basin management coordinated at national level. Although national legislation provides opportunities for delegating specific public administration functions to public and private entities when such arrangements improve governance effectiveness (The Parliament of the Republic of Latvia, 2002; The Parliament of the Republic of Latvia, 2022; Guidelines, 2020), practical implementation remains limited. Nevertheless, several examples indicate the potential of more participatory governance models. Governance assessments conducted in Cesis Municipality have highlighted the advantages of delegated management arrangements in improving administrative efficiency and clarifying institutional responsibilities. Similarly, local NGO involvement in the Dviete River basin demonstrates how bottom-up initiatives can contribute to the management of Natura 2000 territories and flood-prone landscapes where state institutional presence is limited. However, such initiatives remain largely project-based and have not yet become systematically integrated into broader water governance frameworks.

The need for more effective governance arrangements is particularly evident in protected river basins and wetland territories where environmental management requires cooperation among multiple sectors and stakeholder groups. In such areas, water management objectives are closely linked to biodiversity conservation, agricultural activities, fisheries, tourism, and local community development, creating complex governance environments that cannot be effectively addressed through sectoral approaches alone. Strengthening participatory, cross-sectoral, and adaptive governance may improve both water resource management and nature conservation outcomes.

Against this background, this study examines the potential of participatory, cross-sectoral, and delegated governance approaches to strengthen water and nature

resource management in Latvia. Using the Dviete River Basin and Lake Lubans Basin as case studies, the research analyses governance structures, stakeholder interactions, and opportunities for bottom-up co-management within Natura 2000 territories. Particular attention is given to the role of local actors, institutional cooperation, and governance capacities that may contribute to more integrated, adaptive, and socially inclusive water governance practices.

Materials and Methods

The study explored all three complementary governance system dimensions simultaneously through a collaborative governance process perspective, examining governance sectors, governance instruments, and governance stakeholders within the selected case territories. This approach responds to the combined demands of both formal nature conservation and water resource governance frameworks.

Subsequently, this study examines multi-sectoral, multi-stakeholder, and multi-instrumental governance processes in two water resource management case areas in Latvia: the Dviete River Basin and the Lake Lubans region as small, subordinated basins in one out of fore River Water Basin Districts. Particular attention is given to participatory and bottom-up governance approaches supporting Natura 2000 management and the implementation of the EU WFD in territories as two cases selected where national and regional governance capacities are limited.

The primary objective was to identify the key preconditions needed to strengthen sustainable water resources governance locally, with a particular focus on advancing participatory and co-management practices, as well as developing effective governance instruments at the local level.

The study is focusing on two small sub-basins as for river catchment and lake region - both case study areas were selected for their progress in water resource governance and their strong focus on nature conservation, particularly within Natura 2000 sites. This highlights the significance of the water-nature nexus and its broader potential. In both regions, this relationship often extends to include water-nature-food linkages, especially through activities such as agriculture and fisheries.

Furthermore, both areas demonstrate established, society-driven local management practices, including active involvement of NGOs and well-developed communication mechanisms. These territories have already been subject to research in EU Horizon and LIFE Nature projects, respectively, and are now being further examined by our partner universities.

Daugava River Basin District

As required by the EU WFD, each river basin district has its own management plan (RBDMP) for a six-year planning cycle. In Latvia, four river basin districts have been established: Daugava, Gauja, Lielupe, and Venta. The first RBDMP in the European Union was elaborated for the Daugava River Basin District during 2000–2003. In this study, the Daugava River Basin District was characterised as the upper governance and management level for the two selected river sub-basins.

The Daugava River Basin is one of Latvia's most significant hydrological and ecological regions, spanning diverse biogeographical zones, including lowland river valleys, boreo-nemoral forests, and floodplain meadows. It supports numerous protected habitats and species and is characterised by a high level of biodiversity. The total length of the Daugava River is 1,005 km, of which 352 km are located within Latvia. The Latvian part of the basin covers 27,057 km², representing 42% of the national territory.

Land cover within the basin consists of approximately 52% forests, 20% agricultural land, 14% wetlands, 3% lakes, and 0.4% urbanised areas. The basin includes both rural and urban territories and supports economic activities such as hydropower generation, agriculture, forestry, and nature tourism. In 2019, the Daugava River Basin District had a population of approximately 1.14 million inhabitants, representing about 59% of Latvia's total population.

Administratively, the basin fully or partially includes 29 administrative units in Latvia, consisting of 23 rural municipalities and 6 state cities, including capital city Riga. The transboundary nature of the river, which flows through EU Eastern border neighbour countries before reaching Latvia, adds an international governance dimension requiring cross-border coordination.

Dviete River Basin

The Dviete River Basin case study was conducted within the EU Horizon project OPTAIN (2021–2026), which focuses on identifying effective strategies for retaining and reusing water and nutrients in small agricultural catchments under different soil and climate conditions across Europe.

In Latvia, the project is implemented within the Dviete River Basin, covering approximately 250 km², including the Dviete floodplain. The Dviete floodplain was designated as a Natura 2000 protected area in 2004 and covers approximately 4,989 hectares. The protected territory was established to preserve natural floodplain meadows, which represent ecologically diverse habitats and important bird gathering and nesting sites.

The area is located within the Upper Daugava and Jekabpils municipalities in southeastern Latvia and is recognised as one of the larger nature parks in the country.

Lake Lubans region

The Lake Lubans Basin case study was examined within the EU LIFE GOODWATER IP project, which focuses on implementing Latvia's River Basin Management Plans to achieve good surface water status.

The study area is located within the Lake Lubans region and forms a central part of the Lubans Wetland, a Natura 2000 site and a protected area of international

importance recognised under the Ramsar Convention. Covering more than 47,900 hectares, it is the largest protected nature territory in Latvia. The wetland complex was established in 2009 through the consolidation of eleven previously separate protected areas into a single management territory.

Lake Lubans itself covers approximately 80 km² and is the largest lake in Latvia as well as the largest dammed lake in Europe. The surrounding wetland has developed from the historical floodplain of the lake and is located primarily within Rezekne and Madona municipalities in central-eastern Latvia.

The research was carried out as a multi-stage, combining several project-based studies during the period from 2022 to 2025 and in both cases, the importance of community participation in water basin management and nature protection governance was emphasised. In the Lubans lake/wetland area, management functions of the municipality-built wetland tourism information centre were for long period delegated to a local NGO, which has for over a decade successfully provided nature/environmental communication via all related instruments of information, education, public engagement, and promotion of pro-environmental behaviour.

Meanwhile, in the Dviete River Valley, a voluntary civil association of the managers of local parishes and nature-culture protection enthusiasts has been active since 2003, taking on state-like functions in managing the Natura 2000 territory on a voluntary and enthusiasm-driven basis. Additionally, the wider Daugava River Basin was analysed as a case of structured public participation supported by the EU WFD, demonstrating multi-level governance in river basin management.

A research and development (R&D) approach was employed within the case studies framework, partly incorporating elements of socially engaged research (SES). This methodology combined document analysis across local cases and different governance levels with stakeholder mapping and in-depth interviews. It also included site-based fieldwork, involving visits, observations, and visual documentation such as photographs and videos.

The initial tasks in both case studies are to conduct stakeholder mapping. This mapping process was based on a five-main-stakeholder-group model approach (stakeholder governance dimension), categorised into five distinct but complementary governance stakeholders' segments: state, municipalities, businesses, mediators (including media, educators, NGOs, and academia), and society.

In both case studies, interviews were conducted representing also the majority of relevant policy sectors. These included representatives of national-level government institutions, covering water, nature, environment, and agriculture in both cases and additionally fisheries, forestry, tourism, and culture sectors in the Lake Lubans case, thus reflecting a broad range of SES sectors as well as their regional branches.

The Lake Lubans case included around 60 supplementary short interviews, primarily with members of statutory established inhabitants Consultative Councils as of any local administrative community. In-depth interviews were conducted with representatives from the five main complementary stakeholder groups recognised across all three levels of governance and administration, including those from key policy sectors currently involved or expected to be involved, as well as experts. In total, nearly 40 in-depth semi-structured interviews were conducted in the Lake Lubans region case, along with express interviews mentioned. Similarly, almost 30 in-depth semi-structured interviews were conducted in the Dviete River Basin case, including 5 interviews conducted with regional and national stakeholders relevant also to the broader Daugava River Basin management case.

Results and Discussion

As part of this study, we will specifically examine the Daugava River Basin, one of the four WFD-designated basins in Latvia, which includes both the Lubans sub-basin and the Dviete sub-basin. The Dviete and Lubans water basin regions were selected as case studies due to their comprehensive governance assessment processes. However, within the scope of this paper, the focus is placed specifically on challenges related to cross-sectoral policy development and on innovative societal practices in local governance.

1. Daugava river basin district: status, planning and participatory management

The governing bodies of river basin districts in Latvia and their functions are defined by the Water Management Law. The Latvian Environment, Geology and Meteorology Centre (LEGMC), under the Ministry of Climate and Energy (restructured in 2023), prepares and updates river basin management plans and programmes of measures. The State Environmental Service monitors implementation and, based on LEGMC water quality analyses, reviews conditions of water use permits in line with regulations.

LEGMC maintains the River Basin Management Information System (RBIS), which provides publicly accessible data on surface and groundwater bodies, including their location, quality status, pressures, and planned measures. The system enables users to visualise water quality over time and access detailed environmental datasets. The LEGMC website also offers free downloads of data on meteorology, hydrology, air quality, groundwater, and surface water, supported by public funding.

The governing structure involves several ministries, primarily the Ministry of Climate and Energy, alongside the Ministry of Health (drinking and bathing water) and the Ministry of Agriculture (melioration, fishing), with indirect involvement from ministries responsible for economy, business, and transport.

This multi-ministerial involvement reflects the socio-ecological nature of water management but also leads

to a fragmented governance system. Although IRBM is formally centralised, in practice it is weakly coordinated and limits stakeholder participation. Financial resources remain insufficient for planning, monitoring, implementation, and infrastructure, with many activities, such as river restoration, monitoring improvements, and nature protection, relying on project-based funding rather than stable budgets.

Under the EU Water Framework Directive, four River Basin District Advisory Councils (RBDACs) have been established to support planning. These councils aim to coordinate interests among public authorities, municipalities, NGOs, businesses, and other stakeholders in achieving environmental objectives, operating under Cabinet Regulation No. 681 (2003).

Each council consists of up to 18 members, including representatives from key ministries, planning regions, and NGOs representing environmental protection, water users, and landowners. NGO representatives are nominated every six years through LEGMC-organised processes.

In the Daugava basin, the inter-municipal NGO 'Daugava Union' represents local governments along the river and contributes expertise on water management, protection, and sustainable development. It actively participates in council meetings, promotes inter-institutional cooperation, and represents municipal interests. Other NGOs include the Small Hydropower Association, Environmental Protection Club, Farmers' Parliament, and the Baltic Environmental Forum.

Since 1995, the 'Daugava Union' has addressed a wide range of regional issues, including environmental protection, cultural heritage preservation, pollution reduction, fish resource restoration, and regional identity strengthening, alongside social and economic development goals.

Although council protocols are publicly available, meetings occur only 1–2 times per year and are often formal. Due to bureaucratic and funding constraints, discussions on water quality and measures are limited. As a result, councils have weak influence, creating a gap between their objectives and local needs, and many stakeholders feel underrepresented.

Latvia's third River Basin Management Plan shows some ecological improvement, with waters in good or high status increasing from 21% to 32.5%. However, major challenges remain: no surface waters achieve good chemical status due to pollutants such as mercury and PAHs, and risks persist for groundwater. Monitoring coverage is limited, data inconsistencies remain, and implementation of pollution-reduction measures is insufficient.

The European Commission's 7th implementation report confirms these challenges, highlighting EU-wide gaps in achieving water quality goals. Latvia, like many Member States, is unlikely to meet 2027 targets without stronger action.

Key EU recommendations for Latvia include improving monitoring, addressing pressures, enhancing implementation, increasing transparency, and strengthening coordination. Weak administrative capacity and the absence of clearly assigned management responsibilities remain major issues, along with limited collaboration with municipalities.

Similar capacity constraints exist in communication and participation. Despite EU recommendations to improve transparency, stakeholder engagement, and implementation of WFD Article 14, current approaches remain fragmented and non-systemic, reducing the effectiveness of governance instruments.

2. Towards cross-sectorial policies in sub-basins: participation

Comparing two comparatively diverse water basins, which are also contextually quite close, there are to be recognised a quite a number of similarities and perspectives for water and nature further governance, local bottom-up or co-management deeds, already complementing or even substituting (Dviete case) capacities lacking governmental institutions.

Dviete River basin catchment area and Natura 2000 site

In the Dviete River basin, traditional measures aimed at accelerating water and nutrient runoff in rural areas, such as drainage and land melioration, are increasingly being reconsidered. At the EU level, there is growing support, including financial instruments, for small-scale and nature-based solutions that help reduce or delay runoff. Experiences from such initiatives, including the H2020 OPTAIN project, highlight the importance of collecting, evaluating, and sharing practical knowledge.

The findings reveal important insights regarding policy effectiveness and coherence. Many respondents deemed existing sectoral policies misaligned and poorly suited to current challenges. Particularly low compatibility was noted in relation to water scarcity, water quantity management in agricultural fields, and nutrient recovery from water bodies. Broader issues of fragmented and incoherent legislation were also emphasised. Stakeholders across governance levels, especially at the national level, highlighted persistent disconnects between sectors such as agriculture, nature protection, and water management, often reflecting differing objectives and weak coordination.

Perceptions among sectors varied: representatives of the nature sector generally argued that biodiversity concerns are not adequately integrated into broader policies, while actors from other sectors sometimes perceived the opposite. Additionally, inconsistencies in data and monitoring systems across sectors further complicate integrated decision-making, making it difficult for stakeholders to align their efforts and achieve common goals.

Implementation challenges were widely identified, including administrative and cross-sectoral barriers, difficulties in translating policy into practice, and limited institutional capacity. Communication issues, such as low awareness, weak information exchange, and unclear terminology, were also major obstacles to

effective governance.

To address these challenges, stakeholders proposed several improvements. These include strengthening coordination and policy coherence across sectors (nature, environment, agriculture, and economic activities such as tourism), spatially aligning sectoral priorities, clarifying stakeholder roles and responsibilities, and enhancing mutual understanding between governance domains. Greater emphasis was also placed on improving information sharing, stakeholder engagement, and education, both formal and informal, as well as expanding the use of digital communication tools.

Lake Lubana region area and Natura 2000 site

In contrast, governance in the Lake Lubans basin is heavily dominated by a formal nature protection framework. This is primarily overseen by the regional agency of the national Nature Conservation agency, alongside hydrotechnical regulations managed by the Ministry of Agriculture - both of which face challenges stemming from contradictory priorities. This dual structure creates tensions and limits development in sectors such as fisheries, agriculture, forestry, tourism, and cultural activities, particularly due to the absence since 2009 of a long-term integrated nature protection plan (approved only in 2025) for the Lubana Wetland Natura 2000 area.

Governance in the Lubans region has exhibited fragmentation and insufficient inclusivity from a socio-ecological systems (SES) perspective. Stakeholders from socio-economic sectors have historically been under-represented, with limited involvement beyond the tourism sector. Local residents and entrepreneurs also lacked adequate information and opportunities for participation, which has further exacerbated the fragmentation of governance and limited the effectiveness of collaborative efforts in the region.

Overall, the management of the Lake Lubans area remains weakly coordinated. Institutions tend to operate within their respective sectors with limited collaboration, hindering a shared vision for sustainable regional development. Yet, such a vision is crucial for addressing the diverse challenges faced by the Lake Lubans area and ensuring effective resource management. Stakeholders widely recognise the need for improved communication and cooperation, emphasising the importance of initiating a joint, multi-stakeholder governance planning process. Such an approach should aim to establish a more collaborative governance system that addresses the entire lake region as an integrated territory, rather than focusing solely on the wetland.

3. Towards societal practices in sub-basins: communication and management

This subsection examines community-driven bottom-up initiatives that partly compensate for insufficient governmental and municipal institutional capacity in nature and water resource governance and communication. It focuses in detail on two such initiative centres: the Dviete River Valley management and communication centre and the Lake Lubans communication and management centre, which operate as multifunctional, participation-based instruments for strengthening nature conservation and water governance.

Dviete River Valley management and communication centre

The NGO ʻAssociation of Dviete Valley Municipalities was established in 2004 as a coalition of local municipal staff and committed local enthusiasts, with a specific focus on the protection of natural and cultural heritage in the Dviete River Valley. Over time, the NGO has evolved into the key locally rooted actor in coordinating nature governance, community engagement and knowledge transfer in this rural sub-basin.

The Dviete floodplain Nature Park, designated in 2009, is located in the Dviete river basin in the Selonia region on the left bank of the Daugava River and has been recognised as an important habitat for plant and bird species. The main settlements in the Dviete basin are small rural villages and small towns, including Bebrene (331 inhabitants), Dviete (220 inhabitants) and Kaldabruņa (52 inhabitants), which form the social and institutional context for the NGO's activities. The nature park covers about 4 989 ha, which corresponds to approximately 19% of the Dviete River basin, and is designated as a Natura 2000 site.

In practice, the NGO is the only organisation that undertakes the day-to-day management of the Natura 2000 area, acting on a voluntary and project-based basis without regular financial or technical support from the Nature Conservation Agency or municipality. The association effectively manages almost the entire territory of the nature park, carrying out a wide range of practical conservation tasks. These include maintaining semi-natural grasslands to prevent succession and overgrowth; repairing and maintaining fences; organising and supervising nature-based grazing with semi-wild herbivores; and ensuring the provision of winter fodder. In addition, the NGO actively applies for and implements externally funded projects to secure resources for park management and infrastructure maintenance.

In 2008, the association established the ʻGulbji' Information Centre in a culturally and historically significant building within the Dviete River valley. The centre was created with the explicit aim of providing visitors, local residents, school groups and other interested stakeholders with information about the natural assets and cultural-historical values of the Dviete River Valley. It also serves as a knowledge hub for the management of biologically valuable grasslands and the practical organization of nature-based grazing, offering on-site explanations, demonstrations, and advisory support. All in all, the Dviete NGO could already be recognised as a site-based communication and semi-formal administrative-institutional instrument for local nature protection and water governance.

Lubana Lake tourism, communication and management centre

Over time, the centre, being built and established by the Madona municipality during the execution of the EU LIFE project in 2004, has been very successfully run and developed by the youth nature friends local NGO (2009-2022 under the leasing contract) and steadily evolved from a basic tourism and nature information point at the shore of Lubana Lake into a multifunctional and multi-instrumental Wetland Information Centre (WIC).

Today, the WIC performs several interconnected roles – serving not only as a regional hub for environmental communication and tourism information but also delivering education and training activities that promote environmentally responsible behaviour among a wide range of target groups. The centre has increasingly engaged in local and regional planning processes, particularly in the field of nature protection, by collaborating with governmental and non-governmental organisations to influence policy decisions and promote sustainable practices. As a result, it has gradually developed a comprehensive set of communication functions, including information dissemination, education, stakeholder participation, and the promotion of pro-environmental practices.

In addition, WIC fulfils important semi-administrative and institutional functions. It acts as an intermediary between the Nature Protection Agency and all other interest groups – various groups of local residents; diverse groups of visitors; businesses; tourism operators; and governmental agencies and municipalities – while also collaborating with NGOs, educators, and the media. The centre plays a key role in guiding visitors' behaviour by providing information on regulations, permitted activities, and restrictions within protected areas of NATURA 2000, covering a great part of the River/Lake Basin.

Through coordinated action among key governmental-municipal stakeholders, the WIC has the potential to evolve into a site-based communication and semi-formal administrative-institutional instrument for local nature protection and water governance. Due to limited capacity in governmental and municipal nature and water management institutions, including the Regional Nature Protection Agency responsible for Lubans Lake and the Natura 2000 territory, there is a shortage of local administrative, advisory, and communication staff; currently, only regional inspectors are available.

Table 1 provides a comparative overview of governance instruments and institutional roles in the Dviete and Lake Lubans Natura 2000 sub-basins, highlighting both similarities and key differences in local governance approaches. The Association of Dviete Valley Municipalities demonstrates a strong bottom-up, practice-oriented role, effectively compensating for limited governmental capacity by undertaking day-to-day management and conservation activities. In contrast, the Lubans Wetland Information Centre operates primarily as a communication and intermediary platform, bridging gaps between institutions and stakeholders while supporting education, participation, and policy processes. Across both cases, communication, collaboration, and project-based funding emerge as essential instruments, reflecting the importance of integrated and multi-level governance in addressing the challenges of water and nature management (Table 1).

Table 1

Comparison of Governance Instruments and Institutional Roles in the Dviete River and Lake Lubans Natura 2000 Sub-basins

No.	Governance instruments	Association of Dviete Valley Municipalities	Lubans Wetland Information Centre
1	Regulatory instruments	Implements Natura 2000 requirements in the Dviete floodplain (e.g. grassland management, grazing), partly compensating for limited state capacity	Explains Natura 2000 regulations, rules, and permitted activities to visitors and local residents
2	Planning instruments	Contributes to local-level nature management planning; implements project-based territorial development and conservation activities	Participates in regional planning processes, especially in nature protection; collaborates with institutions to influence policy
3	Economic and financial instruments	Actively attracts external funding (e.g. EU projects) to ensure maintenance of the nature park and infrastructure	Operates through project funding (e.g. LIFE), develops ecotourism, provides services (guided tours, accommodation)
4	Administrative and institutional instruments	Functions as a de facto site manager on a voluntary basis, carrying out day-to-day management of the Natura 2000 area without stable governmental support	Acts as an intermediary between the Nature Protection Agency and stakeholders; performs semi-administrative and advisory functions
5	Infrastructure instruments	Maintains grazing infrastructure, fences, nature trails; ensures winter fodder; manages the 'Gulbji' Information Centre	Develops and maintains the centre, exhibitions, birdwatching sites, and tourism/recreation infrastructure

No.	Governance instruments	Association of Dviete Valley Municipalities	Lubans Wetland Information Centre
6	Communication instruments	Provides knowledge transfer (e.g. on biologically valuable grasslands and grazing), organises educational activities, engages local communities	Strongly developed communication role: guided tours, educational programmes, stakeholder engagement, promotion of environmentally responsible behaviour
7	Collaboration instrument	Cooperates with municipalities, local communities, and international projects (e.g. H2020 OPTAIN); promotes bottom-up governance	Collaborates with municipalities, NGOs, entrepreneurs, researchers, and organisations (e.g. Latvian Ornithological Society), building multi-actor networks

Conclusions

This study explored water resources and nature protection governance in two case territories in Latvia. The findings highlight the importance of cross-sectoral integration, stakeholder participation, and local governance instruments in supporting sustainable governance.

1. This study demonstrates that the main challenge of IRBM in Latvia is not the absence of formal governance structures but their limited effectiveness in practice. Although the Daugava River Basin operates within a well-established WFD governance framework and benefits from extensive environmental data systems, implementation remains constrained by fragmented institutional responsibilities, weak cross-sectoral coordination, limited administrative capacity, and insufficient financial resources. The findings highlight the need for stronger integration of governance sectors, stakeholders, and governance instruments to translate policy objectives into coordinated action and achieve sustainable water management outcomes.

2. The Dviete River Basin case demonstrates how local NGOs can successfully compensate for limited governmental capacity in Natura 2000 management. Our findings show that the Association of Dviete Valley Municipalities as local experienced NGO not only plays a key role in community engagement, and knowledge transfer, but also voluntarily administers and manages the Natura 2000 territory on a day-to-day basis without stable governmental financial support, relying largely on project-based funding and local initiative. This provides a strong example of effective bottom-up management in rural areas.

3. The Lubans Lake case reveals that governance remains fragmented due to weak coordination between sectors and limited stakeholder involvement. The study identifies the municipality-based, locally knowledgable NGO that operates the Wetland Information Centre as a key intermediary; by strengthening communication, participation, and cooperation, the NGO demonstrates potential for developing a more integrated governance model for the region.

4. The study shows that stakeholder participation within Latvian river basin governance remains largely procedural rather than genuinely participatory. Existing mechanisms, including River Basin District Advisory Councils, provide opportunities for consultation but have limited influence on decision-making and implementation processes. The findings highlight the need for more inclusive and continuous engagement of local actors to strengthen governance effectiveness and support integrated water management objectives.

5. The study identifies insufficient cross-sectoral understanding as one of the key barriers to sustainable water resource and nature resource governance. The findings reveal persistent disconnects between conservation-focused sectors (water management and nature conservation) and production or development sectors (agriculture, tourism, fisheries, and local development), particularly within Natura 2000 territories. This highlights the need to move beyond sector-specific governance towards integrated socio-ecological governance approaches**.**

6. The application of the Triple Governance Dimensions Systems Framework proved useful in demonstrating the importance of cross-sectorality, participation, and co-management for effective water and nature resources governance. The findings suggest that governance performance depends on the integration of governance sectors, stakeholders, and governance instruments rather than on formal institutional arrangements alone.

7. The Dviete River Basin and Lake Lubans area case studies demonstrate that bottom-up and participatory governance approaches can partially compensate still limited governmental and municipal capacities - there are growing cases of co-management practice. Local initiatives have contributed to stakeholder cooperation, environmental communication, and the implementation of management activities that would otherwise be difficult to achieve through formal governance structures alone.

8. The Dviete and Lubans examples demonstrate that local governance initiatives can perform multiple functions simultaneously within water and nature resource governance. They compensate for limited governmental capacities, strengthen NGO and community participation, facilitate cooperation between top-down and bottom-up actors, and support practical co-management of Natura 2000 territories. The findings further suggest that such initiatives contribute to building local governance capacity, experience, and confidence among civil society actors, thereby strengthening long-term governance resilience.

9. The study identifies two complementary local governance models that support sustainable water and nature resource management: a non-governmental management approach in Dviete and a tourism-communication management approach in Lubans. Both models demonstrate how governance functions can be delegated to or assumed by, local actors where governmental capacities are limited.

10. Overall, the study demonstrates that sustainable water resources governance is shaped by the interaction of governance sectors, stakeholders, and governance instruments. The findings highlight that cross-sectoral integration, stakeholder participation, and co-management arrangements are essential components of adaptive and resilient water governance, particularly in socio-ecologically complex territories such as Natura 2000 areas.

11. The findings suggest that strengthening participatory governance, improving cross-sectoral cooperation, and enhancing multi-level coordination between national, regional, municipal, and local actors are essential prerequisites for more resilient and adaptive water and nature resources governance in Latvia. Further recognition and integration of local NGOs, information-communication centres, other institutionalised community initiatives within formal governance systems could significantly improve the implementation practice of both water and nature resource management objectives.

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TOWARDS LOCAL WATER BASIN GOVERNANCE IN LATVIA: COMPLEMENTARY TRIPLE GOVERNANCE DIMENSIONS FRAMEWORK

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Abstract
A comparative case study research (CSR) approach was applied using the Triple Governance Dimensions framework, which examines governance processes through governance sectors, governance stakeholders and also instrument dimensions. Three contrasting environmental and water governance cases were analysed: a comparatively advanced municipality with a pro-environmental administrative profile; a local river basin located largely within a single municipality; and a local lake-region basin representing a multi-municipal lake-wetland system. The CSR complementary combined document analysis, field visits, local-regional stakeholder mapping and in-depth interviews. Statutory municipal environmental management frameworks, including those related to water governance, are formally established but exhibit functional gaps in both multi-level vertical coordination and horizontal cross-departmental governance, together with broader institutional weaknesses caused by weak coordination and limited stakeholder participation. A local-scale river basin management approach remains only weakly developed, even though planning and monitoring documents exist for Latvia's four main river basin districts at the national level. Municipalities do address the water quality and management of individual rivers and lakes, but these activities are usually shaped by limited financial and institutional capacity and are often carried out independently of a river basin approach, partly because of weak national support, limited communication, and insufficient cooperation with the municipal level. Key constraints include limited institutional and financial capacity, insufficient complementarity among governance instruments, weak environmental communication, and fragmented cross-sectoral coordination. Governance effectiveness depends primarily on the degree of integration among governance sectors, instruments, and stakeholders rather than on the mere formal existence of governance arrangements.
Keywords: environmental governance, water governance, governance instruments, stakeholder participation, socio-ecological systems.

Introduction

Environmental governance has become a key framework for addressing complex environmental issues in which ecological, social, institutional, and political factors intersect. Environmental governance refers to the systems, institutions, processes, stakeholders, and instruments that shape environmental decision-making (Lemos & Agrawal, 2006; de Loë et al., 2009). Emerging in response to the limitations of traditional command-and-control approaches, contemporary environmental governance recognises the environment as a complex socio-ecological system (SES) that requires integration, flexibility, collaboration, and the inclusion of diverse knowledge sources (Levin, 1998; Berkes et al., 2003; Folke et al., 2005). Adaptive governance is particularly important in this context, emphasising stakeholder interaction, responsiveness, and the capacity for effective, equitable, and transparent environmental governance (Olsson et al., 2007; Bennett et al., 2018; Nesbit, 2019).

Water governance has emerged as one of the most important fields of environmental governance, reflecting growing recognition that water crises are often governance failures rather than purely resource-related problems (OECD, 2011; Ernsteins et al., 2025). Water governance encompasses the political, social, economic, and administrative systems that shape water use and management, including both formal and informal institutional arrangements (OECD, 2011, 2015). Effective water governance therefore requires not only technical water management but also institutional capacity, stakeholder participation, multi-level cooperation, and cross-sectoral coordination, capable of balancing environmental protection with socio-economic development needs (Konkovs et al., 2022; Julio et al., 2021).

Within the European Union, the Water Framework Directive (WFD), adopted in 2000, established an integrated ecosystem-based approach to water management based on river basin districts as the principal management units (Hering et al., 2010). The Directive introduced a transition from fragmented and pollution-orientated approaches to more comprehensive and sustainability-oriented water governance. It also emphasised the stakeholder involvement in the preparation, implementation, and evaluation of management plans for river basins. However, the implementation of these principles continues to face challenges in many contexts, particularly regarding integrated water resources management, stakeholder participation, communication, and coordination across governance levels and sectors (Rimmert et al., 2020; Neto et al., 2018).

These challenges are particularly relevant in Latvia. Despite more than two decades of river basin governance under the WFD framework, smaller river basins and lake territories continue to experience governance difficulties associated with limited administrative capacity, insufficient planning instruments, fragmented institutional arrangements, and constrained national and local resources (Ernsteins et al., 2017b; Konkovs et al., 2022). Municipal environmental governance remains predominantly sector-based, resulting in only partial implementation of integrated water resources management approaches.

Consequently, improving water governance requires stronger stakeholder involvement, enhanced cross-sectoral cooperation, and governance structures grounded in SES thinking. Additional guidance is provided by the OECD Principles on Water Governance, which emphasise effectiveness, efficiency, and trust and engagement through clearly defined institutional responsibilities, policy coherence, stakeholder participation, transparency, monitoring, and institutional capacity (Akhmouch & Clavreul, 2016; Julio et al., 2021). Nevertheless, available evidence suggests that these principles have not yet been fully implemented in many locally significant water territories in Latvia, particularly in smaller river basins and lake catchments where governance arrangements often remain fragmented and weakly integrated.

Although environmental governance and water governance have both been addressed in Latvian policy and planning practice, there remains a need for comparative analysis of how governance is organised and implemented across different territorial contexts and governance settings. In particular, limited attention have been devoted to the comparison of municipal environmental governance systems with smaller river basin territories that lack formal integration into municipal statutory planning frameworks. Understanding these differences is important for identifying governance strengths and weaknesses, as well as opportunities for more integrated and adaptive management approaches.

To address this gap, the present study applies the Triple Governance Dimensions framework (Ernsteins et al., 2017b), which examines governance through three complementary dimensions: governance content (what), governance stakeholders (who), and governance instruments (how). Using this framework, the study analyses and compares environmental and water governance in three territorial cases in Latvia representing different governance and ecological contexts: Kekava Municipality, Lake Lubans, and the Dviete River Basin.

The first governance dimension concerns governance sectors, which represent the substantive content of environmental governance. Traditionally, governance focused on specific sectors, particularly environmental infrastructure and protected natural areas, but research has demonstrated the limitations of such a narrow approach (Ernsteins et al., 2025). As environmental problems and solutions are embedded within broader SESs, governance must extend beyond isolated sectors and incorporate linkages with health, education, agriculture, forestry, tourism, culture, and other domains (Ernsteins et al., 2017b). Consequently, environmental governance involves not only nature protection and pollution control but also the integration of ecological considerations into cross-sectoral territorial planning and decision-making, supporting broader sustainability goals that connect environmental, social, and economic dimensions.

The second governance dimension focuses on stakeholder groups. Environmental governance recognises that effective governance cannot be achieved by the state alone and therefore requires the participation of public institutions, municipalities, businesses, households, NGOs, educators, the media, scientists, and consultants (Ernsteins et al., 2017b). These actors are grouped into five segments: the state, municipalities, business, society, and mediators. Mediators, including NGOs, the media, educators, and academia, play a particularly important role in communication, knowledge sharing, and collaboration (Ernsteins et al., 2017b). This approach is consistent with frameworks such as the Quintuple Helix, which emphasise cross-sectoral cooperation and the integration of diverse perspectives and expertise (Schütz et al., 2019; Morawska Jancelewicz, 2021). Stakeholder participation throughout the governance cycle, from analysis to evaluation, strengthens knowledge integration, learning, acceptance, and implementation, thereby making it a core component of adaptive environmental governance (Kochskamper et al., 2016; Ernsteins et al., 2017b).

The third governance dimension concerns governance instruments, which translate governance objectives into practice. It distinguishes six complementary groups of instruments (Ernsteins et al., 2017b): infrastructure and technologies, economic and financial instruments, communication instruments, institutional frameworks, planning approaches, and legal regulations. Effective environmental governance requires a balanced combination of legal, financial, organisational, technological, planning, and communication instruments, tailored to specific contexts. Communication instruments are particularly important because they support information exchange, education, training, public engagement, social learning, behavioural change, and stakeholder participation (Ernsteins et al., 2017a). This concept is especially relevant in water governance, where water crises are increasingly recognised as governance failures resulting from fragmented, ineffective, and insufficiently inclusive decision-making processes rather than solely from resource shortages (OECD, 2011; Ernsteins et al., 2025).

The aim of this study is to analyse and compare environmental and water governance in local territorial systems in Latvia, including municipal statutory governance systems and small river basin territories that are not formally integrated into mandatory municipal planning frameworks. The purpose is to identify opportunities for more integrated, adaptive, and participatory governance.

To examine environmental governance under different territorial conditions, the study applies the triple governance dimensions framework to three contrasting cases in Latvia: Kekava Municipality, representing a comparatively advanced peri-urban municipality; the Dviete River Basin, representing a small river basin SES largely within a single municipality; and the Lake

Lubans Basin, representing a complex multi-municipal lake–wetland SES. Together, these cases enable comparison of governance across administrative and socio-ecological territorial settings.

Materials and Methods

This study employed a comparative case study design to analyse environmental governance across three territorial cases in Latvia: Kekava Municipality, the Dviete River Basin, and the Lake Lubans Basin. The cases were selected to represent different socio-ecological and governance contexts, ranging from a comparatively advanced peri-urban municipality (Kekava) to a small river basin system largely situated within a single municipality (Dviete River) and a complex multi-municipal lake–wetland SES (Lake Lubans). Together, these cases provide an opportunity to compare environmental governance under different territorial and institutional conditions.

The study applies the Triple Governance Dimensions framework (Ernsteins et al., 2017a, 2017b), which conceptualises environmental governance through three complementary dimensions: governance content (what) - environmental governance sectors and SES components; governance stakeholders (who) - actors involved in governance processes; and governance instruments (how) - mechanisms used to implement governance objectives.

Particular attention was devoted to governance instruments, including policy and legislative, planning, institutional and administrative, economic and financial, infrastructure and technological, and communication and collaboration instruments (Ernsteins et al., 2017a; Konkovs & Ernsteins, 2020). Governance content was analysed using an SES perspective, while stakeholder analysis focused on identifying the principal stakeholder groups participating in governance processes.

The comparative case study design was chosen to analyse how environmental governance is organised and practised across territorially different socio-ecological contexts while using a shared analytical framework. The three cases: Kekava Municipality, Lake Lubans, and the Dviete River Basin, were selected because each represents a distinct territorial governance setting and a different combination of environmental issues, governance arrangements, and stakeholder constellations, yet all can be examined through the same Triple Governance Dimensions framework.

Across all three cases, the methodological approach combined qualitative case study research with a research-and-development orientation. A common research logic was applied in each case: to assess governance arrangements at different administrative levels, analyse relevant policy, planning, and management documents, identify the stakeholder groups involved, and evaluate the use and complementarity of governance instruments. Accordingly, the empirical strategy relied on a combination of document analysis, field-based inquiry, and stakeholder interviews. In each case, the territorial unit was viewed as an SES, and the analysis sought to capture both formal governance arrangements and actual management practices.

To support comparative assessment, a SWOT (Strengths, Weaknesses, Threats and Opportunities) analysis was conducted for all three case studies. The SWOT framework was structured around the three governance dimensions and examined strengths, weaknesses, opportunities, and threats related to governance sectors, governance stakeholders, and governance instruments. This enabled a systematic comparison of governance performance across the selected territorial cases.

In the Lake Lubans case, the empirical work relied heavily on interviews and field inquiry. In total, 45 face-to-face interviews were conducted through visits to organisations and institutions in Rezekne and Madona municipalities, especially in Nagli, Gaigalava, Barkava, and Osupe parishes. These site visits also included observations at relevant locations in the field, enabling the researchers to relate stakeholder perspectives to the territorial context. Following the fieldwork stage, 27 additional remote interviews were conducted, including short express interviews lasting approximately 10–15 minutes. The questionnaire was organised into four thematic blocks: (1) introduction and respondent profile in relation to stakeholder representation; (2) perceptions of Lake Lubans as an SES and of the population and professional groups connected to it; (3) values associated with Lake Lubans and its surrounding territory and (4) management problems and governance of Lake Lubans, including all six groups of governance instruments as well as governance sectors and stakeholder groups. Overall, the Lake Lubans case covered finterviews with five main stakeholder groups and assessed the governance system of the lake through the triple governance dimensions framework.

In the Dviete River Basin case, the study applied an integrated case study methodology developed within the BLIFE and OPTAIN project frameworks. The case was selected because of its distinctive combination of natural values, cultural landscape, and bottom-up governance experience. The analysis proceeded through several interrelated steps: environmental governance audit, environmental communication audit, municipal monitoring audit, stakeholder mapping and consultations, assessment of the multi-stakeholder MARG process, and complementary in-depth semi-structured interviews. First, governmental, municipal, and research databases were reviewed. This was followed by an analysis of legal, policy, and planning frameworks at the national, regional, and local levels. Particular attention was paid to municipal statutory and voluntary planning documents, including the Sustainable Development Strategy, Development Programme, Spatial Plan, Environmental Report, and Monitoring Report of the former Ilukste Municipality,

as well as subsequent documents produced by the newly established Augsdaugava Municipality after the 2021 territorial–administrative reform. These analyses were complemented by field visits, photo documentation, and stakeholder interviews.

An additional component of the Dviete methodology was stakeholder mapping and engagement conducted within the OPTAIN project. Using the Quintuple Helix Stakeholders Constellation and Collaboration Model, stakeholders were identified and grouped into five meta-groups: the state, municipalities, businesses, society, and mediators (Ernsteins et al., 2017a, 2017b). In total, 50 stakeholder organisations were mapped: the state (8), municipalities (10), businesses (6), society (5), and mediators (21). On the basis of this mapping, a Multi-Actor Reference Group (MARG) was established as a collaborative platform for local and regional water retention assessment and planning. Three annual MARG meetings were organised, each involving 10–12 participants representing the identified stakeholder groups, and action research elements were used to facilitate and analyse the process. Finally, 21 in-depth semi-structured interviews were conducted, mostly in person, with representatives of all stakeholder groups: state agencies (3), municipalities (5), businesses (3), society (2), and mediators, including NGOs, the media, educators, and academic actors.

The Kekava Municipality case was analysed using the same comparative methodological framework. The assessment applied the triple governance dimensions framework and examined governance content, governance stakeholders, and governance instruments. Data collection included analysis of municipal governance documents, environmental planning materials, stakeholder involvement practices, and governance implementation mechanisms. Applying the same analytical framework across all three cases ensured methodological consistency and enabled direct comparison between different territorial governance contexts.

Overall, the comparative case study design enabled analysis of environmental governance across three distinct SESs while maintaining a common analytical structure. The approach facilitated comparison of governance arrangements, stakeholder participation, governance instruments, and governance content, providing a basis for identifying common patterns, governance challenges, and opportunities for strengthening integrated and participatory environmental governance in Latvia.

Results and Discussion

The Results section presents the findings of environmental governance audits carried out in three contrasting territorial cases in Latvia: the Dviete River Basin, the Lake Lubans Basin, and Kekava Municipality. Using a common analytical framework, the section examines each case through three interrelated governance dimensions - governance instruments, governance sectors, and governance stakeholders - while also incorporating a SWOT perspective to synthesise the main strengths, weaknesses, opportunities, and threats. The purpose is to identify how environmental governance is structured and functions in different administrative and socio-ecological contexts, and to highlight similarities and differences in governance maturity, integration, coordination, and capacity across the selected cases.

National and local frameworks for environmental and water governance

Latvia's legal framework requires municipalities to manage the environment through a comprehensive but fragmented system of laws and governance instruments that define their functions, planning duties, financing options, and cooperation with the public. Municipal environmental governance is organised around six groups of instruments - legal and political, planning, economic and financial, institutional and administrative, infrastructure and technology, and communication - and local governments, as public law entities may act only on the basis of regulatory enactments that specify their environmental functions, rights, and duties.

Key acts are the Law on Local Governments, the Environmental Protection Law, the Law on Spatial Development Planning, and regulations on local government development planning documents, which together regulate both the content and procedures of municipal environmental governance. The Law on Local Governments (in force since 2023) sets autonomous environmental functions, including organising water, heating, and municipal waste management; maintaining public areas and green spaces; promoting the sustainable management of natural capital; and contributing to climate change mitigation and adaptation.

Municipal environmental governance is to be integrated into three statutory planning documents - the Sustainable Development Strategy, the Development Programme, and the Spatial Plan - which must conform to national strategies and policy guidelines, while municipalities may also prepare additional sectoral plans (e.g., on energy, climate, mobility, or waste). In the financial field, municipalities work within their own budget and a special budget formed from natural resources tax revenues, which may be used only for environmental protection measures. They also rely on EU and national financial instruments for larger investments in climate and environmental projects.

Institutionally, municipalities must ensure basic environmental utilities, but the internal administrative structures responsible for environmental governance differ widely between municipalities, ranging from dedicated departments to individual specialists or shared responsibilities. Environmental governance also covers infrastructure systems such as centralised water supply, sewerage, treatment plants, and landfills, where eligibility for external funding is often linked to

innovative, energy-efficient solutions. Communication instruments based on constitutional and environmental law guarantee the public's right to environmental information and participation in planning through consultations and public involvement.

In Latvia, water resources governance follows a multi-level governance approach, in which responsibilities are divided between state institutions, municipalities, and other stakeholders in line with the Water Management Law (Parliament of the Republic of Latvia, 2002) and related regulations. The Water Management Law establishes the institutional framework for river basin management, monitoring, planning, and public participation, coordinated by environmental authorities, including the Latvian Environment, Geology and Meteorology Centre. The Land Management Law (The Parliament of the Republic of Latvia, 2014) allocates holding rights over inland public waters and coastal areas between the environmental ministry, local governments, and private owners, and defines when municipalities act on behalf of the owner in authorising activities in public waters.

Municipalities, as stipulated by the Local Government Law (The Parliament of the Republic of Latvia, 2022), possess both rights and responsibilities concerning water governance. These encompass the organisation of water services, the facilitation of territorial development, the maintenance of sanitary conditions, and flood protection, and the advancement of sustainable natural resource management and climate change adaptation. Within their administrative boundaries, municipalities are tasked with the organisation of public water services, which may be executed through municipal institutions or delegated to entities such as municipal capital companies. Despite these delegations, municipalities retain ultimate accountability for legal compliance and service quality. Furthermore, they are empowered to engage residents through consultative councils and the mandatory participatory budget, as mandated by the Local Government Law. This budget, which allocates a minimum of 0.5% of designated tax revenues, enables local communities to propose and vote on projects pertaining to water infrastructure, flood risk mitigation, and coastal management.

Environmental governance audit in the Kekava Municipality

Kekava Municipality is located near Riga, covers 443.91 km² and has about 32,000 inhabitants. Its main natural resources include forests (about half of the territory), the Daugava River, smaller rivers, and Lake Titurga. Key environmental challenges involve maintaining environmental quality for living and working, ensuring access to public green spaces, supporting tourism, limiting polluting industries, and promoting local agriculture and crafts. The 2025 municipal budget is about EUR 91 million, with EUR 0.27 million allocated to environmental measures.

Environmental governance is relatively well-developed and guided by planning documents. Environmental specialists are integrated within the Municipal Property Management Department, ensuring cross-sectoral coordination. The municipality's vision aims to ensure a high-quality living environment, particularly for families.

Environmental governance instruments

Environmental governance is supported by a diverse set of instruments. Political instruments include party programmes that prioritise energy transition, mobility, and green infrastructure.

Legislative and planning instruments align with national frameworks and include documents such as the Sustainable Development Strategy 2030, the Development Programme 2021-2027, the Investment Plan, and the Spatial Plan. These voluntary initiatives, such as GMO restrictions, the Territory Improvement Plan, the Energy and Climate Action Plan, and the Hogweed Control Plan, complement these efforts.

Economic instruments are based on the municipal budget and additional revenues such as the Natural Resources Tax. Funding supports environmental education, biodiversity, climate action, water and soil protection, waste management, and restoration.

Institutional instruments rely on a structured administration with embedded environmental expertise, supported by interdepartmental cooperation and project-based working groups. Infrastructure-related instruments reflect regional cooperation - for example, wastewater treatment in Riga, shared water supply, and waste disposal at the Getlini landfill.

Communication instruments include public consultations, streamed council meetings, and active use of social media platforms to engage residents.

Overall, governance effectiveness depends on the interaction of sectors, stakeholders, and instruments, enabling the municipality to address challenges such as mobility, energy transition, and waste management.

Environmental governance content (sectors)

Environmental governance covers both traditional and cross-sectoral areas. Core sectors include water management (supply, wastewater, and surface waters), waste management, and district heating.

The municipality integrates cross-sectoral activities such as energy efficiency, renewable energy transition, and sustainable mobility. Landscape planning and unified territorial design systems are also developed.

Green infrastructure management (forests, parks, and riverbanks), land melioration, rainwater drainage, and maintenance of natural areas are key activities. Biodiversity conservation, environmental protection, and education further complement these sectors.

Implementation is ensured by specialists within the Municipal Property Management Department, including environmental, forestry, landscape, and melioration experts, who contribute to planning documents and project development.

Environmental governance stakeholders

A broad range of stakeholders is involved. Cooperation with state institutions (ministries and environmental authorities) and neighbouring municipalities (Riga, Marupe, Olaine, Salaspils, and

Bauska) is essential, particularly for shared infrastructure and services.

The private sector is engaged through the Business Council, tax incentives, and support for local producers (e.g., 'Made in Kekava'). Civil society participates through NGO co-financing, joint initiatives, and regional partnerships. The public is involved via consultations and participation processes. Within the municipality, governance is led by the Municipal Property Management Department, supported by other departments and supervised by the Council and its committees. Working groups address specific issues and include external experts. Municipal companies provide key services such as water, wastewater, heating, and territory management.

The municipality also participates in international networks, such as the INTERREG URBACT project 'CITIES4CSR', which promotes social responsibility.

SWOT analysis: governance system framework

Before presenting the SWOT analysis, it is important to note that the findings results provide a holistic view of the strengths and limitations of environmental governance in Kekava Municipality. The SWOT framework (Table 1) serves as a synthetic analytical instrument that helps structure the key findings across the three examined dimensions - governance instruments, sectors, and stakeholders - by identifying internal capacities and constraints, as well as external development opportunities and risks. This approach allows a clearer understanding of the municipal administration's current performance while also highlighting priority areas for future improvement and strategic development in environmental governance.

Table 1

SWOT analysis of strength and weaknesses: environmental governance in the Kekava Municipality

Strengths	Weaknesses
Sectors. Environmental governance is integrated across sectors including forestry, water resources, energy efficiency, and landscape planning. Specialist positions for forestry, melioration, and environment are embedded within the municipal property department to ensure coordination. **Instruments.** The municipality utilizes statutory documents and voluntary initiatives (Energy and Climate Action Plan, GMO prohibition). Institutional branding and territorial signs are used as instruments to promote the local environment. Financial autonomy, participatory budget. **Stakeholders.** Cooperation with the Business Council, local NGOs via co-financing projects. The municipality serves as a primary environmental link between national institutions and the local society. Active stakeholder engagement and communication including with inhabitants.	**Sectors.** The transition to renewable energy within the private household and industrial sectors remains a significant challenge. There is an identified internal need for more effective waste reduction strategies across municipal sectors. Insufficient coordination of measures with neighbourhood municipalities and state institutions, scientifical institutions. Fragmentation in cross-sector coordination. **Instruments.** Current governance instruments insufficient for high-level goals in sustainable mobility. Policy implementation regarding the transition from fossil fuels requires more robust management mechanisms. Limited budget for direct environment improvement purposes and public involvement activities. **Stakeholders.** The governance system lacks broad, active involvement of researchers, local grassroots communities. Interaction with specific private sector segments regarding energy transition is still in development.

Kekava: triple governance dimensions

Sectors. Sectoral governance demonstrates a high level of integration, combining environmental governance areas such as forestry, water resources, energy efficiency, and spatial planning, and is supported by embedded specialist roles within the municipal structure. However, significant challenges remain in advancing renewable energy adoption and implementing effective waste reduction strategies, indicating gaps between strategic integration and practical implementation. The sectoral dimension is characterised by strong integration and alignment with environmental priorities, providing a solid foundation for sustainable development. Opportunities such as eco-tourism and scientific innovation can further strengthen this system. However, external pressures, including industrial pollution and climate change, as well as internal challenges related to energy transition and waste management may hinder progress. Strengthening capacity and resilience is essential.

Instruments. The municipality employs a diverse set of governance instruments, including both mandatory planning frameworks and voluntary initiatives, complemented by branding instruments that enhance environmental awareness and territorial identity. Despite these efforts, the existing instruments are insufficient to fully achieve sustainability goals, particularly in sustainable mobility and the transition away from fossil fuels, because of limited implementation capacity and the lack of robust mechanisms. The governance framework includes a combination of regulatory and voluntary instruments, creating a flexible basis for sustainability policies. External funding opportunities and methodological instruments can significantly improve governance effectiveness. Nevertheless, financial constraints, complex national regulations, and insufficiently developed instruments limit the municipality's ability to achieve ambitious goals. A more coherent, better-funded, and implementation-oriented instrument system is needed.

Stakeholders. Stakeholder engagement is supported through active cooperation with business organisations and NGOs, with the municipality effectively acting as a mediator between the national and local levels. At the same time, engagement remains incomplete, with insufficient involvement of researchers, grassroots communities, and certain private-sector group, particularly in the context of the energy transition. Stakeholder cooperation is relatively well-developed at the institutional and organisational levels, with potential to expand through international partnerships and intermunicipal collaboration. However, limited inclusiveness and external economic and political pressures weaken stakeholder engagement and autonomy. Broadening participation and strengthening local capacity are key to ensuring sustainability.

Overall conclusion on the governance system. The governance system demonstrates a comparatively high level of integration and strategic orientation toward sustainability, supported by diverse instruments and municipal institutional cooperation. However, its effectiveness is constrained by implementation gaps, limited stakeholder inclusiveness, and external pressures such as financial restrictions, regulatory complexity, and environmental risks.

Environmental governance audit in the Dviete River basin

The Dviete River Basin represents a territorially distinctive SES in which environmental governance is shaped by the interaction of protected natural values, agricultural land use, floodplain dynamics, local community practices, and limited formal governance capacity. As part of the Natura 2000 network, the basin is characterised by valuable habitats, cultural heritage, and the growing importance of participatory approaches. However, governance remains fragmented, with responsibilities distributed across the national, regional, and local levels without a coordinated system, leading to inefficiencies in decision-making and environmental governance.

The environmental governance audit was structured around three dimensions - governance instruments, sectors, and stakeholders - and focused on water resources, environmental protection, and socio-economic development, with environmental communication as a cross-cutting component.

The results show that governance in the basin is institutionally present but operationally weak. While a broad set of instruments, sectors, and actors exists, their interaction remains limited. Vertical coordination between governance levels is insufficient, horizontal integration across sectors is uneven, and local bottom-up initiatives often compensate for the lack of long-term administrative capacity. Thus, governance is present but requires stronger complementarity, continuity, and collaboration to ensure effectiveness.

Environmental governance instruments

The audit identified a broad spectrum of governance instruments, including political, legislative, institutional, planning, financial, infrastructural, and communication instruments. However, despite this formal completeness, their implementation remains fragmented and weakly coordinated.

The main challenge lies not in the absence of instruments but in their limited integration and inconsistent application. Responsibilities are distributed across institutions with overlapping competences, complicating implementation.

Political and regulatory instruments, such as Natura 2000 regulations and the Dviete Nature Park framework, provide a strong legal basis. However, the absence of a stable, long-term management structure limits their effectiveness. As a result, legal provisions are not consistently translated into practice, leading to ineffective conservation management.

Institutional capacity is constrained, especially at the local level. Cooperation between institutions is often weak, with actors operating within separate domains. Differing priorities and limited information exchange further reduce implementation effectiveness, particularly in water governance.

Planning instruments are formally well-developed but insufficiently operationalised. Strategic documents define long-term objectives, but lack effective monitoring, feedback, and implementation mechanisms. Key issues such as water retention and cross-sectoral coordination remain only partially integrated.

Financial instruments rely heavily on short-term project funding, municipal budgets, and conservation investments. Although these sources support restoration and ecotourism, funding instability limits long-term capacity. The lack of stable financing reduces conservation effectiveness and results in insufficient infrastructure and technological capacity.

Infrastructure and technological instruments are critical because of floodplain conditions but remain underdeveloped. Outdated drainage systems and insufficient river maintenance increase environmental risks, reflecting both technical and governance gaps.

Communication instruments are comparatively stronger, and include digital platforms, tourism materials, and educational activities. Local NGOs and the Dviete Valley Information Centre play key roles. However, communication is uneven across sectors and depends largely on local initiatives rather than on systematic institutional support. Overall, despite a comprehensive formal framework, governance instruments remain weakly integrated and lack long-term coordination.

Environmental governance sectors

Governance in the basin extends beyond nature protection to include water management, environmental protection, and socio-economic development, yet these sectors remain poorly integrated.

Water governance is both critical and weak. Despite its importance, local implementation capacity is limited. Monitoring exists, but communication and management measures are insufficient. The lack of

coordinated management contributes to environmental risks, indicating that local water governance remains underdeveloped.

The environmental protection sector is comparatively stronger because of the Natura 2000 and biodiversity conservation frameworks. The Nature Conservation Agency plays a central role, supported by NGOs and local actors. However, reliance on project-based and voluntary efforts limits long-term sustainability.

The socio-economic sector reflects the basin's dual role as both a protected and a productive landscape. Agriculture is economically important but exerts pressure on water quality and biodiversity. Ecotourism potential is significant but not yet fully integrated with environmental objectives. Weak coordination between sectors limits sustainable development. Overall, sectoral fragmentation persists, with relatively strong environmental protection, weak water governance, and limited integration across sectors.

Environmental governance stakeholders

The stakeholder landscape is diverse but weakly connected. State institutions provide regulatory and monitoring functions but are often perceived as distant, with limited involvement in local problem-solving. Municipalities play a central role but face significant constraints.

Business actors, particularly farmers and tourism providers, influence land use but are insufficiently integrated into governance processes. This contributes to conflicts and limits sustainable resource management.

Societal actors participate in governance, but their engagement is uneven and often depends on individual initiative rather than on structured mechanisms.

NGOs, especially Dviete Valley organisations, play a critical mediating role by undertaking functions such as biodiversity management, communication, and coordination. While this reflects strong local engagement, it also indicates structural weaknesses, as governance relies heavily on voluntary, project-based efforts.

Overall, although many stakeholders are present, their interaction remains limited. Strengthening coordination, communication, and trust-building is essential for more integrated and effective environmental governance in the Dviete River Basin.

SWOT analysis: governance system framework

The SWOT analysis (Table 2) confirms that the Dviete River Basin possesses strong natural, cultural, and social assets, including Natura 2000 status, biodiversity value, active local initiatives, and ecotourism potential. At the same time, governance weaknesses, such as fragmented institutional structures, insufficient funding, outdated infrastructure, and weak sectoral integration, limit the effectiveness of environmental governance.

Internal opportunities include improved use of EU funding, strengthened local governance capacity, and better sectoral integration. However, threats such as climate change, flooding, depopulation, and continued institutional fragmentation pose significant risks.

Overall, the results demonstrate that the Dviete River Basin has a solid governance foundation but lacks the integration, coordination, and long-term capacity required for effective environmental governance. Strengthening both vertical and horizontal integration, as well as supporting local participatory actors, will be essential for future development.

Dviete: triple governance dimensions

Sector dimension. The sector dimension shows a development base in certain areas, such as waste management and environmentally adaptive sectors (organic agriculture and tourism), indicating the system's capacity for adaptation. The sector dimension is significantly constrained by outdated environmental infrastructure, which increases environmental risks and limits effective resource management. The sector dimension, despite the development potential of certain sectors (e.g., environmentally friendly agriculture and tourism), is significantly constrained by outdated infrastructure and conflicting interests; however, its development can be supported by growing demand for ecotourism and the availability of EU funding, while being threatened by climate change, invasive species, and increasing economic pressure on natural resources.

Instruments dimension. The instrument dimension is strengthened by an established planning and monitoring system with a regulatory framework, providing in general a structured approach to environmental governance. The instrument dimension is weakened by having comparatively complex and formal planning documents with low implementation levels, as well as a strong dependence on short-term project funding. The instrument dimension is characterised by a formally established and structured plan; however, its effectiveness is limited by implementation challenges and dependence on short-term funding. Development opportunities exist in EU programmes and innovation in governance instruments, but their effectiveness is also limited by implementation challenges and dependence on short-term funding, while development opportunities lie in EU programmes and innovation in governance instruments; at the same time, it is threatened by inconsistent state policies and the risk of failing to meet international environmental targets.

Stakeholders dimension. The stakeholder group dimension benefits from high expert competence and some active involvement of NGOs, ensuring/assisting the practical implementation of environmental governance. The stakeholder's dimension is limited by weak cooperation, lack of trust, and insufficient capacity, which restrict effective participation and governance. The stakeholder's dimension is strengthened by high expert capacity and active NGO involvement but constrained by weak cooperation, low public participation, and limited capacity, while its development potential lies in cooperation with

scientific institutions and advancing participatory mechanisms; however, it is threatened by low environmental awareness, depopulation, and conflicts between landowners and environmental objectives.

Table 2

SWOT analysis of strength and weaknesses: environmental governance in the Dviete River basin

Strengths	Weaknesses
Sectors. Overall statutory sectorial planning, relatively developed waste management system. Ability of certain sectors (organic agriculture, tourism) to adapt to environmental requirements. Established environmental monitoring and data system, including digital instruments for load/violation analysis. Developed local nature and tourism infrastructure (nature trails, viewing towers, infostands, birdwatching towers). Part of the Natura 2000 network. Unique habitats and high biodiversity value. Rich cultural history and landscape value. Strong ecotourism potential. **Instruments.** Developed Municipal Statutory planning system, including monitoring system, with regulatory framework and general data instruments. Good availability of environmental information at local level through local media and portals. Organised waste sorting and collection infrastructure and residents' habits to use it. Cooperation between municipalities and science in implementation of research projects. Established economic and financial instruments, including environmental taxes, subsidies and project-based EU funding schemes. Use of consult-first administrative practices that prioritise guidance and voluntary compliance over punitive sanctions. Existing communication and education initiatives, including the 'Gulbji' centre. **Stakeholders.** High level competence, project involvement Active NGOs, local leaders for practical management. Self-organization/participation potential: communities. Practical experience of businesses and NGOs in maintaining the territory (river cleaning, maintenance of drainage ditches, maintenance of nature infrastructure). Businesses adaption: organic farming, ecotourism.	**Sectors.** Outdated infrastructure and data gaps Overgrown riverbeds, insufficient regular river cleaning, leading to waterlogged floodplain areas Lack of professional specialists in municipalities for cultural heritage and research issues. Conflicts between nature protection requirements in protected areas and the practical needs of agricultural land use, including restrictive regimes and low compensation levels for farmers. Limited financial support. Agricultural pressure on groundwater and surface water. Potentially polluted sites in the basin. **Instruments.** Formal planning documents – limited implementation, monitoring. Institutional fragmentation and weak cross-sectoral cooperation. Insufficient capacity and shortage of specialists. Dependence on short-term project funding as constantly limited municipal budgetary funding for any development programms and projects. Public receives limited and mainly formal top-down communication, resulting in insufficient, poorly targeted information. **Stakeholders.** Weak and formal communication with society. Low and selective public participation. Dependence on voluntary work and individual enthusiasm. Lack of administrative capacity in NGOs and municipalities to perform broad governance functions in the long term. Low public activity in planning/decision-making processes, especially among young people.

Overall conclusion on the governance system. The municipal and river basin environmental governance system is formally established at the municipal level; however, it is functionally fragmented. While there are strengths such as a formal municipal territorial planning framework, overall municipal development in certain sectors, and some expert competence, these are insufficient to compensate for structural weaknesses. As a result, the system operates more reactively than strategically and is heavily dependent on municipal capacities, particularly administrative and financial resources.

Environmental governance audit in the Lake Lubans basin

Lake Lubans is one of the most complex environmental governance cases in Latvia, and requires an integrated, cross-sectoral approach. As Latvia's the largest lake and part of a broader wetland system, it constitutes a SES shaped by long-term human intervention, including water regulation and infrastructure. Governance must therefore extend beyond the lake itself to the surrounding ecosystems, infrastructure, and socio-economic activities. However, governance has been hindered by the late adoption, in 2024, of a comprehensive wetland protection plan, resulting in fragmented and inconsistent management.

Although it is part of Natura 2000, the lake long lacked a clear framework for balancing protection and development. Restrictions were introduced without an integrated strategy, creating tensions between conservation objectives, local livelihoods, and economic interests. The analysis is structured around three dimensions: sectors, stakeholders, and instruments.

Environmental governance instruments

A wide range of governance instruments exists, including political, legislative, institutional, planning, economic, infrastructural, communication, and collaborative instruments. However, their development and application remain uneven.

Political and legislative instruments, including the Natura 2000 and Ramsar frameworks, provide strong regulatory foundations but often create tensions by restricting local development. Institutional instruments involve key actors, but coordination remains limited.

Planning instruments are relatively weak because comprehensive strategies were only recently developed, contributing to fragmented governance. Economic instruments (taxes, permits, funding mechanisms) exist but are not aligned with integrated lake development.

Infrastructure and technological instruments are critical because of the regulated water system but remain underdeveloped and poorly maintained. Communication instruments exist but remain fragmented, with unclear information and limited stakeholder engagement. Collaborative instruments, such as NGOs and community initiatives, are weakly integrated into the overall governance system.

Overall, although all instrument groups are present, weak planning, coordination, and communication limit effective governance and prevent the lake from being managed as a coherent SES.

Environmental governance content (sectors)

Governance content in Lake Lubans extends beyond the lake itself to include wetlands, infrastructure, and the surrounding territories. The absence of a unified governance plan has reduced clarity regarding priorities and slowed implementation, contributing to fragmented and inefficient management.

Governance is currently dominated by three clusters: nature protection, tourism and recreation, and economic activities (mainly fishing and agriculture). However, a broader SES perspective encompasses governance, environmental protection, natural resources, economic activities, recreation, education, culture, and waste management.

The governance sector includes municipalities, state institutions, NGOs, and local initiatives, but it is increasingly dominated by municipalities because of declining civic engagement. Nature protection is the strongest sector, driven by strict conservation rules within the Natura 2000 wetland system. However, restrictions introduced without clear development strategies have negatively affected local economies and shaped negative perceptions of governance.

Key environmental challenges include overgrowth, wetland expansion, pollution, reed spread, invasive species, and flooding. Bird protection is significant but creates conflicts with agricultural interests.

The environmental protection sector encompasses the regulation of natural resources, fishing, hunting, and pollution. It is essential but conflict-prone, because restrictions often limit economic activities. Waste management remains insufficiently integrated, with persistent issues of littering and illegal dumping.

Recreation and tourism remain underdeveloped despite their strong potential. Activities such as fishing, hunting, and nature tourism are present but remain poorly integrated into governance. Tourism remains seasonal and limited in diversity, with substantial untapped potential in cultural and sustainable tourism.

The social sector supports community life, culture, and education, although its integration with lake governance remains partial. The economic sector (agriculture, fisheries, forestry, tourism) is constrained by environmental restrictions and declining productivity.

Overall, governance is unbalanced: nature protection dominates, while the economic, social, and recreational sectors remains weaker and insufficiently integrated.

Environmental governance stakeholders

Stakeholders include state institutions, municipalities, businesses, mediators, residents, and tourists, each with diverse and sometimes conflicting interests.

State institutions (e.g., the Nature Conservation Agency and the State Environmental Service) provide regulatory and monitoring functions but lack strong integration. Municipalities (Madona and Rezekne) play key roles in local management but face coordination challenges because of the absence of a clear governance framework.

Business actors, including farmers, fish farms, and tourism providers, are economically important but remain weakly integrated into governance. Local residents are also underrepresented despite their historical connection to the lake.

Tourists represent an important but underutilised group, while mediators (NGOs, educators, experts) have strong potential but limited involvement.

Overall, governance is characterised by weak stakeholder integration, limited communication, and conflicts of interest. State and municipal actors dominate, while other groups remain underengaged.

SWOT analysis: governance system framework

The SWOT analysis (Table 3) shows that Lake Luban governance has a solid foundation, supported by multi-sectoral cooperation, strong local environmental awareness, and a development vision focused on nature tourism. However, it is constrained by fragmentation, weak stakeholder involvement, and insufficient coordination, which can lead to ineffective decision-making and hinder the implementation of sustainable practices. The region also offers opportunities, such as access to EU funding and the growth of nature tourism under relatively low environmental pressure. At the same time, risks including stakeholder conflicts, climate change, and infrastructure pressures may further hinder sustainable and integrated governance.

Table 3

SWOT analysis of strength and weaknesses: environmental governance in the Lake Lubans basin

Strengths	Weaknesses
Sectors. Governance is dominated by nature protection and Natura 2000 status. Educational institutions introduce environment. Systematic fish resource restoration is carried out. Unique inland fishing traditions in Idena village. **Instruments.** The sluice system provides full water level control. Municipalities own tourism information centres. The water tourism centre 'Baka' is operational. Political/legal regulation of fishing net leases. The Wetland Information Centre is a key nature centre in the Lubana region. Tourism as a regional development instrument. **Stakeholders.** Municipalities act as the main intermediaries between institutions and residents. Local specialists perform daily management tasks. Citizen Advisory Councils have been established in the Rezekne district. Local hunting and angling clubs are active. Lubana Lake region is popular among bird watching groups and nature tourism groups. Local tourism and recreation-related business owners benefit from the lake and territory development plans.	**Sectors.** Sectoral governance is fragmented and uncoordinated. The socio-economic and tourism sectors are underdeveloped. Lack of sufficient waste management control on the coast. No companies in the region process lake reeds. **Instruments.** Missing lake-wetland management plan. Insufficient communication, involvement instruments. Recreation infrastructure and the road network are worn. Information maps regarding nature objects and recreation sites are lacking. The Lubana Wetland Information Center is the only nature information center in the region. Financial instruments are limited and underused. **Stakeholders.** Residents are not sufficiently involved in decision-making. Entrepreneurs receive weak institutional support. Limited cooperation: state institutions and municipalities. Interests of hunters and anglers are poorly represented in planning documents. Environmental activists are divided regarding nature conservation and lake water levels. All types of stakeholders have conflicts of interest regarding the development of the region.

Lubans: triple governance dimensions

Sectors. Sectoral development is strongly rooted in nature protection, with the active involvement of educational institutions and the preservation of traditional practices, thereby supporting ecological sustainability and cultural continuity. However, sectoral governance is fragmented, with weak integration of socio-economic and tourism development, insufficient environmental control, and limited value-added economic activity. The sectoral dimension shows a strong environmental orientation and substantial cultural value, but its long-term sustainability depends on better integration with economic sectors. Opportunities such as eco-tourism, innovation, and bioresource use could significantly enhance development, yet they are constrained by environmental degradation, economic decline, and climate-related pressures. A more balanced and coordinated sectoral approach is essential.

Instruments. Existing instruments provide a solid technical and regulatory foundation, particularly in water-level management, tourism support infrastructure, and legal frameworks for resource use. At the same time, he lack of strategic planning, insufficient communication instruments, outdated infrastructure, and missing informational resources limitseffective governance and public engagement. The instrument framework has a functional base but lacks strategic coherence and modernisation. External funding opportunities and new planning initiatives could substantially strengthen governance capacity. However, institutional complexity, insufficient funding, and regulatory constraints pose significant risks. Developing a unified management system and improving infrastructure and communication instruments are critical priorities.

Stakeholders. Local stakeholders, especially municipalities and community organisations, play an active role in daily management and serve as important intermediaries between institutions and residents. Nevertheless, stakeholder involvement is uneven, with low participation by residents, weak support for entrepreneurs, limited institutional cooperation, and under-representation of key interest groups in planning processes. Stakeholder engagement is locally grounded but insufficiently inclusive and coordinated. There is strong potential to expand cooperation with scientific institutions, NGOs, investors, and international visitors, which could drive innovation and economic growth. However, social and environmental pressures, including emigration, pollution, and unmanaged tourism, threaten stakeholder cohesion and long-term participation. Strengthening collaboration and inclusion is essential.

Overall conclusion on the governance system. The governance system is characterised by a strong focus on environmental protection, supported by dedicated local actors. However, it suffers from a lack of integration, coordination, and strategic alignment across sectors, instruments, and stakeholders. This fragmentation undermines the effectiveness of governance structures, limits stakeholder involvement, and hampers innovation and the development of nature tourism and recreation. Additionally, external

environmental and economic threats pose further challenges. To ensure long-term sustainability, it is essential to establish a structured and participatory governance system based on a unified management approach. This should include new forms of institutional cooperation with a local administrative presence or, at minimum, consultation and communication structures, such as a Wetland Communication Centre. It is also important to apply a complementary planning approach that encompasses all governance instruments while ensuring a balanced integration of ecological, economic, social, and managerial priorities.

Municipal environmental and water governance developmental status and practice limitations

A relatively well-established legislative and institutional framework generally shapes environmental governance in Latvian municipalities. Local governments and municipalities operate within a national system that defines environmental responsibilities, planning requirements, and governance instruments such as spatial planning, environmental protection regulations, and public participation procedures. This results in a moderately developed municipal governance structure where environmental issues are formally addressed, although their integration into broader municipal development planning remains incomplete and uneven across territories (Ozolins et al., 2023). Administrative capacities have improved, particularly after the administrative-territorial municipal aggregation reform, yet they still vary significantly between municipalities and depend on local available resources and institutional arrangements, according to each municipality's traditions and decisions. At the same time, municipal environmental governance faces key challenges in cross-sectoral integration, coordination, and stakeholder engagement, hindering effective policy implementation and sustainable development.

Environmental governance empirics: summaries from municipal and water basin case studies

Latvia's environmental and water governance is characterised by a relatively comprehensive, although fragmented, legal structure, also oriented towards harmonising national objectives with municipal implementation. Local authorities are instrumental in implementing environmental duties, spatial planning, and sustainable resource management, as also stipulated by the Law on Local Governments; however, because municipalities exhibit institutional and financial inequalities, the system requires stronger multi-level coordination, clearer legal responsibility, and more robust public engagement practices.

The Kekava Municipality case confirms that the three-dimensional environmental governance model, linking governance instruments, stakeholders, and sectors, provides a coherent framework for integrating environmental objectives into local development practice. The interaction between a diverse set of instruments, a broad and actively involved stakeholder network, and an expanding sectoral scope enables more coordinated, cross-cutting, and participatory decision-making, while also revealing the need for continuous capacity-building and monitoring to ensure that this integrated model is fully operationalised in everyday municipal governance.

The Dviete River Basin case demonstrates that the three-dimensional environmental governance model reveals a clear mismatch between formal design and practical functioning: although a broad mix of instruments, sectors, and stakeholders is present, their interactions remain weak, fragmented, and only partially coordinated. Governance instruments are formally diverse but insufficiently complementary, sectoral governance is uneven, with water management particularly underdeveloped, and stakeholder networks are active yet weakly interconnected and highly dependent on bottom-up NGO initiatives. As a result, the basin's governance system rests on a structurally solid but operationally fragile foundation, and strengthening vertical and horizontal integration among instruments, sectors, and stakeholders becomes a precondition for moving from fragmented arrangements to integrated river basin governance.

The Lake Lubans case study demonstrates that the three-dimensional governance model reveals a significant disparity among governance content, stakeholder composition, and instrument application: conservation-oriented sectors predominate, stakeholder integration is weak, and essential instruments, particularly those related to planning, communication, and collaboration, are inadequately developed. Although all main sectoral domains are present and a wide range of state, municipal, corporate, community, and visitor groups interact around the lake, their relationships are poorly coordinated, conflicts between conservation and economic use remain largely unresolved, and local residents are only marginally involved in strategic decisions. Similarly, the full set of instrument groups exists in formal terms, but the long-standing absence of a unified wetland governance plan has led to fragmented, reactive, and often contradictory implementation. As a result, Lake Lubans continues to be governed more as a constrained municipal territory than as a coherent SES, making stronger integration across sectors, stakeholders, and instruments a necessary precondition for genuinely sustainable lake governance.

Current and previous research shows that not all environmental issues are sufficiently integrated into municipal planning systems, partly because of limited national-level methodological support and weak public pressure (Ozolins et al., 2023). In addition, communication instruments, such as information provision, public participation, education, stakeholder involvement, and the promotion of pro-environmental behaviour, are often underdeveloped despite general participatory progress, thereby reducing the effectiveness of governance processes. This broader context is essential for interpreting the selected cases,

as even the more advanced example of Kekava Municipality, defined by statutory administrative boundaries, represents a relatively strong case within a still-developing municipal governance landscape.

Comparisons and learning outcomes

The comparison of the three cases: Kekava Municipality, Lake Lubans basin (Aiviekste River basin) and the Dviete River Basin reveals clear differences in the maturity and integration of environmental governance, especially between territories with legal boundaries and those territories defined by socio-ecological criteria. The Kekava Municipality demonstrates the most developed and balanced governance system, with relatively strong institutional integration, broader use of governance instruments, and more structured stakeholder involvement. In contrast, basin-based territorial cases such as Lake Lubans are characterised by fragmented governance arrangements, a lack of unified management planning, and overlapping, potentially conflicting institutional responsibilities between national and local actors (Konkovs et al., 2022). In these territories, especially in Natura 2000 sites, governance is often dominated by nature protection objectives, while socio-economic and participatory dimensions remain insufficiently integrated.

In particular, the Lake Lubans case highlights that governance challenges are strongly linked to the absence of a unified governance approach and management plan, as well as to insufficient stakeholder involvement. Despite the presence of multiple institutions, coordination remains weak, and local communities, businesses, and NGOs are inadequately engaged in planning and decision-making processes (Konkovs et al., 2022); in some Natura 2000 cases, they are almost ignored. This results in a fragmented governance system in which different sectors, such as nature protection, agriculture, tourism, and fisheries, are poorly integrated into local and regional statutory development planning, thereby only weakly reflecting the necessary SES approach.

A common finding across all cases is that governance problems are caused less by the absence of formal instruments than by weak coordination, limited complementarity of instruments, and, especially, insufficient institutional capacity across all administrative levels of governance.

Even where legal frameworks and governance instruments exist, they are not fully implemented in integrated territorial management (Ozolins et al., 2023; Konkovs et al., 2022). This is especially evident in river and lake basin governance, where planning and communication mechanisms for the territory as a whole SES remain underdeveloped.

Sectoral integration differs between municipal and basin cases. Kekava reflects a more integrative, sustainability-oriented approach, increasingly incorporating environmental considerations across sectors. In contrast, Lake Lubans governance remains sector-based, dominated by nature protection with limited integration of economic and social dimensions (Konkovs et al., 2022).

Stakeholder involvement follows a similar pattern: while municipalities such as Kekava have more institutionalised participation mechanisms, basin governance relies more on fragmented, project-based, or weakly coordinated engagement processes. Even in municipalities that include these river basin areas, at least formal-statutory engagement processes are in place.

Towards local developments of system-based and cross-sectoral understanding

The main questions concern the development of two complementary approaches: how to extend the gradually evolving municipal environmental governance practice to river basin territories so that it becomes SES-based territorial governance, and how system-based river basin governance can be effectively integrated into statutory municipal environmental and broader development planning and practice. The main findings from all three case studies are broadly transferable to many local territorial governance practices in Latvia (Ernsteins et al., 2017a, 2017b, 2025; Konkovs et al., 2022; Ozolins et al., 2023).

These findings are broadly consistent with the international literature on municipal environmental governance, which emphasises that effective governance in SESs depends on integration, adaptability, collaboration, and learning rather than on regulation alone (Folke et al., 2005; Olsson et al., 2007). The results also support existing critiques of hierarchical command-and-control approaches, which often prove insufficient in territorially complex environmental contexts (Levin, 1999; Holling et al., 2002). In addition, the cases confirm earlier studies showing that the implementation of WFD principles often remains limited in practice, particularly in smaller water basins and rural territories where participation, coordination, and long-term institutional capacity are weaker or absent (Neto et al., 2018; Rimmert et al., 2020). At the same time, the national river basin governance system is still in the process of extending to small river basins through successive administrative levels, from the comparatively established national level to regional planning and further to the local municipal level (Ernsteins et al., 2025).

SWOT-based opportunities - threats: municipal and basin-based environmental governance

Across all three cases, Kekava Municipality, Lake Lubans and the Dviete River Basin, the identified opportunities are closely linked to sectoral diversification, external financing and stakeholder mobilisation. Nature-based and cultural tourism, together with broader eco-recreational activities, provides shared potential for simultaneously strengthening local economies and supporting conservation objectives. At the same time, EU and other international funding instruments, scientific cooperation, and new technological or digital solutions can reinforce evidence-based planning and help

operationalise system-based, cross-sectoral environmental governance at both municipal and river-basin scales.

The three cases also share several systemic threats that constrain effective environmental and water governance. Climate-change-related risks, including increasing eutrophication, extreme weather events and changing hydrological regimes, intensify pressures on ecosystems and local livelihoods. In addition, fragmented or rigid legal frameworks, insufficient and unstable funding for water management, overlapping institutional responsibilities and weak coordination across administrative levels limit the implementation of integrated, SES-oriented approaches. Social challenges such as depopulation, ageing and low environmental awareness further undermine stakeholder engagement and reduce the effectiveness of participatory governance instruments.

At the same time, case-specific opportunities and risks highlight clear differences between municipal and basin-type territories. In Kekava, urban proximity, stronger economic activity, regional cooperation, and participation in international networks create favourable conditions for integrating environmental objectives into development planning, but these advantages are offset by industrial pressures, rapid suburbanisation, and dependence on national financial equalisation. In contrast, the Lake Lubans and Dviete basin cases highlight opportunities related to unified basin management and tourism strategies, local consultative councils, and bottom-up conservation partnerships, yet they remain constrained by stricter nature-protection rules, invasive species and disease risks, unresolved land-use conflicts, and weak compensation mechanisms. These contrasts suggest that, although a common national framework and three-dimensional governance model apply, instrument design and participation must be territorially adapted by building on municipal economic and institutional capacities in Kekava and by prioritising conflict resolution, basin-level planning, and livelihood-based conservation in more peripheral lake and small-river territories.

Conclusions

The following conclusions are derived from a comparative assessment of three Latvian territorial environmental governance cases. Together, they reveal governance strengths, limitations, and development opportunities across different municipal and socio-ecological governance contexts.

Environmental governance: Kekava Municipality

1. The case of Kekava Municipality demonstrates that integrating environmental governance into the overall municipal management structure contributes to the effective incorporation of environmental considerations into development planning, property management, mobility, energy efficiency, and other municipal functions.

2. Kekava Municipality represents the most integrated governance case among the studied territories, combining diverse governance instruments, active stakeholder cooperation, environmental communication practices, and cross-sectoral environmental planning. However, its long-term effectiveness depends on strengthening the implementation of sustainability measures, particularly in renewable energy transition, sustainable mobility, waste reduction, broader stakeholder participation, and systematic monitoring and evaluation of environmental governance outcomes.

Environmental governance: Dviete River Basin

3. The Dviete River Basin demonstrates that the existence of formal environmental governance structures and instruments alone is insufficient to ensure effective governance, as fragmented institutional responsibilities, weak cross-sectoral coordination, and limited long-term administrative capacity continue to constrain environmental management and decision-making processes.

4. Although the Dviete River Basin possesses a strong environmental governance foundation based on valuable natural assets, planning frameworks, environmental monitoring practices, and active local initiatives, its future development depends on stronger stakeholder cooperation, participatory and bottom-up governance approaches, environmental communication, and the integration of environmental, water management, and socio-economic sectors through complementary governance instruments and collaborative governance arrangements.

Environmental governance: Lake Lubans

5. The case of Lake Lubans demonstrates that fragmented governance structures, insufficient stakeholder involvement, and the absence of a unified management framework significantly reduce the effectiveness of environmental governance and limit the integration of ecological, socio-economic, and tourism-related development objectives.

6. The long-term sustainable development of Lake Lubans requires the application of an SES approach that balances nature conservation objectives with local economic development, tourism, recreation, and community interests through integrated governance and planning mechanisms. This requires stronger stakeholder participation, environmental communication, collaborative governance structures, and monitoring-based adaptive management.

Comparative analysis and general conclusions

7. The application of the triple governance dimensions framework in three contrasting Latvian territorial cases demonstrates that governance effectiveness is determined by the degree of integration among governance sectors, stakeholder groups, and governance instruments. The findings show that governance performance depends less on individual governance arrangements than on their complementarity, interaction, and capacity to support adaptive and collaborative governance.

8. The comparative case-study analysis reveals a clear governance gradient between municipal and basin-based territories. The Kekava Municipality case demonstrates comparatively mature and integrated environmental governance, while the Dviete and Lake Lubans cases reveal lower levels of integration, coordination, and stakeholder involvement, particularly in SES-based governance.

9. Governance effectiveness depends not only on the existence of governance instruments but also on their complementary and coordinated application. Although planning, legal, financial, institutional, technological, and communication instruments are widely used, their implementation is often constrained by limited resources, short-term project dependence, regulatory complexity, and insufficient administrative capacity.

10. Stakeholder participation and environmental communication remain among the weakest components of local environmental governance. Communication, public involvement, environmental education, monitoring feedback, and collaborative decision-making are often fragmented or overly formalised, thereby limiting transparency, trust, social learning, adaptive management, and long-term stakeholder engagement.

11. The findings suggest that several governance limitations identified across the three cases - fragmented coordination, weak environmental communication, insufficient stakeholder participation, and limited implementation capacity - are not case-specific phenomena but are likely characteristic of a broader share of Latvian local environmental governance. This conclusion is consistent with previous Latvian and international environmental governance research.

12. Opportunities for strengthening environmental governance in Latvia include stronger municipal capacity, broader stakeholder cooperation among state institutions, municipalities, businesses, civil society, and mediating actors, greater involvement of NGOs, educators, the media, and scientific institutions, nature-based development, scientific cooperation, environmental communication, and EU funding mechanisms. However, these opportunities must be addressed alongside common challenges, such as climate change, demographic decline, infrastructure deterioration, institutional fragmentation, and increasing pressures on natural resources.

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GOVERNANCE FRAMEWORK FOR ENERGY-EFFICIENT HOUSING RENOVATION PROCESS: MULTI-APARTMENT BUILDING WITH COMPLEMENTARY ROOF-TOP SOLAR TECHNOLOGIES

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Abstract
The paper deals with the challenges of the complex renovation of multi-apartment buildings (MABs), joining within a single project both the 'traditional' increase in energy efficiency of MABs and the installation of on-site zero-emission technologies. Wide inclusion of rooftop solar technologies within the projects is still one of the weak points for necessary radical improvement of the renovation process of the MABs in Latvia. MABs could make an important contribution to this goal, and both solar thermal collectors (STCs) and solar PV panels must be adequately considered. However, up to now, rooftop solar energy in MABs in Latvia is a rare practice, meeting its penetration with both engineering and economic and social obstacles. Utilizing a case study research methodology approach centered on Valmiera municipality, the study employs a complementary mixed qualitative methodology comprising document and database studies, in-depth semi-structured stakeholder interviews, and observational studies. The results demonstrate that successful thermal renovation requires a dual approach: robust technical engineering must coexist with structured energy governance tripartite framework and process preconditions. Consequently, this underscores the significance of the standard governance process lifecycle, also post-implementation phases, and the application of an integrated triple-dimension-based governance framework that encompasses governance stakeholders, sectors, and instruments. Beyond these institutional frameworks, there are recognized crucial localised driving factors, including the accessibility of European Regional Development Fund (ERDF) and municipal co-funding, civic participation and household leadership, and a robust municipal intermediary management system, coordinated by the municipal management intermediary agency, serving as facilitating and renovation project manager.
Keywords: preconditions, governance framework, governance content, stakeholders, driving factors.

Introduction

The overall aim of the study is to structure and analyse success case of energy-efficient multi-apartment building (MAB) renovation with particular interest in rooftop solar technologies' application, recognising that successful thermal renovation requires not only robust technical engineering, but shall be complemented with structured energy governance process framing, and, subsequently, requesting to suggest and evaluate the potential governance framework and to recognise main preconditions and riving factors.

The European Union (EU) strives to be the first climate-neutral continent. The EU 'Climate Law' (European Parliament and Council, 2021) enshrines in the EU legal system the binding objective of climate neutrality at the latest by 2050, aiming to achieve negative greenhouse gas (GHG) emissions thereafter, first (December, 2019) stated by the European Green Deal (European Commission, 2019) in pursuit of the long-term temperature goal ('to limit the temperature increase to 1.5 °C above pre-industrial levels') set out in the Paris Agreement. The intermediate steps, relative to 1990, are a domestic reduction of net GHG emissions by 2030 by at least 55% (European Parliament and Council, 2021) and by 2040 by 90% (European Commission, 2025).

Renewable energy source (RES) deployment is one of the principal strategies to reduce GHG emissions. The revised in 2023 Renewable Energy Directive (European Parliament and Council, 2018) states the binding ensuring of the 42.5% share of energy from RES in the EU's gross final energy consumption (FEC) in 2030, endeavouring to increase it up to 45%. Mainstreaming of RES and increasing of renewable energy share should be provided in all energy end-use sectors. Particularly in the building sector FEC, the EU-wide indicative target is at least a 49% share of energy from RES in 2030.

Thermal renovations of MABs with roof-top solar technologies

In line with EU renewable energy policy and based on a high historical share (43.22% in 2023 (Official Statistics Portal of Latvia, 2023)), Latvia shall reach a 61% share of energy from RES in total gross FEC in 2030 (Republic of Latvia, 2024). Particularly in Latvia's building sector FEC, the share of energy from RES should increase up to 65% (indicative) from 60.6% in 2022. By installing on-site RES technologies, MABs could provide an important contribution for the further mainstreaming of RES in the building sector. For it, both rooftop solar photovoltaic (PV) panels and solar thermal collectors (STCs) and their combination with heat pumps (HPs) must be adequately considered. In the previous our study (Kudreņickis et al., 2024b), Latvia's potential for rooftop PV systems, to be installed by energy communities comprising MABs residents, has been evaluated at around 77 GWh electricity production in 2030 as the most substantiated scenario.

The revised in 2024 Directive on energy performance in buildings (European Parliament and Council, 2024) states the EU member states shall ensure the deployment of solar energy installations, if technically suitable and economically and functionally feasible, by 31.12.2029 on all new residential buildings. At the national level, the criteria for the practical implementation of this obligation shall be established,

and the supporting framework providing the necessary administrative, technical, and financial measures must be put in place. Although the directive does not contain the obligation to provide the deployment of solar energy in the MABs undergoing renovation, the research studies we refer to in the literature review section below confirm the solar energy technologies as one of the buildings' principal retrofit measures.

In the latest years Latvia has had a boom in the installation of solar PV microgeneration technologies in the residential sector – single-family buildings. However, the interest for SCTs is significantly lower.

By June 2025, the total PV systems generation capacity in Latvia has already reached 770 MW (around 30% of total RES facilities' capacity) (Sadales tīkls, 2025); five years ago, PV systems capacity was negligible (only around 3 MW). One can see the PV systems have become a highly important electricity generation source in Latvia. On the other hand, such development might also be evaluated as a disproportionately rapid increase in solar PV systems' capacity when many installers, particularly of large ground-mounted solar PV facilities, see the economic profit, not the ensuring of self-consumption.

The residential sector provides a highly important contribution to total solar PV capacity in Latvia. The total number of microgenerators (capacity up to 11.1 kW), connected to the power distribution grid at the end of June 2025, was 23,8 thousand, with the total capacity of 202 MW (Sadales tīkls, 2025). An important promoter of the PV system installation in single-family and detached houses is the national green investment scheme-emission allowances. Auctioning Instrument (EAAI, revenues of EU ETS emission allowances auctioning), established in 2022 and ongoing up to 2029 (inclusive), with the currently allocated aid volume of 85 MEUR, the programme supports the purchase of PV panel systems as well as electricity-storage equipment. At the end of 2024, within this programme, around 12,5 thousand PV microgeneration systems were installed with the total capacity slightly exceeding 100 MW. Techno-economic data are presented in Table 1.

In our case study region, Valmiera municipality, 380 PV panel systems (3% of Latvia's total) with a total capacity of around 3 MW have been installed (December 2024) (Latvian Environmental Investment Fund, n.d.). However, in the future, the installation path might decrease due to the change in the provisions for electricity exchange with the grid, namely, the net metering (in kWh) system for new entrants has been closed from the 01.05.2024, and currently the net payment system is available. We evaluate solar PV systems that are currently installed in around 4.2% of total single-family dwellings in Latvia, which is a good example of energy citizenship at the individual household level.

However, up to now, rooftop solar energy in MABs in Latvia is a (very) rare practice, meeting its penetration with engineering, economic and social obstacles.

At first, the PV technologies had not been included as the eligible ones within the MABs' renovation aid programme of the EU funds' 2014-2020 planning period; only RES technologies for heat production, such as STCs and HPs, were eligible. For the ongoing aid programmes, both financed by Latvia's Recovery and Resilience Facility Plan (RRFP) (Cabinet of Ministers, 2022) and Latvia's EU Cohesion Policy Programme for the 2021-2027 planning period (Cabinet of Ministers, 2024b), electricity microgeneration technologies are included as well as the eligible technologies to produce electricity for self-consumption (considered as the use of at least 80% of the electricity produced on an annual basis) to be consumed both in MAB's common areas and for serving engineering systems and equipment; however, this aid does not deal with the electricity sharing in MAB apartments.

Table 1

Average techno-economic data for the single project, supported by EAAI programme (Cabinet of Ministers, 2022)

	Capacity, per project	Financial volume, EUR		EAAI support volume	
		per project	per kW (kWh)	per project	per kW (kWh)
PV panels system	8.1 kW	6400	860	3260	400
Electricity storage system	12.2 kWh	4070	335	2427	200

Secondly, the adoption of energy communities' legislation in Latvia has been significantly delayed. Clear provisions for the operation of both jointly acting renewable energy customers and energy communities are the necessary precondition to unlock solar electricity generation at the MAB and neighbourhood levels. Although the general provisions related to active customers and energy communities have been adopted in July 2022 (The Parliament of the Republic of Latvia, 1998, 2005), the governmental regulation for registration and operation of energy communities has been adopted only recently, in December 2024, and only in May 2025 was it included in the regulation the detailed provisions on obligation electricity traders shall include the universal service of the energy community in their electricity trading offers (Cabinet of Ministers, 2024a). Also, the financial aid programme for energy communities in summer 2025 was still in interinstitutional harmonisation.

Thirdly, there are hindering governance obstacles. Installation of on-site zero-emission technologies in MABs in Latvia would contribute, through the

development of prosumerism, to the wider involvement of citizens in the energy system transformation processes. Studies on the success stories can provide valuable lessons for rooftop solar technologies' penetration.

The current study particularly focuses on the case of rooftop solar technologies in MAB in Valmiera City. In Latvia, we also are referring to the pilot practice of rooftop solar technologies in MABs in the Marupe municipality. An example of an STC (around 11 kW) installation in a historical building is a 7-apartment building (built 1898, comprises a private kindergarten on the ground floor) in Riga capital city. As in the earlier cases of STC installations in MABs in Latvia, it can be noted that a 30-apartment building in Sigulda town (combined installation in 2010 of 29 kW STCs and a 100-kW wood pellet boiler (Zandeckis et al., 2012) and an 11-apartment building in Rezekne (10 STCs). Worth noting also is the case of installing a ground-mounted larger-scale (259 kWp, 720 panels) solar PV facility, initiated by the village owner, to provide almost a fifth of electricity demand of Amatciems' green lifestyle community's detached single-family buildings (PV Magazine, 2022).

Integration of solar energy technologies along with the MAB retrofit

The application of solar energy technologies, as has been recognised from the literature review performed, is widely studied as one of the building retrofitting measures to upgrade it to a net zero energy building (ZEB). The recent review (Ibrahim & Harkouss, 2024), including more than fifty cases, presents that the installation of PV panels was done in all cases to achieve net ZEB. Regarding PV technologies, the 1st-generation silicon-based one still represents over 95% of the market due to its cost-effectiveness and maturity (International Energy Agency, 2022). Today PV panels are available in different types, expressions and colours, allowing them to be integrated aesthetically. At the same time, the rooftop or facade-sited PV panels are not the only solar technology; adequate attention has to be paid to the installation of STCs as well, particularly to the combined installation of PV panels and STCs. E.g., the recent (10.2024) review (Weerasinghe et al., 2024) has shown solar energy technologies are widely applied as one of the measures to retrofit existing buildings (considering all use-types) to net zero carbon ones and has identified 58 research papers analysing the installation of them, of which 17 papers relate to combined installation, 38 papers relate to only PV panels and 3 cases relate to only STCs; the reviewed papers had studied the performance of this retrofitting measure together with the economic feasibility and environmental impacts.

The studies, referred to below, characterise the research directions on rooftop solar technologies implementation along with building energy efficiency improvement; of course, the reference list provided is not exhaustive. Several studies have analysed solar technologies in single-family buildings, but we focus below on MABs.

The (Aljashaami et al., 2023) consider the solar heating installations currently available in the market as a successful alternative to traditional heating methods and evaluate their economic feasibility; the study is based on heating a house in Warsaw with the annual heat demand of 12.53 MWh. Two options have been considered: (1) using STCs in direct heat generation, while (2) using PV panels to generate electricity for DHW. The results indicated that STCs and PV panels contributed to the annual energy demand by 40% and 43%. Authors have found the annual costs saved when using STCs are 252 EUR if natural gas is the conventional energy used for heating.

Author of (Galvin, 2024a) underlines that rooftop PV has decreased sharply in price and continues to do so and, by exploring the economics of installing PV systems along with building energy-efficient renovation based on the case study of two typical apartment buildings in North Rhine-Westphalia, applying net-present value cost-benefit analysis, demonstrates that rooftop PV systems can provide significant gains, particularly in combination with HPs. The author emphasises that the costs of energy efficiency renovation of Germany's postwar apartment buildings have sharply increased since pre-Covid years and thus considers rooftop PV systems as the important measure to increase the economic viability of MABs retrofit. Improvement of retrofit economic viability by solar technologies is a particularly important solution due to several studies: (Kazukauskas & Li, 2024) (Lithuania case); (Galvin, 2024b) (Germany case) and (Hirvonen et al., 2022) (Finish case) have concluded that in case of enough deep renovation, the costs of renovation might not be offset by energy cost savings. Also, in our previous paper (Kudreņickis et al., 2024a), there were identified MABs with high specific renovation costs within Latvia's related 2016-2023 national programme, being co-financed by the European Regional Development Fund (ERDF).

The (Galvin, 2024a) also clearly shows the opposite link, namely, not only does PV improve the economic viability of MAB retrofit, but also MAB retrofit improves economic viability of rooftop PV systems. Without such a combination with the retrofit, installing PV systems makes it useful only for the normal electricity load, while the rest of the electricity production must be fed into the grid for the small gain. Thus (Galvin, 2024a) emphasises both policymakers and property owners should consider the economic usefulness of rooftop PV systems not only for new buildings but also as an important supplement to energy-efficient renovation and recommends the promotion of the shared rooftop PV systems as the norm within comprehensive energy-efficient renovation of MABs.

Well-governed subsidy schemes must be understood as the important tool to promote solar technologies, and high attention must be paid to improve existing

aid, both at national and municipal levels. On the other hand, Galvin (2022) calls for a careful assessment of PV systems' size, namely, the approach of installing PV panels to generate as much energy as the building uses over the year (if roof area is available) may lead to the installation of a significantly larger PV system than is technically optimal, and it would be more economical to invest in remote wind power (e.g., the energy community approach) than in excess PV capacity. Importantly, optimising the size of the HP and incorporating thermal storage can provide good systems performance and efficient use of PV panel-produced electricity even in colder climates (Mussard, 2017), such as Germany.

Regarding the expected future cost reduction of residential rooftop PV panels systems, the Danish Energy Agency (n.d.) provides for a 32% cost reduction in 2030, a 44% cost reduction in 2040 and a 48% cost reduction in 2050, compared to the 2020 cost; it is also expected the decrease in the specific space requirement per installed kW will be around 10% in 2030, 16% in 2040 and 21% in 2050, compared to 2020, as well as the technical lifetime will increase by 5 years in 2040.

The study (Hajian, 2024) analyses the renovation measures implemented under the ARA renovation subsidy program in MABs in Finland - the most typical renovated building from the 1970s. Authors conclude, ʻExhaust air HP, window replacement and PV were the most cost-effective options, while packages with additional insulation faced considerably higher costs. Both STCs and PV panels are included in the optimal energy retrofit scenario of the Finish building stock by 2050 (Hirvonen, 2021). In its turn, Rehman et al. (2022) design and model a renewable-based energy system for a real demo apartment building in Finland to be a positive energy one; the simulation of the integration within the building of such technologies as a PV-thermal system, HP, seasonal thermal storage, and wind turbines is provided.

The authors conclude that in the Nordic conditions, it is difficult to reach the positive energy building level in urban areas if all the building's energy demands (heating, cooling and plug loads) are included, and for it, both on-site and off-site (the building boundary is extended to a virtual boundary outside its physical boundary that allows the addition of more renewable generations) technologies will be needed as well as, if applicable, changing the building's shape that allows more installations on the roof.

Authors evaluate, compared to the building cost, the energy system cost is generally low, i.e., around 1.2–4.3% of the building cost. Similarly, PV modules on all buildings with available roof for it (assumed to be installed on 30% of all available roof space) and switches to HPs of different types (ground source, air source, and hybrid ones) are included in the net zero by 2050 retrofit scenario for the English housing stock (Li, 2022).

It is important to evaluate the integration of rooftop solar technologies within the renovation of Soviet-type MABs; for this, we refer to cases in the Baltic States.

The 5-storey concrete prefabricated panel MAB (built in 1986, 80 apartments) has been renovated in 2017 to realise the near-ZEB renovation pilot. District heating (DH) remains as a heat source. It has been installed: (i) PV panels (55 ones, total peak power of 14 kW); (ii) half of the building has an additional heat source from STCs (50 STCs with a total effective area of 100 m², four 1.5 t storage tanks); and (iii) half of the building has an additional heat source to pre-heat the incoming cold water before the heating sub-station from a passive wastewater (grey water from showers and sinks) heat recovery system (Hamburg, 2020). Ex-ante total renovation costs (excluding costs of the modernisation of apartments), taken from the estimations of the construction companies, were around 860 thousand EUR, of which PV panel costs are around 6% and STC costs around 10.4% (Kuusk & Kalamees, 2015). After renovation: heat energy need – 51 kWh m^{-2} per year, of this STCs provide 7 kWh m^{-2} per year and wastewater heat recovery 15 kWh m^{-2} per year; electricity need – 36 kWh m^{-2} per year, of this PV panels provide 2 kWh m^{-2} per year.

The study (Valančius & Mikucioniene, 2020) analyses in-depth the technical options to install rooftop solar technologies during the renovation of Soviet-type MABs in Lithuania; the buildings are connected to the DH system. Applying a computer simulation tool, the authors conclude that to optimally generate energy in these buildings, the following areas of solar technologies are efficient: 120 m² of flat-plate STCs, balanced along with two 3 m³ storage tanks, and 205 m² (30.6 kW) of PV panels for a 5-storey building (roof area 723 m²); (ii) 70 m² of STCs, balanced along with two 2 m³ storage tanks, and 105 m² (17 kW) of PV panels for a 9-storey building (roof area 545 m²); and (iii) 60 m² of STCs, balanced along with two 2 m³ storage tanks, and 100 m² (16 kW) of PV panels for a 16-storey building (roof area 542 m²). Authors underline ʻFrom an architectural point of view, the roof of a 9-storey multi-apartment building is inconvenient when modelling solar technologies due to large constructional areas for lifts which causes shading'. The completed model shows that one kW of installed PV panels produces 944.85 kWh (5-storey building), 892.8 kWh (9-storey building) and 848.73 kWh (16-storey building) of electricity annually, e.g., there is about 10.7% constituting losses from shading as from structures on the roof of the 16-storey building.

Table 2 presents the simulated solar energy production. Part of the demand for domestic hot water (DHW) preparation in a 16-storey building is covered by HP as well. Considering only the electricity demand of common areas (stairwell lighting and lifts, the latest for 9- and 16-storey buildings), 100% of the demand would be met in the case of 5-storey and 9-storey buildings and around 50% of the demand for 16-storey buildings.

The study by Borodinecs et al. (2024) analyses actual (hourly real) electricity consumption data from 31

dwellings in a typical 5-storey 60-apartment building in Riga. Authors provide the detailed analysis of both household electricity consumption data and household characterising parameters (household size, population, etc.) to predict household load and ensure the optimal design of a MAB-scale PV system. Findings indicate a rooftop PV system on such a building can cover up to 77% of annual electricity consumption (the difference with the results of the Lithuanian study might be explained by the fact that in the previous reference the part of the roof was used for the installation of STCs); the results of the study also provide valuable information for the optimisation of on-site energy storage.

Table 2

Solar energy production in soviet-type multi-apartment buildings: single table for simulation data as from (adapted from Valančius & Mikucioniene, 2020)

Building	Number of occupants	Annual heat production by STCs	Share of DHW preparation, covered by STCs	Annual electricity produced by PV panels	Share of electricity demand, covered by PV panels	Annual electricity still to be supplied by the grid
		MWh	%	MWh	%	MWh
5-storey	140	62.8	60.9	29.980	44.7	37.07
9-storey	160	43.9	43	15.714	15.6	84.93
16-storey	184	37.7	33.7	13.537	9	149.56

The study in Latvia comprises two apartment buildings in the Marupe municipality: (1) a 3-storey MAB counts 4 PV panels (1.32 kWp) and 18 STCs (27 kW, expected annual heat production of 20 MWh). The produced electricity is used to cover electricity consumption in the common areas of the MAB; the produced heat is used for pre-heating of DHW for the needs of all residents (the building is connected to the DH system). (2) The row-house building counts 6 rooftop PV systems, each with 4 PV panels with an individual capacity of 330 W; each PV panel system has its own inverter connected to the inner power grid of the particular section of the building. Thus, the total PV system comprises 24 PV panels with a total capacity of 7.92 kWp. In annual terms, it covers around 30% of annual consumption, and there is net zero electricity supply from the grid in summer months. The produced electricity is used also for the charging of electric vehicles owned by residents of the row houses.

Energy Governance: theoretical approaches and best practices in residential renovation

The European Court of Auditors (ECA, 2026) summarized the core strategic mandates of the European Union, noting that renewable energy developments are vital to achieving the EU's long-term objective of climate neutrality by 2050. To this end, the EU established a target to increase the renewable energy share from 25.4% in 2024 to 42.5% by 2030, projecting that half of all EU citizens could generate approximately 50% of the bloc's renewable energy by 2050. Crucially, the 2022 EU Solar Energy Strategy introduced a political objective binding the EU and its Member States to establish at least one renewables-based energy community in every municipality with a population exceeding 10,000 by 2025 (European Court of Auditors, 2026). Directive (EU) 2018/2001 on the promotion of the use of energy from renewable sources (RED II) legally defines these energy communities as 'legal entities that empower citizens, small businesses and local authorities to produce, manage, share and consume their own energy'. However, the European Court of Auditors' Special Report 10/2026, titled *'Energy communities – Potential yet to be fulfilled',* concluded that the EU failed to meet this target. By January 2025, only 27% of the objective had been realized, primarily because national governments failed to establish the regulatory and administrative conditions necessary to support community development (European Court of Auditors, 2026). Complementing these findings, an Interreg Europe (2026) policy brief emphasized that energy efficiency management barriers in multi-apartment building renovations—such as fragmented ownership and disparate financial capacities—necessitate tailored local governance, targeted technical assistance, and dedicated funding models to overcome the logistical and social hurdles inherent in collective action.

Energy governance is increasingly understood as a multi-level, multi-actor process rather than a purely technical management challenge. Contemporary research emphasizes that achieving climate neutrality requires coordinated action among governments, municipalities, private organizations, financial institutions, and citizens (Björklund et al., 2023). Consequently, energy governance has shifted **from traditional regulatory frameworks toward collaborative models** that integrate policy coordination, stakeholder participation, and institutional capacity across all levels of government. These approaches recognize that successful energy transitions depend on the strategic interplay of regulatory, economic, technological, and social

instruments, rather than on isolated policy measures (Björklund et al., 2023).

The literature highlights that building renovation should be analyzed as **a socio-technical system**, wherein technical solutions interact dynamically with institutional arrangements, financial mechanisms, behavioral factors, and governance structures (McCarthy et al., 2018). Systems thinking, multi-level governance theory, and collaborative governance represent the dominant theoretical perspectives explaining how diverse actors collectively influence energy transition outcomes. These frameworks demonstrate that fragmented responsibilities and weak institutional coordination remain primary barriers to achieving large-scale energy efficiency improvements in the residential building sector (McCarthy et al., 2018; Björklund et al., 2023).

A particularly critical governance perspective concerns multi-owner residential buildings, where renovation initiatives require collective agreement among apartment co-owners. Ownership structures, voting rules, legal responsibilities, and organizational frameworks heavily influence whether energy renovation projects are initiated and successfully executed (Bright & Weatherall, 2017). Research consistently concludes that **institutional and governance arrangements often constitute greater barriers** to progress than technical limitations, particularly within European condominium and apartment buildings (Bright & Weatherall, 2017; McCarthy et al., 2018).

International evidence indicates that the most successful building renovation programs pair regulatory mandates with financial incentives, technical assistance, and robust stakeholder engagement. Rather than relying on a single policy instrument, best practices integrate legislation, subsidies, advisory services, one-stop-shop support structures, digital tools, and long-term governance coordination. Such integrated frameworks substantially increase renovation rates while simultaneously optimizing energy efficiency and fostering public acceptance of renovation initiatives (Björklund et al., 2023).

For multi-family residential buildings, established best practices place additional emphasis on participatory governance and collective decision-making. Studies demonstrate that successful renovation outcomes rely on transparent communication, mutual trust among residents, effective property management, clear institutional mandates, and accessible financial mechanisms. Early stakeholder involvement and coordinated governance mitigate conflicts among apartment owners and significantly improve the implementation rate of deep energy renovation projects. Ultimately, this **positions governance quality as a decisive factor alongside technical and financial variables** (Bright & Weatherall, 2017; McCarthy et al., 2018).

The Triple Governance Dimensions Framework model application

The environmental governance process—spanning sectors such as energy, climate, water and other—is rooted in the effective realization of a cyclical societal decision-making process that encompasses decision preparation, making, execution, implementation, and monitoring. The success of this cycle depends heavily on institutions, formal and informal structures, stakeholder engagement, and collaborative interactions aimed at problem-solving within a particular environmental domain or sector. Drawing from environmental science and management research, as well as development project practices, ther was proposed (Ernsteins et al., 2017, 2024) the generic **Triple Governance Dimensions (TGD) framework.** This model integrates three complementary pillars: governance stakeholders (who), governance content (where/what), and governance instruments (how). Together, these components provide a comprehensive framework for both **analytically examining and structurally framing governance processes.** The TGD framework is grounded in core governance principles operating within a complex, multi-sector social-ecological system (SES), interlinking a multi-actor stakeholder system with an adequate, complementary multi-instrumental system.

The governance content (sectors) dimension covers all thematic areas addressed by environmental governance. Beyond traditional environmental protection and infrastructure sectors - such as biodiversity, water, energy, waste and others - this dimension increasingly incorporates socio-economic sectors to reflect a holistic social-ecological systems approach. This includes fields such as health, education, agriculture, forestry, tourism, and culture, thereby aligning governance with an integrated sustainable development perspective (Ernsteins et al., 2017).

The governance stakeholders (segments) dimension encompasses the entire system of principal actor groupings involved in or influencing the governance process. Five distinct stakeholder segments are identified: the state/national level, municipalities, businesses, society/households, and mediators. The mediator segment - comprising media, formal-nonformal educators, NGOs, and academia - plays a vital role in facilitating communication, knowledge exchange and collaboration across governance segments, sectors, and levels (Ernsteins et al., 2017).

The governance instruments dimension refers to the mechanisms deployed to implement the governance process. These instruments encompass policy and legislation, planning, institutional and administrative measures, economic and financial tools, infrastructure and technology, and communication and collaboration. Together, this is a complementary system for effectively addressing complex governance challenges (Ernsteins et al., 2017).

Presumably, the technical and engineering excellence,

alone cannot solve the residential energy efficiency gap. Successful **thermal renovation requires a dual approach** – also the governance process and structured governance framework are to be studied and potentially elaborated for further application in municipalities to translate climate policies into community-led, solar-integrated building transitions.

Research Aim for this Valmiera municipality energy renovation case study is to analyze how energy governance framework and process cycle and localized driving factors influence the successful implementation of energy-efficient renovations and rooftop solar integration in multi-apartment buildings.

Research Tasks: 1. To conceptualize and apply as analitical frame a three-dimensional energy governance framework complementing stakeholders, institutional sectors, and governance instruments; **2.** To evaluate the entire governance lifecycle, including implementation and post-implementation phases, of building retrofits in Latvia; **3.** To investigate the localized drivers and intermediary structuring in Valmiera municipality case study.

Materials and Methods

The current study particularly focuses on the MAB renovation case with rooftop solar technologies in the Valmiera City municipality, which is one of the most pro-environmental and pro-energy active municipalities in Latvia. The **case study research methodology** has been applied, using complementary research methods: document and database studies, deep semi-structured interviews, and visual observation, thus allowing application of analytical frame of chosen the **tripartite complementary governance dimensions framework** - involvement of relevant stakeholders, understanding related governance sectors, and, finally, all the governance instrument groups that are to be applied.

The energy-efficient renovation of the multi-apartment buildings was analysed in the context of the energy citizenship (ENCI) concept as a part of the EU Horizon project (2021–2024) EnergyProspects (EnergyProspects Project, 2024). As outlined in this EU project, the methodology for gathering comprehensive cases has been formulated to encompass and amalgamate various research interests and methodological needs.

The **case study-based research and development framework** was applied for the chosen non-traditional MAB's energy-efficient renovation case, possessing also in Latvia still quite rare renovation projects with the distinction of the complementary application of rooftop-based solar technologies. MAB is in Latvia's north-eastern Vidzeme region in Valmiera city centre on Riga Street 18 (MAB-RS18). Valmiera county municipality (Valmiera city and rural municipal administrative territories), having developed and introduced several energy governance initiatives and governance, also practical management, instruments.

During energy-efficient MAB renovation case studies, complementary (also eventually integrated) research approaches and methods were used, combining engineering-building work studies and sociological-governance process studies, realised by a set of sociological research methods.

Engineering framing and building process studies context

The overall summary of the MAB energy-efficient renovation work developments and situation in Latvia in general and for the whole territory of Valmiera city municipality and all Valmiera district (rural) municipalities (separate municipalities before the national administrative-territorial reform of 2021) has been realised already during the first phase of the case study research of the EU Horizon project EnergyProspects, which has been already presented in our previous paper (Kudreņickis et al., 2024a).

Besides various results recognised at the first phase of the research, there are to be mentioned that though ~ 60% of building renovation cases are carried out by the MABs which have established a legal management form – a housing association – the municipal housing companies still have a role, if such a municipal company has proven its operational reliability. Also, it was recognised that the installation of renewable energy technologies as an integral part of MAB's complex renovation was a very rare practice. Taking both mentioned aspects into account, it was decided for further studies (second phase) to focus on a realised practice example where rooftop-based solar technologies have been successfully carried out and the coordination role of municipal housing enterprise was comparatively crucial.

During the second phase, currently described for this paper, there was an initial evaluation of the results of the multi-apartment building renovation programme in 2016-2023 – the database (EXCEL sheet) of the national level MAB programme administrating institution ALTUM (JSC Development Finance Institution ALTUM) (ALTUM, 2025). The database has detailed information for all and each project in Latvia, both completed and ongoing. The summarised information from the database was prepared and could be seen as additional value of the presented study. The analysed MAB-RS18 case renovation example was submitted for the national competition 'Most Energy-Efficient Building in Latvia 2020' and received:

- The innovation award by the MABs' national-level renovation programme administrator ALTUM,
- A Certificate of Appreciation from the competition organisers for installing STCs during the renovation.

The governance process of socio-ecological system changes studies context

Further on, there were studies done of the MAB renovation building works processes in the Valmiera municipality and, especially, its municipal enterprise 'Valmiera Housekeeper' Ltd (PSIA *'Valmieras namsaimnieks'* in Latvian), working with contracted

MAB's everyday management and exactly with renovation projects if assigned and, subsequently, cooperating with MAB apartment owners and owners' associations.

The case study research complementarily included the following set of methods:

- all related document studies (national and municipal legal, planning, administrative, etc., documents, including also project-based documentation).
- Already mentioned and various other available regional and local database analyses.
- Six deep semi-structured interviews with the main MAB renovation case content-based stakeholders at the municipal level – 3 specialists from various related municipal administration levels and departments, 2 related specialists (including MAB-RS18 project manager) from municipal enterprise 'Valmiera Housekeeper', as well as MAB-RS18 flat-owners council chairman (house elder, also initiator of the project). The results of the interviews were complementary to those of document studies and the database analysis.

Besides MAB-RS18 flat-owners and their council, the project case key management stakeholder was Valmiera municipal enterprise 'Valmiera Housekeeper', as all the MAB-RS18 case project process cycle was planned and realised by this municipal enterprise – starting from the preparatory stage; design and development stage, including all stakeholders' and contractors' (building company and loan-issuing bank) involvement; and, further on, also coordination work during the implementation management stage.

In 2001 the municipality of Valmiera city decided to establish a limited liability company to be 100% owned by the municipality itself, and, besides several minor private housekeeping companies in the market, it is now the leading MAB management company in Valmiera. The company now manages 94 multi-apartment residential buildings; 4 multi-apartment residential buildings belonging to the municipality, as those cannot be transferred for privatisation; and, finally, also 14 multi-apartment residential buildings where apartment owners still have not chosen a housing management company. Until now, the company has managed complex renovation work in the 54 multi-apartment buildings of the city, but 5 buildings are partially renovated.

Direct information as well as the combination of information allowed the study of the following key research questions (in general, prescribed for all case studies of all partner countries of the EnergyProspects Project (EnergyProspects Project, 2021–2024) related to energy-efficient renovation of MABs and the perspective of STCs, e.g., rooftop solar panel project extensions – questions on basic **conditioning and driving factors and intermediation**.

The central research question: Why and under which conditions do energy-efficient MAB renovation cases achieve their goal(s) and make achievements towards the democratisation of the energy system? Relatedly, the prescribed interview questionnaire for all the case studies was elaborated in the EnergyProspects Project, having additional expansion on triple dimensions governance framework and Latvia case specifics.

Results and Discussion

Case study research was performed for the one MAB renovation case, but non-traditionally in Latvia, also complementary doing it with the installation of solar thermal panels – the MAB-RS18 case – focusing on renovation works and, especially, on governance processes and frames.

1. MAB renovation: engineering framing and building process context

The silicate brick 3-storey (with underground storey) MAB located in the Valmiera township municipality centre (120 km north-east from the capital city Riga) on Riga Street 18 (MAB-RS18) was built in 1960 and comprises 16 apartments with a total area of 1374 m² and 3 commercial areas.

An energy audit and efficiency assessments of MAB were done in 2013, and its report and forecasts are available, providing information about the building's energy efficiency for the further project design.

The components of preparing the renovation project application shall include the calculated energy efficiency assessment of the building, which covers the following main energy consumption areas, such as heating and DHW preparation. Regarding heating, evaluation includes the building's heating system, an analysis of heat loss, and potential improvements to reduce energy consumption during the colder months. For DHW preparation, the efficiency of DHW production systems is evaluated, and elaborated proposals for improvements, including the installation of STCs, are made.

These areas are thoroughly analysed to provide accurate forecasts of possible improvements that could reduce overall energy consumption and ensure more sustainable building operations. Additionally, various assessments and forecasts of energy efficiency improvements are made, considering the latest technologies and solutions. Furthermore, a certified construction evaluation is included, which is a crucial part to ensure that the proposed changes comply with all technical requirements and regulations. This evaluation provides a well-founded analysis of the planned actions, ensuring that the building meets energy efficiency standards and will be economically viable in the long term.

The energy audit also includes the cooling system (evaluation of climate control systems, determining energy consumption during the cooling season and possible improvements) and the mechanical ventilation system (the efficiency of the building's ventilation system, evaluating energy consumption and opportunities to improve air quality while reducing energy loss); however, for the particular building in these categories, there is no energy consumption.

However, an appropriately assessed and designed renovation project proposal has been dormant for several years, as the MAB-RS18 house case, due to its specific legal and administrative status conditions, was not directly corresponding to EU co-financing requirements, being established by the Cabinet of Ministers in Latvia.

2. MAB renovation: solar thermal panels

The MAB, located at Riga Street 18 in Valmiera city in 2018, has realised a successful self-initiated project for building renovation and improving its energy efficiency, combining it with **the simultaneous installation of rooftop STCs**. The initiative was led by the building residents' council chairman (house elder) and approved by the apartment owners. Thus, this is a sustainable and environmentally friendly pioneering example of combining such a complex house upgrade with MAB-scale energy self-production.

Before the renovation of the MAB, the energy efficiency performance for heating was higher than the maximum threshold of an 'E' class building (125 kWh m^{-2}), as stated by Latvia's national legislation (Cabinet of Ministers, 2021). As the result of the project, high specific heat energy saving is reached, contributing to climate change mitigation by saving 22.85 CO_2 eq. tonnes (SIA Valmieras Namsaimnieks, n.d.). According to the provisional energy performance certificate, the building's energy efficiency rating is 89.09 kWh/m^2 per year. In its turn, 2024 consumption data indicate total heat consumption, supplied from the DH system, is around 74 kWh m^{-2}, of which 67 kWh m^{-2} is for heating and only 7 kWh m^{-2} is for hot water preparation. Thus, the building now is close to the 'B' class (maximum threshold for thermal energy consumption for heating is 60 kWh m^{-2}). More details regarding building energy performance are presented in Table 3 below.

Older apartment buildings not yet renovated require not only facade insulation but also internal system upgrades using various infrastructure and engineering solutions. Thus, the renovation was complex, including house wall, basement, and attic insulation; foundation's hydro-insulation; window, door, and roof replacement; water and heating system reconstruction; ventilation system improvements; electrical system upgrades; and lightning protection installation. An important factor is the implementation of an internal heat supply system with an independent connection to each apartment and hydraulic balancing valves - this activity was also part of the building upgrade project. The summary on technical details of upgrade activities is provided in (National Competition 'Energoefektīvākā ēka Latvijā', n.d.).

Table 3

Riga Street 18 Building energy performance

Indicators/indices	Units of measurement	ALTUM before renovation	Target indices by energy certificate
1.Energy efficiency performance	kWh m^{-2} per year	200.7	137.6
1.1 for heating	kWh m^{-2} per year	139.5	79.3
1.2 for hot water preparation	kWh m^{-2} per year	61.2	58.3
2. Heat loss factor of the buildings enclosing structures (H_t)	W K^{-1}	1798	737
3. Heat loss factor of the building ventilation (H_{ve})	W K^{-1}	460	418
4.Air exchange rate	1 h^{-1}	0.55	0.5
5. Internal heat gains	kWh m^{-2} per heating period	38.9	38.9
6.Solar heat gains	kWh m^{-2} per heating period	16.6	12.8

Thus, inclusion in the project of the rooftop STCs was bringing a rather small addition to the project's total costs. Although installing rooftop solar energy facilities requires additional investment, it provides long-term financial savings for residents.

Nevertheless, during the EU funding period of 2013-2020, Riga Street 18 building is one of only two MABs in Latvia where residents have used ERDF co-financed MABs' energy efficiency improvement programme.

The project's total financial volume is 266,856 thousand EUR, of which ERDF co-financing had been planned for 50% (133,428 thousand EUR). The decision on granting ERDF co-financing was done on 23.05.2018. The upgrade works were performed from 05.07. to 14.12.2018. After completion of the project, ALTUM evaluated the eligibility of costs and, on 18.04.2019, approved the grant of 132,572 thousand EUR (ALTUM, 2025). Thus, the project had been well implemented along with the planned course. The co-financing was also provided by the Valmiera municipality budget sources (co-funding is available up to 20,000 EUR for renovation and other works in MABs' housing and courtyards upgrade).

The total capacity of installed rooftop solar thermal collectors is 14.74 kW. The solar system operates for 6-7 months per year (April–October), covering 60-70% of the annual energy demand for water heating. However, there was also the indicated imperfection in the initial project – namely, the building's roof load capacity was not properly assessed in the project; as a result, cracks have formed in the roof due to the excessive load from the installed solar thermal collectors.

Most renovation building tenders for MAB are won by

building companies which develop standard renovation projects sometimes without conducting on-site inspections. To mitigate this, the 'Valmiera Housekeeper' has introduced a new practice: hiring an additional engineer to verify project accuracy and correct errors before final approval.

3. MAB renovation: governance process and framework requirement

All inhabitants took part in the preparation process and making a joint decision (majority decision-making) to collaborate jointly to prepare a project proposal for energy renovation of their house and using solar panels for water heating – this was done in 2013, but the building project was accepted by the municipal building department in 2014. Then they were contacting their house management organisation – the municipal enterprise 'Valmiera Housekeeper' – to proceed with all necessary steps to get co-funding from both the Valmiera municipality (up to 20,000 EUR, bylaw of the municipality) and the national housing energy renovation support/co-funding financial institution Altum (with ERDF funding).

Due to the legal status, etc., specifics of their building and some limitations by national legal documents (related regulations of the Cabinet of Ministers of the Republic of Latvia), this was initially not possible; even the community of apartment owners of this house have managed to stepwise gather their own co-funding for any works on/with their building. After certain changes of the mentioned regulations in 2017, there finally appeared a possibility to re-activate their project proposal, and after a whole range of preparation procedures, organised by their communal services provider municipal enterprise 'Valmiera Housekeeper', the renovation works started in 2018.

The legal status of all inhabitants of this building is the community of apartment owners, and there is special national law for this. The general community of apartment owners of this apartment building have not decided to establish a particular association of apartment owners as a next and legal status, but instead they have agreed (long ago) to be participants of the municipal enterprise 'Valmiera Housekeeper', which has agreements with about 1/2 of multi-apartment buildings in Valmiera town to organise energy supply and other household services.

As said in the interview – the main reason to establish an association of apartment owners is the non-satisfactory work (also attitude and communication with inhabitants) of the mentioned municipal enterprise, which was not the case for this situation, even though there are issues which apartment owners would like to be solved better, incl. having more communication and housing parameters monitoring.

This collective case relates to direct energy consumption (energy saving) and decentralised energy production building projects. The case has been implemented in an urban area. **The three aims were**:

1. get energy savings and thus get economic benefits,
2. increase heat energy self-production and greater local community ownership of a decentralised energy system as the energy use and local independence in the preparation of hot water for inhabitants.
3. increase of inhabitant's self-awareness and being proud to be part of a sustainably thinking community.

Initially there was some scepticism on the necessity of solar panels since limited info was available around; also, municipal service provider companies have had no experience with solar panels as well as not clear info/background to get co-funding.

The general situation with the dwelling was comparatively negative (energy supply system, visual aspects of the dwelling, house yard qualities, etc.), but there were no real initiatives and active participation to start to work with these housing problems – in this situation, initiative was taken by the house council chairperson (contact person of this questionnaire – having an engineering education and working for Valmiera municipal water company). Coming with his ideas/proposals and being supported by some other persons from the council. Stepwise, most of the inhabitants were informed and negotiated, and finally, the majority agreed – all inhabitants are satisfied with the project results.

The decisions by the community of apartment owners of the building were done by consensual decision as majority decision-making.

The first initiative was taken by two individual persons, being members of the House Council (to be elected) and expressing their view on the bad situation with the inner and outer status of the common dwelling. This was followed by individual discussions, particularly done by MAB older members (members of the House Council) of each staircase of the dwelling with their flat owners. Finally, at the joint meeting (there were first several meetings) of the community of apartment owners, it was decided to go for the project – the majority were supporting this decision, a few persons had no pros/cons, and a few were worried about long-term investments.

Two persons from the House Council, understanding the potential of sun panels to reduce inhabitants' expenses and being environmentally friendly, and knowing that exactly one side of the roof is located towards the south, came with a proposal to include solar panels in the project.

3.1. Governance framework instruments dimension

In the MAB renovation process, there could be recognised all the six various groups of instruments being needed so that the case can achieve its goals:

*a) **Institutional and administration instruments***

Structuration and organisation of the functioning of the case: entities composing the case, legal status, coordination of the various activities (capacity building – energy production retail, etc.), negotiating with administrative authorities, etc. – The main/key player for this case – Municipal company 'Valmiera Housekeeper' – all initial audits and project works,

also financial management and building works, were done via this company in principal partnership with RS-18 house flat owners.

Including also - ***Networking and coordination intermediation*** with actors that present similarities with the case, enabling cooperation between actors, building and managing networks of multiple stakeholders, and exchange of knowledge and visions – for knowledge/expertise exchange again, company 'Valmiera Housekeeper'

b) ***Financial and economic instruments***

Capitalisation and resource mobilisation are required for the case to build up and sustain/grow – crediting bank, company 'Valmiera Housekeeper', co-funding by municipality and national agency Altum.

c) ***Communication complementary instruments***

Communication activities making the case public: consult demand-side for implementation, mediation activities, and put suppliers in contact with end users – very limited, as this case was quite closed as just a particular building activity (municipal public relations department and company 'Valmiera Housekeeper').

Including also - ***Technical and scientific intermediation***. Technical and scientific expertise activities for concretising the project: ICT conception, planners, architects, PV or wind power specialists, monitoring of the project, facilitating experimentation and pilots, facilitating/supporting adoption and implementation of innovations, etc. - as a technically based project – auditors, architects/planners, solar panel experts.

d) ***Policy and legal-regulatory instruments***

There was legal/regulatory intermediation in terms of project proposal dependency on governmental legal acts and regulations, particularly on co-funding possibilities. So, also, the national cabinet of ministers is to be mentioned here.

e) ***Planning instruments***

Here is to be mentioned both: mandatory/statutory planning documents (not only at the national but also, importantly, at the local level); voluntary thematic documents such as municipal climate, energy planning, etc., being interlinked with related financial and admin structures, etc.

f) ***Infrastructure and technology instruments***

Also, the key instruments group being studied in detail to some extent by all stakeholder groups and being enough carefully monitored during the project management process and afterwords.

3.2. Governance framework sectors and stakeholder's dimensions

The sector dimension distinguishes four closely connected fields, also being parts of building renovation project and process: environmental-energy, socio-economic, technological-housing and administrative-institutional. While Latvia has achieved substantial milestones regarding legal frameworks and technological integration, progress surrounding economic affordability and institutional implementation capacity remains fragmented. Households navigate these structural dimensions simultaneously. Subsequently, the role of stakeholders, especially, intermediaries are high.

There are to be recognised several groups of stakeholders, that were part of this renovation project, and actually the full set of all 5 stakeholder's (actors) groupings.

a) ***Governmental actors*** (i.e., intermediaries created by government): agencies that manage programmes with loans and technical assistance); governmental agency ALTUM was commissioned for managing programmes with loans (EU EBRD).

b) ***Municipal actors.*** *V*arious involved municipal departments and institutions, and, especially, the main/key player for this case again shall be mentioned also – the municipal company 'Valmiera Housekeeper' – all initial audits, project works, financial management, and building works were done via this company. Also, the municipal building department – to approve building projects.

c) ***Community/households actors.*** Individual flat owners of the MAB in Rigas street 18 and their representation being in regular communication process with all stakeholders around.

d) ***Business actors.*** For knowledge-intensive business services (banks who offer loans, mortgages, consultants, business lawyers, etc.) - bank for getting a loan and building company, as well as various materials and constructions suppliers.

e) ***Mediators segment actors:***

- ***Media and other information*** stakeholders – limited involvement for current project, but important for long time period renovation process.
- ***Education actors - intermediaries*** (independent research and education organisations/networks) – very limited engagement for this project, but with certain function in long-time municipal efforts for renovation.
- ***Non-government actors - intermediaries.*** Sector organisations (civil society umbrella organisations, transition towns) – non-existent here for this sector. Locally there are no environmental/energy NGOs, nor national energy NGO associations.
- ***Academia-knowledge institutions*** – very limited involvement for current project, but growing role ahead as having university college in the town.
- also, could be mentioned ***Intercessors*** (Individuals who talk to different actors with the aim of learning about possibilities for collective action, cooperation, partnerships, and institutional change by learning about the beliefs, material interests, mandates, responsibilities, capabilities and resources of specific actors) – several organisations/persons could be recognised here:

1- Inner processes within dwelling – each staircase leader and House Council Chairman was speaking one by one to all flat owners and often several times.

2- Outer processes – looking outside for consultancies: visiting specialised solar/heating etc. expositions, meeting solar panel experts (planners, builders), heat supply experts.

f) ***Other: energy auditor*** (individual expert) which provides the decision on the project. Building company, which did the project, included the necessity for communication with flat owners as flats were partially closed during the building process.

3.3. Driving factors for MAB renovation governance

When looking for the driving factors for the MAB cases, such as type of energy citizenship and initiating changes and step-wise achieving their goals, making particular achievements towards both democratisation and particularly the practical change of the energy system, the following four factors should be easily mentioned in relation to multi-apartment buildings, as from experience of this particular case.

The first basic factor - ***motivation and preparedness.*** Most important initially is the interest and perceived need for change for those with limited standard living conditions for multi-apartment building flat owners, living in almost never-renovated Soviet-era multi-apartment buildings, being in the situation of slowly degrading those dwellings further. Also, there's the issue of energy resource expense reduction, obviously. Motivation is to be followed by readiness to act individually and as MAB inhabitants' group.

Second factor – ***co-funding availability and applicability.*** Sure, to be mentioned is availability of main/various co-funding possibilities at the national level (actually, ERDF funding) and possibly co-funding at the local level. Also, legal conditions for that funding applicability to the existent types/situations of dwellings.

Third and main success driving factor – ***municipal intermediary management.*** Availability of such municipal management company 'Valmiera Housekeeper' is taking most of the MAB energy renovation project preparation and management load. There are also similar but private companies in the town, taking care of their MABs and renovation works if inhabitants' interest appears or is co-created.

Fourth driving factor – ***environmental/climate-friendly awareness.*** As in the case of this MAB, but also in general, there are certainly to be recognised the growing interest and understanding of changing socio-economic conditions for quality life in MAB, even if it may not be first as environmental/climate awareness. These processes are to be widely/selectively/actively facilitated from national/local management levels, including more effective demonstration of such success cases as this MAB-RS18 case.

4. MAB renovation: internationalization context

Renovation of multi-apartment buildings in Latvia, co-financed by EU funds (ERDF), started in 2009. Within two planning periods (2007-2013 and 2014-2020), around 1400 multi-apartment buildings are renovated, of which 620 buildings (22,8 thousand apartments, around 4% of Latvia's total apartment number) are in the 2016-2024 period. After renovation, the 'B' energy efficiency class is achieved on average.

Findings (Kazukauskas & Li, 2024; Kudreņickis et al., 2024a) indicate that upgrading existing MABs to meet 'B' class energy performance in the Baltic states requires investment and a long-time payback period, and the internal rate can even be negative; the same is indicated by (Galvin, 2024b; Hirvonen et al., 2022). Thus, such renovation in Latvia's economic current conditions is hardly possible without the public/EU (ERDF) grant part.

In the first phase (Kudreņickis et al., 2024a) of the EnergyProspects project, energy-efficient MAB renovations in Latvia have been analysed, and the results of the 2016-2024 national programme of MAB renovations have been analysed, providing in-depth analysis of energy savings and related costs. In general, the energy efficiency improvement (improvement of specific thermal energy consumption after renovation project implementation) on average is high, 60+%; however, it is achieved with a high specific cost per saved kWh and a long (around 30 years) payback time. The specific saving costs depend on the MAB type (construction series, number of apartments); particularly, the specific saving costs for small-scale MABs (3-9 apartments) are significantly higher than average ones; thus, the number of renovated small MABs within the national programme was very low. These significantly higher specific costs in the case of small MABs (3-9 apartments) renovations require for these buildings the rooftop solar facilities as the instrument to increase the economic viability of the renovation project and must be evaluated first.

Also, it was found that ~60% of MAB renovations have been done by flat owners established housing associations, as opposed to the municipal housing enterprises' led MAB renovation cases still being in the game too. Various installations of renewable energy technologies complementary to MAB renovation are still rare in practice. Both these situations confirmed our interest in the second phase of the study focusing in detail on a practical example where both aspects have been successfully carried out.

The justification of the high energy efficiency investments must be found. One of the justifications for high energy efficiency investments is to consider additional benefits, such as better comfort, improved health conditions and, due to it, avoided health costs and improvement of labour productivity, or the general promotion of economics bringing an overall positive impact on household budgets. In research studies during the last years, these energy efficiency benefits are actively discussed.

For instance, the average price of a CO_2 allowance (one tonne) in the EU Emission Trading System auctioned for Latvia in 2023 was 83.5 EUR (Ministry of Climate and Energy of the Republic of Latvia, 2023), and thus the total annual price of CO_2 mitigated within the project can be evaluated at around 2 thousand EUR, which for 15-year renovation measures' technical lifetime contributes around 11% of project costs. The CO_2 mitigation impact is limited by the high already existing renewables share in the district heating system.

Regarding health impact, the study (Chatterjee & Urge-Vorsatz, 2021) has evaluated that a German worker can gain 5.2 productive days a year, while a Hungarian worker can gain 2.2 days, by avoiding sick days after living in high-efficiency buildings. Applying the average figure of 3.7 days per Latvia and 130-295 EUR cost per day (Preiss & Klotz, 2008), it can be calculated as 480-1090 EUR annual savings for workers. Cautiously considering 30 working-age residents in the building, this sum corresponds to 5.4-12.3% of the project costs.

However, all these are indirect benefits. In its turn, the addition of rooftop solar technologies can provide a direct positive impact on the MAB upgrade project.

Conclusions

MAB renovation case documentation and building and governance process with rooftop solar technologies in Valmiera was studied, including its **governance process cycle and framework preconditions and driving factors,** also in the general context of national and local energy governance.

1. Rooftop solar technologies and aspects of their installation are rather actively studied in Baltic states' research, as we have shown in literature analysis; however, there is the gap between scientific research and practical implementation and especially for rooftop solar PV technologies in Latvia.

2. This gap shows that MAB resident communities themselves are unlikely to be sufficient drivers for the implementation of rooftop solar technologies. For such development a coordinated facilitating framework is needed at both state and municipal levels.

3. In the currently ongoing MABs renovation programme within Latvia's EU Cohesion Policy Programme for the 2021-2027 planning period, increased ERDF support intensity (above general support intensity) has been planned to be provided for rooftop RES technologies. The expected national support programme, financed by the Modernisation Fund, which will provide support for zero-emission RES technologies in both MABs and energy communities, can be a significant facilitator.

4. At the municipal level, the support provided by municipalities for increasing the energy efficiency of MABs is important. However, the application of real estate discounts for rooftop solar technologies is a rare practice (not available in the Valmiera municipality either) or applies to solar PV, not solar thermal panels.

5. The rooftop solar technologies can provide a significant share of thermal energy for domestic hot water preparation and electricity energy consumed by the MAB residents, 50+% depending on the type of MAB (number of floors, number of apartments, etc.).

6. The literature overview shows the most attention is paid to solar PV panels. The interest in solar PV panels, in a great sense, is caused by the development of energy communities. In its turn, despite the range of valuable studies that are in place, the STCs seem to be 'undeservedly forgotten'. The optimal combination of both thermal collectors and PV panels may maximise the benefits.

7. However, the studies (Galvin, 2022; Rehman et al., 2022) also call for being rational and installing the on-site rooftop technologies on a scale which is optimal from the technical and economic points of view – namely, the objective 'net zero energy building' shall not be self-interest due to the fact that physically the electricity exchange with the power grid will take place in dominating cases. The gap between 'optimal self-production' and zero energy building' is rational to be covered by the overall decarbonisation of the power supply system, including that residents might also be members of the renewable energy community owing/operating off-site facilities.

8. Analysed Valmiera case study included complex multi-apartment building renovation measures together with the installation of rooftop solar thermal collectors (14.74 kW), significantly improving building energy performance and reducing thermal energy consumption and CO_2 emissions.

The case confirms that rooftop solar technologies can provide an important contribution to domestic hot water preparation, covering approximately 60–70% of annual hot water energy demand during the operating season. However, the up-to-now (very) rare deployment of rooftop solar technologies in Latvia's MABs, compared to the solar PV panels boom in single-family buildings, shows the imperfections also in national-level governance instruments.

9. The mainstreaming of solar energy in MABs must be part of the overall national strategy for both mainstreaming renewable energy in buildings in general and the national buildings' renovation plan. In any case the target shall be met by the interaction of top-down (national to municipal) and bottom-up (starting with local champions) initiatives.

10. For the MABs energy renovation process (project) there shall be built and implemented necessary **energy efficient renovation governance framework,** to be potentially constructed by the complementary triple governance dimensions framework model, applied here as analytical governance process studies tool, and, subsequently, these dimensions can be seen as the energy renovation process success **preconditions.**

10.1. **Governance stakeholders' dimension precondition.** The set of all stakeholders' groupings (governance segments) to be involved are house inhabitants/association, municipality, municipal housekeeping service-project management company, and, of course, also international-national funding institutions. Additionally, there shall be stressed the role of the last stakeholders grouping of mediators - all four local/regional mediators (media, educators, NGOS's, science-knowledge institutions-experts) as for this particular renovation case pre- and up to post-project facilitation, but also, generally, for the whole municipal energy renovation development process communication (information, education-training, participation, pro-environmental/climate behavior).

10.2. **Governance content dimension precondition.** One of the reasons for the municipalities and state's limited renovation cases success rate has been that the other multiple thematic sectoral benefits provided by energy renovation and also rooftop solar technologies are not fully recognized and utilised. Besides general social-ecological systems approach application, there are different particular sub-sectors where additional benefits can be achieved.

10.3. **Governance instruments dimension precondition.** The whole set of governance instruments established and to be applied in complementarity manor – from national legislation and further on local municipal policy and legal bylaws, planning documents and process instruments, economic-financial, also infrastructure-technological, particularly, institutional-administration instruments, and finally the communication instruments. All parties involved are stressing the crucial role of established **communication processes and instruments,** and further **collaborative approach** development.

11. From the experience of this particular case, **critical localized driving factors** were identified also. The first initial and basic factor - motivation and preparedness. Second factor – co-funding availability and applicability. Third and main success driving factor – municipal intermediary management. Fourth driving factor – stepwise growing environmental-climate-friendly awareness.

In the project practice it means: the strategic availability
of European Regional Development Fund (ERDF) and municipal co-funding, active resident participation, localized household leadership, and a robust municipal intermediary management system - exemplified by the municipal property management enterprise 'Valmieras Namsaimnieks' (Valmiera Housekeeper).

12. Technical and engineering excellence alone cannot solve the residential energy efficiency gap. Successful multi-apartment building renovations require a **complete, lifecycle-based governance process** (governance process cycle incl. consecutive initial situation-system analysis, followed by policy design and planning, management and monitoring, even also post-project monitoring and management) **structured by triple governance dimensions framework** of governance stakeholders, governance content and governance instruments, municipalities can translate climate policies into community-led, solar-integrated building transitions.

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WATER RESOUCE AND AGRICULTURAL GOVERNANCE ARRANGEMENTS AND HARMONISATION IN LATVIA: TOWARDS IMPERATIVE POLICY COHERENCE AND PRACTICE IMPLEMENTATION

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Abstract
This study assesses policy arrangements and implementation practices related to water resources and agricultural governance developments in Latvia, focusing on the agriculture-water governance framework supporting nature-based water retention and general policy coherence. The research combines analysis of national policy and legal frameworks with a case study of the Dviete River basin, a floodplain landscape characterised by seasonal flooding, intensive agriculture, and Natura 2000 protected areas. The assessment comprised two stages: (1) top-down approach as a multi-sectoral, multi-level governance analysis within the EU Horizon OPTAIN project framework and (2) bottom-up approach as a multi-stakeholder assessment of local/regional governance, and both stage studies were realised at all governance levels and in the Dviete River basin. Case studies research included document studies, visual evaluations, stakeholder mapping and a deep semi-structured stakeholder interview. Interviews were conducted in two stages with altogether 39 representatives of key policy sectors and all governance levels from the public environmental/nature protection, water and agriculture sectors, municipalities, entrepreneurs/farmers, NGOs and others. Existing policies were considered inadequate, and respondents emphasised insufficient cooperation among all main stakeholders mentioned, alongside administrative complexity, limited cost-effectiveness, weak communication, voluntary implementation, and weak control systems. Key governance gaps included fragmented legislation, limited administrative capacity, inadequate funding, insufficient technical support, and low awareness. Effective implementation of water retention and general water-agricultural harmonisation towards policy coherence in Latvia is constrained less by the legislation limitations than by fragmented governance – weak cross-sectoral coordination, insufficient stakeholder collaboration, and poor integration of complementary governance instruments across governance levels.
Keywords: water governance, policy coherence, cross-sectoral collaboration, agricultural governance.

Introduction

In the European Union (EU), water resource governance is determined by a complex set of policies that involve both environmental and agricultural areas. These policies establish both regulatory and economic instruments. The Water Framework Directive (2000/60/EC) (WFD) (European Parliament & Council of the European Union, 2000), the Nitrates Directive (91/676/EEC) (Council of the European Union, 2026), the Common Agricultural Policy (CAP), and the Floods Directive provide a broad regulatory structure; however, research indicates (Platjouw et al., 2023; Nilsson et al., 2012; Pereira Dos Santos et al., 2025) that significant challenges persist in implementation, particularly regarding policy coherence across policy sectors and governance levels. Policy coherence between different sectors is one of the most important issues in water and agricultural management. Studies emphasise that this coherence should be assessed not only between water policy instruments but also between water, biodiversity, and agricultural sectorial policies (Platjouw et al., 2023) and an even wider list of governance sectors directly and indirectly involved or to be involved, particularly environmental sectors and climate adaptation governance (cross) sectors (Ernsteins et al., 2025). However, in practice, potential inconsistencies between different directives and policy instruments still exist. For example, while the Nitrates Directive contributes to the WFD objective of preventing the deterioration of water bodies, its objectives do not always fully align with the WFD's objectives of achieving a satisfactory ecological status for water bodies (European Commission, 2025).

Policy coherence across policy areas is one of the major challenges in water and agricultural governance. The OECD (2025) defines policy coherence as 'the systematic promotion of mutually reinforcing policy actions across government departments and agencies, creating synergies towards achieving the agreed objectives'. This approach means that policy instruments in different sectors should be mutually coordinated and aimed at achieving common policy objectives. Furthermore, this definition suggests that coordinating policy instruments across sectors is essential for achieving common policy objectives. However, achieving policy coherence is often difficult because of conflicting political policies, designs and stakeholders' interests and the way institutions are divided across different policy areas (Nilsson et al., 2012).

Agricultural policy significantly influences the quality and availability of water resources. The effectiveness of water resource management relies on the alignment of water policy instruments with agricultural policies, a basic relationship again highlighted by the OECD (2025). CAP significantly impacts agricultural practices across the EU—yet a recent study (Platjouw et al., 2023) indicates that agricultural subsidy systems may, in certain cases, undermine environmental goals. The financial components of the CAP may obstruct the objectives of the WFD and the Nitrates Directive.

Although the 2023–2027 CAP places greater emphasis on environmental sustainability, recent research (Pereira Dos Santos et al., 2025) indicates that direct support for river restoration remains limited. Existing

eco-schemes and agri-environmental measures provide only partial support, while many restoration measures remain underfunded, lack a coherent EU-wide approach, and are insufficiently aligned with broader freshwater restoration objectives.

The coordination of institutions is a critical determinant of policy effectiveness. The effectiveness of policy implementation is closely related to policy capacity, which Wu et al. (2017) define as 'the competencies and capabilities important to policymaking'. Furthermore, policy capacity encompasses the analytical, operational, and political skills needed to create and implement policies at different levels of government.

Furthermore, the importance of multi-stakeholder governance and stakeholder engagement is growing, alongside existing regulatory frameworks. Research suggests that addressing complex environmental issues requires the active involvement and cooperation of various stakeholders (Nilsson, 2012; Nesheim et al., 2021; Glavan et al., 2022). Even environmental NGOs have a long-standing history and well-developed practices, including also lobbying for environmental policies in the EU and nation-states; the establishment of multi-stakeholder platforms is now getting a new wave in the rise, thereby actively facilitating dialogue among institutions, researchers, farmers, and other relevant parties. These platforms serve to integrate scientific understanding with local expertise, consequently fostering the creation of solutions tailored to the unique conditions of a given territory. However, EU legislation supports, but does not prescribe, specific participatory mechanisms but rather requires Member States to ensure public participation, resulting in opportunities for local actors to influence policymaking.

Environmental governance research emphasises that effective policy implementation depends not only on regulatory frameworks but also on the entire range of instruments, particularly governance structures and stakeholder interactions. In this context, a generic triple governance dimensions framework model was proposed (Ernsteins et al., 2017), consisting of three mutually complementary systems of governance dimensions: governance stakeholders (who), governance content/sectors (doing what), and governance instruments/processes (how), all interacting during an environmental governance process cycle – these triple dimensions altogether form an integrated governance system frame for both analysing existent governance processes and framing within complex socio-ecological systems, but first of all, serving/building a governance framework for decision-makers and practitioners.

Governance sectors (content/domains) refer to the environmental thematic areas addressed within environmental governance, which increasingly extend beyond traditional environmental pollution and infrastructure, biodiversity/nature and resource protection and rational use sectors to non-traditional environmental health, communication and climate change governance sectors. Furthermore, there are integrated linkages with socio-economic sectors (e.g., agriculture, forestry, tourism, culture) within a broader sustainable development governance perspective.

Governance stakeholder groups refer to the main societal actors involved in or influencing environmental governance, etc. According to Ernsteins et al. (2017), this framework identifies five stakeholder segments: the state, municipalities, businesses, general society/households, and four complementary mediator groups (media, educators, NGOs, and academia), which facilitate stakeholder and governance subsystem interaction, information and knowledge exchange, participation, and pro-environmental behaviour at local, regional, and national levels.

Environmental governance also integrated water resource governance/management (IWRM) uses governance instruments, as the policy and implementation tools and methods applied to put governance into management practice. These instruments comprise a spectrum of interrelated elements intended to address the institutional, socio-economic, and technical facets of governance. The complementary governance instrumental framework includes policy & legislation, planning, institutional & administrative, economic & financial, infrastructure & technology, and communication & collaboration instrument groupings (Ernsteins et al., 2017).

Effective governance, therefore, requires both horizontal integration between sectors and vertical integration across governance levels, supported by active involvement of multiple stakeholder groups, possessing various instrumental possibilities. Collaborative governance and stakeholder communication play an essential role in bridging science, policy, and practice and supporting sustainable environmental decision-making (Ernsteins et al., 2017; Nesheim et al., 2021).

The findings of policy and document analysis confirm that in Latvia water resource governance takes place at multiple levels stipulated by national laws, Cabinet of Ministers regulations and policy planning documents; even this governance is not fully vertically integrated (Ernsteins et al., 2025).

The Water Management Law introduces an integrated approach to water resources governance based on the river basin management principle (Parliament of the Republic of Latvia, 2002). In turn, Cabinet Regulation No. 834 sets out specific requirements for reducing pollution caused by agriculture, including restrictions on fertiliser use and requirements for the preparation of fertiliser plans (Cabinet of Ministers, 2014).

Latvia employs various, also economic, instruments, alongside regulatory ones, exemplified by the Common Agricultural Policy Strategic Plan 2023–2027, which allocates funds for agri-environmental initiatives and sustainable water resource management (Ministry of Agriculture, 2022). Nevertheless, mirroring challenges faced by other European nations,

the efficacy of policy instruments in Latvia may be constrained by sectoral fragmentation, inadequate data integration, and institutional coordination deficiencies (European Commission, 2025).

The initial examination of environmental governance within the Dviete River basin (Ernsteins et al., 2025) as a case study research area chosen for the current study identified several structural challenges that impede sustainable water resources and landscape management. Research suggests that the water basin is subject to various environmental pressures, including pollution stemming from wastewater, intensive agriculture, seasonal flooding, and inadequate institutional capacity for the management of the Natura 2000 site.

Researchers emphasise the need for a more integrated and adaptable governance framework (Ernsteins et al., 2025); such a framework should strengthen collaboration across different sectors, improve communication and stakeholder involvement, and support grassroots governance initiatives, while potentially receiving institutional support from higher levels. Multi-actor collaboration platforms (Ernsteins et al., 2025; Nesheim et al., 2021) and participatory governance are important mechanisms for improving policy coordination, knowledge exchange, and co-developing locally appropriate environmental management solutions.

Current research is conducted within the framework of the EU Horizon 2020 project OPTAIN (2025) ‘Optimal strategies to retain and reuse water and nutrients in small agricultural catchments across different soil-climatic regions in Europe’ (OPTAIN, n.d.). The project was orientated to improve water and nutrient management in small agricultural catchments across Europe by analysing Natural/Small Water Retention Measures (NSWRM) and their potential to enhance water retention, reduce nutrient losses, and increase climate resilience in EU partner countries and wider afield (Glavan et al., 2022; Lemann et al., 2022). NSWRM are understood as nature-based measures aimed at increasing water retention in the landscape, reducing runoff, improving water quality and enhancing ecosystem services (Magnier et al., 2024).

The overall aim of the OPTAIN project was to identify effective combinations of water retention measures and develop science-based recommendations for their implementation at farm, catchment and national policy levels. The project combines modelling, case study analysis in partner countries and stakeholder engagement to better understand both environmental and governance factors influencing the implementation of these measures.

Within the wider European framework of environmental policy integration, the objectives concerning water management, agricultural production, biodiversity conservation, and climate adaptation are becoming increasingly interconnected. Deliverable 6.2 (OPTAIN, n.d.) of the OPTAIN project assessed the coherence of water and agricultural policies across local, regional, national, and EU governance levels through policy reviews, comparative case studies from twelve European countries, and a survey of policy experts. The findings revealed common governance challenges across countries, including fragmented responsibilities, weak cross-sectoral coordination, insufficient administrative capacity, limited financial and technical support, and inadequate communication and knowledge transfer, all of which constrain the implementation of NSWRMs (Glavan et al., 2022).

Building on these cross-national findings, this study shifts the focus from a comparative European assessment to an in-depth national and local analysis of Latvia. It evaluates how the identified governance challenges and policy integration issues are reflected within the Latvian governance system and the Dviete River basin case study.

Specifically, the study was tasked to investigate the interplay between the water, agriculture, environmental and nature protection sectors (horizontal integration) and the interactions among national, regional, and local governance levels (vertical integration) to potentially assess the coherence of governance arrangements and practices supporting water resources and agricultural policy implementation. In doing so, the study identifies governance gaps and opportunities for strengthening governmental policy coherence and cross-sectoral coordination within the Latvian context.

In the context of the Horizon 2020 project, the current research in Latvia aimed to investigate the governance framework determining the implementation of NSWRM and small river basin water resource governance, with an emphasis on policy coherence and integration across various sectors and governance tiers.

Materials and Methods

Although nature-based water retention measures are implemented primarily at farm and small catchment levels, their successful implementation depends largely on coherent national governance linking the water and agricultural sectors. The Latvian whole-set stakeholder interviews assessment (Ernsteins et al., 2025) likewise indicates that the principal barriers arise from fragmented sectoral policies, insufficient institutional coordination and weak vertical integration rather than from a lack of local willingness to act. Consequently, analysing the governance interactions between the water and agricultural sectors is essential, since local initiatives alone cannot ensure effective and large-scale implementation without coherent national policy, legislation and financial programme support.

The Dviete River basin in southeastern Latvia covers approximately 254 km² (similarly to all other countries’ case areas in the OPTAIN project in Europe), with a river length of 37 km, being a single and comparatively small sub-basin as a contributory part of the Daugava River Basin District (RBD) covering 27057 km² (one of four RBDs in Latvia

according to WFD) and was selected as the case study area in Latvia. The area was selected due to its distinctive nature-culture landscape, including annually long-term formed floodplain waterscape shaped by tensions between agriculture and nature and representing long-standing experience with local bottom-up environmental initiatives.

The seasonal hydrological dynamics of the basin are characterised by extensive annual spring flooding lasting one to three months, largely influenced by the Daugava River water's direct inflow into the Dviete River (Nature Conservation Agency, 2018).

Historically, the area's floodplain was extensively meliorated in the 1930s to support intensive agriculture, establishing a strong agricultural tradition but also contributing to nutrient pollution affecting the Daugava River and ultimately the Baltic Sea. Since the 1990s, gradual nature conservation efforts have been introduced in the area, including the designation of a Natura 2000 site 'Dviete Floodplains' in 2004 (Cabinet of Ministers, 2007) as one of the most diverse and species-rich bird sites in Latvia. Despite several national and international nature protection projects realised within parts of the basin, its governance system and management structures remain non-basin-based, unplanned, largely sectorial and fragmented.

The research is based on a social-ecological systems (SES) research and development (R&D) approach, implemented through a case study research methodology to examine the governance framework supporting NSWRM implementation practice and, actually, wider looking for national governance frames and their functioning, using complementary methods: document analysis, stakeholder mapping, and semi-structured interviews with key stakeholders.

The interviews aimed to obtain stakeholders' perspectives on challenges and potential solutions related to water-use efficiency, the use of water and nutrient management tools and techniques, and the economic sustainability of technologies at farm and catchment levels. It also examined how environmental concerns such as water quality, water quantity, climate change and nature conservation are incorporated into policy and management systems. These empirical data were collected in two complementary research stages during the OPTAIN project – in 2022 and 2025.

The first stage studies (2022)

There was a vertical across administrative levels governance approach applied primarily following a top-down perspective from the national governance level while maintaining a thematic focus on agriculture and water in both mono- and cross-sectoral contexts. Accordingly, interviews were conducted, selecting national-level stakeholders from environmental-nature protection sectors and agriculture-water management sectors representing ministries, and further on, approaching also related regional/municipal governance levels to capture policy design and regulatory frameworks and institutional perspectives influencing NSWRM implementation.

A document analysis was conducted to examine policy instruments, governance responsibilities, and institutional arrangements influencing water and nutrient management and the implementation of NSWRM in Latvia. The analysis covered relevant legislation and policy documents across sectors – agriculture, water governance, nature protection, climate policy, and spatial planning – and governance levels, enabling an assessment of policy coherence.

At the EU level, the analysis included key directives influencing national environmental and water policy, such as the WFD, the Nitrates Directive, the Urban Wastewater Treatment Directive (91/271/EEC), and the Environmental Quality Standards Directive (2008/105/EC). These directives form the basis for national environmental regulation and water governance across EU member states.

For the agricultural sector, the analysis included the Strategic Plan for the Common Agricultural Policy of Latvia 2023–2027, the Law on Agriculture and Rural Development, the Law on Circulation of Fertilisers and the Amelioration Law. Additional relevant Cabinet of Ministers regulations included Regulations No. 834 on protection of water, soil and air from pollution caused by agricultural activities and Regulations No. 600 and No. 776 regulating financial support instruments for environmental and agricultural investments.

For the water resources management sector, the analysis included the Water Management Law, the Law on Pollution, and several Cabinet of Ministers regulations governing water use permits, water quality standards, and the discharge of pollutants. Strategic planning documents included river basin management and flood risk management plans for Latvia's four river basin districts (Daugava, Gauja, Lielupe, and Venta), with particular attention to the Daugava River Basin Management Plan relevant to the Dviete River basin.

Additional legislation included the Law on the Conservation of Species and Biotopes (The Parliament of the Republic of Latvia, 2000) and the Law On Specially Protected Nature Territories (Legal acts of the Republic of Latvia, 1993), together with planning documents relevant to the study area: the Nature Protection Plan for the Nature Park 'Dviete Floodplain' (2020–2032) and Cabinet of Ministers Regulation No. 274 on individual protection and use regulations for the nature park (Cabinet of Ministers, 2007).

Initial top-down governance-based approach interviews were carried out during Spring 2022 and involved a total of 18 informants. Six respondents represented national policy-making authorities, including the Ministry of Agriculture (three respondents) and the Ministry of Environmental Protection and Regional Development (two respondents), while three informants represented a policy-implementation authority: the Latvian Environment, Geology and Meteorology Centre, responsible for water resources monitoring and planning of River Basin District Management plans

(RBDMPs). Six interviews were conducted with regional-level structures of national authorities and two with municipal, local-level authorities. All participants possessed a high level of policy expertise and were directly involved in action-policy design, legislative development and the preparation of support strategies and financing schemes responsible for policy implementation. All informants hold at least a university master's degree, with expertise in agriculture, water and environmental governance.

Semi-structured in-depth interviews were carried out online via Microsoft Teams, allowing for synchronous audio-visual communication and recording with respondents' consent. Interviews lasted approximately two hours on average. As some ministerial respondents had limited cross-sectoral expertise in NSWRM, several group interviews brought together experts from different policy fields within the same institution to improve response completeness and quality.

The OPTAIN project-designed questionnaire form used in the first studies stage of the research was structured into several thematic blocks starting with respondents' professional background, knowledge and experience with water-related environmental challenges, familiarity with relevant policy frameworks, and then including perceptions of policy compatibility across sectors such as agriculture, water management, environmental protection, spatial planning and climate policy. Additional sections explored governance practices at farm and catchment levels, policy communication to end-users, perceived barriers to implementing water and nutrient retention measures, and possible policy improvements (Glavan et al., 2022).

The second stage studies (2025)

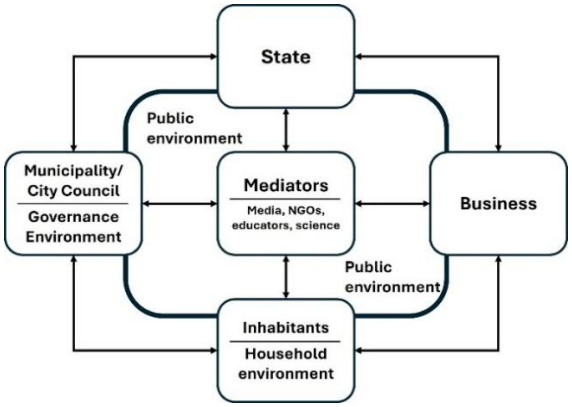
The methodologically complementary design was the second stage (2025) of studies - there was a horizontal across local/regional stakeholders' governance approach primarily following a bottom-up perspective and from the all-set of stakeholders' (Figure 1) points of view on water/environmental governance processes in the particular Dviete River basin and related upper governance levels.

Studies included document analysis, stakeholder mapping and semi-structured in-depth interviews designed to further explore first research stage results, but with particular attention given to all main local Dviete River basin and related sub-regional stakeholders, emphasising a bottom-up approach as, to some extent, opposite but complementary to the first-stage study realised as a top-down approach.

The quintuple network governance structured stakeholder's constellation collaboration model (Ernsteins et al., 2017) was applied, based on an interrelation framework that encompasses five complementary stakeholder group-based segments (Figure 1), namely the state, municipalities, businesses, local residents, and mediators (which include NGOs, educators, academia, and media). Stakeholders were identified and purposively selected for each segment based on their thematic relevance and expertise, ensuring comprehensive coverage of all principal stakeholder groups.

Figure 1

The hierarchically structured collaboration model of 5 governance stakeholder's segments as all existent stakeholders' core groupings (Ernsteins et al., 2017)



In total, in spring 2025, altogether 19 participants representing the whole set of different core stakeholder groupings were interviewed, including representatives of the state sector/national level (3), municipalities (5), businesses (3), civil society (2) and mediators (6). Semi-structured interviews allow for in-depth exploration of stakeholders' experiences, attitudes and perspectives while enabling a multidimensional understanding of environmental governance processes. The interview structure was developed around four interrelated analytical dimensions – the hierarchically structured collaboration governance model (Ernsteins et al., 2017) complementary incorporates governance content/sectors, governance instruments, governance stakeholder groups and governance monitoring-indicator systems, but communication complementary was conceptualised as a cross-cutting component and studied via the information, education, participation and behaviour dimensions model (Ernsteins et al., 2017).

The interviews examined key issues related to the integration of development planning, water and nature protection objectives, possibly cross-sectorial; the application of regulatory and economic policy and all other instruments; all the stakeholder network involvement in decision-making processes; and existing top-down and bottom-up governance monitoring systems and indicators in environmental-nature-water-agri and other sectors' governance.

All interviews were conducted individually, either in person or remotely via telephone, and lasted for about one hour. A pre-developed interview guide structured the discussions while allowing respondents to elaborate on their perspectives and experiences. Interview transcripts were analysed thematically to identify key governance challenges, policy gaps, and opportunities to improve governance and management implementation in the study area.

Results and Discussion

The subsequent chapters synthesise the principal outcomes of the investigation, derived from policy and documents analysis, stakeholder mapping and interviews undertaken during two stages of the study:
- first, multi-sectoral public institutions' governance across all three administrative levels in the country, from the national to the local municipal level in the Dviete basin, - second, multi-stakeholders' network co-governance interests locally within the Dviete River basin area.

Collectively, these findings elucidate the institutional, policy, and governance factors influencing the adoption of water and nutrient retention measures across key stakeholder groups (state, municipalities, businesses, society/households, and mediators), major sectors (e.g., agriculture, water governance, environment, forestry, spatial planning, and related fields), and governance instrument groups: policy & legislation, planning, institutional & administrative, economic & financial, infrastructure/technology, and communication & collaboration.

1. Multi-sectorial public governance studies across administrative levels in Latvia

First-stage findings primarily address the multisectoral governance framework's approaches and impacts on the execution of NSWRM in Latvia. The first research stage analysis, applying the OPTAIN project-designed interview matrix, specifically scrutinises crucial structural policy instruments; legislative stipulations concerning water quality and quantity management; policy compatibility deficiencies and inter-sectoral conflicts; communication strategies with end-users; practical applications of NSWRM tools; and stakeholder-recommended approaches for enhancing policy coherence and implementation.

1.1. Structural policies towards implementation

The CAP Strategic Plan 2023–2027 represents the most significant agricultural policy tool influencing the adoption of NSWRM in Latvia. Interviewed specialists emphasised that the CAP support mechanisms are the primary method through which farmers are encouraged to adopt environmental practices related to water retention and nutrient management. Although the previous CAP programming period supported retention measures across the country, the adoption rates were relatively low, and observable improvements in water quality were limited. Informants highlighted that the new CAP Strategic Plan aims to address these shortcomings by concentrating on nitrate-risk areas with increased precision, particularly within the agriculturally intensive Zemgale region in Latvia. This focused approach aligns national agricultural policy with EU environmental directives and broader Green Deal objectives (European Commission, 2019), including the Farm-to-Fork and Biodiversity strategies (European Commission, 2020a, 2020b). Conversely, several respondents cautioned that the efficacy of these measures will be contingent upon sufficient funding, administrative capabilities, and farmer participation.

RBDMPs represent the main framework for water governance in Latvia. The country is divided into four river basin districts, Daugava, Gauja, Lielupe and Venta, each governed by a mid-term management plan together with a Flood Risk Management Plan (FRMP) that is periodically updated. These plans define mandatory and additional measures for achieving satisfactory ecological status of water bodies, based on assessments of water quality, water quantity, sectoral pressures and spatial planning impacts. Informants noted that RBDMPs provide important strategic guidance for implementing water management measures, including those related to nutrient retention and ecosystem restoration.

However, a structural governance limitation was also identified. RBDMPs are approved at the ministerial level rather than by the Cabinet of Ministers, which limits their cross-sectoral binding force. As a result, coordination between water management objectives and other policy domains, such as agriculture, spatial planning and nature protection, remains weak. Several informants described the plans as important strategic frameworks but emphasised they are not compulsory for all sectors involved in water management.

1.2. Legislation: Water Quality-Quantity, Nutrients

The legislative framework addressing water quantity and water quality challenges is extensive but unevenly integrated across sectors. Informants generally considered that legislation addresses excess water challenges, such as flooding, to an intermediate or high degree. Flood protection measures are primarily treated as planning and civil protection issues rather than being integrated into ecosystem-based water retention or landscape-scale water management strategies.

The link between NSWRM and spatial planning is weak and occurs mainly through RBDMPs. Because these plans are approved at a ministerial rather than governmental (Cabinet of Ministers) level, their formal authority across other policy domains remains limited. Consequently, spatial planning processes do not systematically incorporate water retention measures or ecosystem-based solutions.

Conversely, agricultural legislation demonstrates a comparatively robust integration of nutrient management, primarily through the establishment of manure management regulations and the enactment of the Nitrates Directive. Informants emphasised that the stipulations governing fertilisation planning, manure storage, and livestock density establish explicit benchmarks for nutrient management in the agricultural sector. Nevertheless, the institutionalisation of nutrient recovery from streams and landscape-scale nutrient retention strategies is less pronounced. While certain retention measures are included in river basin plans, especially in nitrate-sensitive areas, these measures are largely programmatic in nature, lacking the force of binding legislation.

Water quantity regulation focuses mainly on water

abstraction permits and environmental resource taxes, which apply when water extraction exceeds 10 m³ per day. While these instruments control water use, they do not actively promote retention or ecosystem-based water management approaches. Similarly, drought management is not strongly reflected in current legislation, and informants noted that regulatory mechanisms addressing water scarcity remain limited.

Most NSWRM measures remain voluntary. Some practices, such as artificial wetlands, reduced tillage and precision fertilisation technologies, are supported through CAP financial instruments. However, informants emphasised that uptake remains limited due to weak financial incentives and insufficient CAP funding for agri-environmental measures. For example, only a small proportion of identified potential sites currently receive financial support for implementation.

Key structural barriers identified by informants include legislative gaps, policy incoherence between sectors, fragmented land ownership and insufficient trust and engagement between institutions and landowners.

1.3. Policy Compatibility and Cross Sectors

Significant incompatibilities exist between agricultural and forestry objectives and the goals of nature conservation, water management and climate policy. Informants frequently highlighted that sectoral policies pursue different priorities, creating structural tensions in land-use governance.

Key horizontal conflicts include tensions between nature protection and climate strategies, where climate-driven land-use measures such as afforestation may conflict with biodiversity conservation objectives. Drainage (amelioration) systems represent another major source of conflict. These systems increase agricultural productivity but may negatively affect wetlands and ecosystem restoration efforts.

Afforestation and forest intensification policies may also contradict habitat protection goals, while river regulation and riverbank cleaning can improve hydraulic flow but damage protected habitats. Buffer zones along water bodies, which are important for nutrient retention, are often perceived by farmers as reducing productive agricultural land. Spatial planning conflicts also occur when settlement development is permitted in flood-prone areas, contradicting water management and climate adaptation objectives.

These sectoral conflicts reflect broader governance challenges related to insufficient horizontal policy integration. Informants emphasised that coordination between agriculture, water management and nature protection sectors remains limited. At the catchment level, these compatibility gaps become more visible, particularly in interactions between agricultural policies, water governance and spatial planning.

Informants also highlighted that climate–water integration remains weak due to limited locally specific data on climate impacts at the catchment scale. Improved policy synergies therefore require stronger cross-sectoral coordination, enhanced monitoring and hydrological modelling, and a revision of technical standards for drainage systems to ensure compatibility with biodiversity and ecosystem protection.

1.4. Communication: complementary instruments

Environmental communication is not only about transferring information but also about promoting knowledge exchange, engagement, and behavioural change as part of communication process cycle. Therefore, communication instruments play an important role in education, training, strengthening public participation, and encouraging environmentally responsible behaviour (Ernsteins et al., 2017). Their effectiveness relies on collaborative, results-oriented approaches that foster social learning, behavioural change, and stakeholder involvement.

Low farmer interest and limited uptake of available funding were frequently linked by informants to insufficient understanding of the economic benefits and long-term cost-effectiveness of NSWRM for farm development. Although several policy instruments promote environmentally friendly practices, policy communication to end-users remains insufficient.

Communication practices were described as mainly reactive, with information often provided only upon request. While advisory services and project-based seminars exist, much policy information is distributed through web-based platforms that are extensive but difficult for users to navigate.

Informants noted that improving the implementation of retention measures requires stronger advisory support and awareness-raising activities demonstrating the potential ‘win-win’ benefits of NSWRM, combining improved farm productivity, long-term economic stability and environmental protection.

Existing knowledge-sharing networks could play a greater role in improving policy communication. These include agricultural advisory services, river basin management boards acting as multi-stakeholder platforms, and local intermediaries such as nature guides. Public participation processes related to local nature protection planning and LEADER-supported rural development initiatives were also identified as underutilised opportunities for stakeholder engagement.

Informants further emphasised that establishing open educational platforms and structured training programmes addressing agriculture, forestry, water quality and climate issues could significantly improve knowledge exchange and strengthen policy integration from national objectives to farm-level practice.

1.5. Instrumental techniques for NSWRM

The use of specific tools and techniques for implementing NSWRM varies significantly across sectors. In agriculture, several practices are already widely recognised as important for improving water quality and reducing eutrophication. These include green cover crops, meadows and pastures, buffer strips and hedges, crop rotation and low-tillage practices.

Informants reported that many stakeholders have

practical experience with agricultural and hydro-morphological measures, although implementation levels differ depending on local conditions and financial support availability. Most respondents also indicated that they had addressed issues related to excess water management, water quality improvement and nature conservation in their professional work, while experience with drought management and in-field water retention measures was more limited.

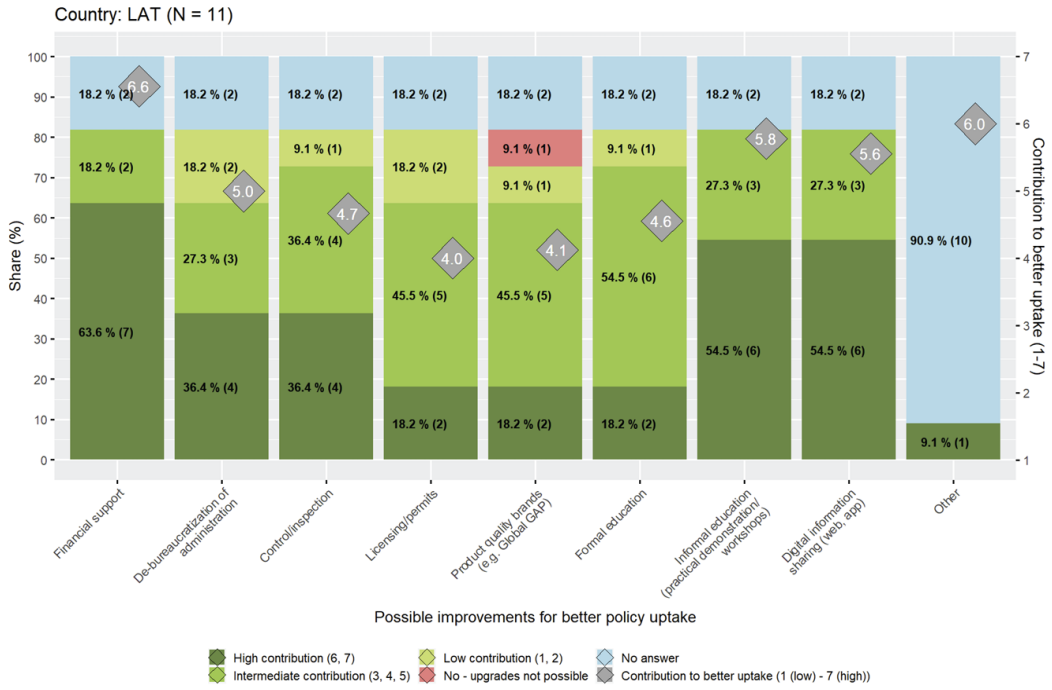
Examples of nutrient recovery from aquatic ecosystems also exist, although these measures are typically implemented primarily for nature conservation purposes rather than water management objectives. For instance, lake ecosystem restoration through reed cutting has been used to restore habitats for protected bird species while improving water quality conditions.

1.6. Instruments for compatibility and implementation

This section presents the solutions suggested by informants to address compatibility issues and improve the implementation and acceptance of measures. The respondents evaluated different policies and legislative changes aimed at encouraging the use of water and nutrient retention measures; see Figure 1. Within the governance instrument framework shown in Figure 1, the analysis focused on various instrument types, including financial support, reducing administrative bureaucracy, control and inspection methods, licensing and regulatory processes, product quality brands, formal education, informal education, digital information, and other supportive measures. The analysis is based on the OPTAIN D6.2 methodology (Glavan et al., 2022), which combines cross-sectoral survey data from stakeholders, case study analysis across multiple European countries, and quantitative evaluation using Likert-scale-based assessments to identify key barriers and improvement pathways.

Figure 1

Information provided by the informants as response to the question on how to upgrade policy/legislation for improved uptake implementation of water and nutrient retention measures in Latvia (Glavan et al., 2022)



Additional qualitative suggestions from informants highlight several governance improvements needed to enhance the implementation of water and nutrient retention measures. Respondents emphasised strengthening the legislative framework, including government approval of RBDMPs to ensure their measures become binding and properly financed. They also suggested increasing environmental fines to discourage rule violations. Improved cross-sector coordination was identified as essential, particularly through spatial planning that aligns sectoral priorities and integrates environmental, agricultural, and regional development objectives. Informants also stressed the importance of clearer stakeholder responsibilities, better consultation between agricultural experts and farmers, stronger cooperation platforms for NGOs and authorities, and increased environmental awareness.

Enhancing administrative capacity and policy instruments constituted a further critical area of focus. Informants suggested the establishment of a user-centric national monitoring system, designed to facilitate efficient data exchange and to bolster evidence-based decision-making processes. Furthermore, the reduction of administrative burdens and the enhancement of information accessibility were deemed essential for promoting the adoption of environmental measures. Increased financial backing,

particularly compensatory subsidies for agricultural limitations such as buffer zones, was recognised as a vital incentive. Furthermore, stakeholders pointed out the need for enhanced technical assistance, which included improved access to geospatial data, more detailed guidance on the planning and design of water retention strategies, and a stronger focus on educational programmes, training initiatives, and awareness campaigns.

Following the initial findings, recommendations were directed toward specific environmental issues, including water quality, water availability, biodiversity preservation, and climate change mitigation. Participants emphasised the necessity of prioritising interventions that would most effectively improve water quality, refining fertiliser and manure management practices on farms, and reinforcing the importance of buffer zones and sustainable agricultural methods. For water quantity management, respondents highlighted the importance of integrating flood risk management with basin planning and maintaining melioration systems to improve water retention and soil productivity. Additional recommendations included expanding compensation schemes for protected habitats, improving spatial planning to reflect environmental restrictions, and strengthening information and policy support related to climate change mitigation and adaptation.

2. Multi-stakeholder's network studies for local co-governance in the Dviete River basin area

Second-stage findings primarily address cross-stakeholder, cross-sectoral, and cross-instrumental governance in the Dviete floodplain, focusing on institutional fragmentation, stakeholder perspectives, policy coordination, communication, and implementation of nature-based water and nutrient retention measures across governance levels.

2.1. Governance: comparative studies across Europe

Comparative case studies across Europe indicate that environmental objectives are frequently present in policy frameworks but remain weakly integrated in practice (Glavan et al., 2022). In Latvia, this situation is illustrated by the absence of explicit legal references to NSWRM in water legislation and the programmatic rather than binding nature of many retention measures within river basin management planning. Likewise, flood protection measures and spatial planning initiatives exhibit a tenuous relationship with ecosystem-based water management strategies. These observations corroborate prior investigations indicating that environmental governance structures frequently encounter challenges in achieving cross-sectoral integration, notwithstanding the presence of common policy objectives. Regional analyses additionally underscore variations in policy priorities, which are contingent upon specific hydro-climatic contexts.

Despite the availability of various policy instruments, such as the CAP Strategic Plan and RBDMPs, their execution frequently suffers from a lack of robust coordination mechanisms spanning different governance tiers and policy areas. This fragmentation is not exclusive to the Latvian context.

The findings of this research underscore several structural governance impediments that hinder the effective execution of NSWRM in Latvia. These challenges largely reflect observations from wider European assessments undertaken within the OPTAIN project (Glavan et al., 2022). Specifically, the Latvian context exemplifies fragmented governance, particularly among the water governance, agricultural, nature conservation, and climate policy sectors.

In Pannonian and continental areas in Europe, the focus is primarily on water scarcity and the management of droughts; conversely, boreal regions prioritise water quality and the mitigation of nutrient runoff, as noted by Glavan et al. (2022). Latvia's governance structure mirrors this emphasis, with nutrient management receiving more explicit attention in its legal framework, particularly through regulations pertaining to nitrates and the management of manure. However, broader landscape-scale nutrient retention and ecosystem-based governance measures remain weakly institutionalised.

2.2. Governance: towards cross-stakeholder collaboration

During the initial phase of the study, a stakeholder mapping and situational audit were conducted in the Dviete River basin within the OPTAIN Project framework to identify relevant actors for the interview process and analyse their potential roles in environmental governance. Based on the upgraded quintuple Helix stakeholder framework, stakeholders were grouped into five interconnected categories: state institutions, municipalities, businesses, mediator groups, and society. The mapping revealed a diverse but weakly interconnected stakeholder landscape, highlighting the need for targeted communication, collaboration platforms, and supportive governance mechanisms to strengthen cross-sectoral cooperation in water, nature, and agricultural management.

Another important challenge concerns the practical uptake of retention measures by land managers and farmers at their farm level. The results indicate that most NSWRM practices in Latvia remain voluntary and rely heavily on CAP-based financial incentives. Limited funding availability and insufficient advisory support significantly reduce the adoption of such measures. Similar barriers have been identified in other European case studies, where financial instruments, administrative complexity and limited guidance hinder the implementation of water and nutrient retention measures at the farm level (Glavan et al., 2022).

2.3. Governance: towards cross-sectoral collaboration

Cross-sectoral collaboration within the governance of the Dviete floodplain, as revealed during the second research stage by an analysis of interviews spanning five stakeholder segments, such as state institutions, municipalities, entrepreneurs, local society, and

mediators, demonstrates a formal existence, yet its practical application is inconsistent and structurally disjointed. Despite a shared recognition of the necessity to reconcile nature conservation, agricultural practices, and economic advancement, the interviews expose considerable disparities in the actors' interpretations of problem origins, governance frameworks, and the allocation of responsibilities.

Initially, governance fragmentation surfaces as a primary concern across all sectors. This fragmentation manifests in insufficient horizontal coordination between policy domains and institutions. Interviews with representatives of the state sector indicate that responsibilities related to environment, water management, and nature protection are divided among several institutions and ministries, which complicates coordinated decision-making. As a result, planning instruments and monitoring systems exist, yet their practical implementation is often limited by political priorities, institutional capacity, or insufficient funding. Similar concerns are raised by municipal representatives, who note that responsibility for managing protected areas is often shared between state institutions, local governments, and landowners, but these responsibilities are not always clearly defined.

Overall, the interview analysis suggests that the key challenge in cross-sectoral governance of the Dviete floodplain is not the diversity of interests itself, but rather the lack of effective coordination mechanisms and stable collaborative structures. While there is broad recognition across sectors of the need to integrate environmental protection, agriculture, and regional development objectives, achieving effective collaboration requires clearer institutional frameworks, long-term financing mechanisms, and more targeted communication between institutions and local communities. Without such instruments, cross-sectoral cooperation remains fragmented and largely dependent on individual initiative rather than systematic governance practices.

2.4. Governance: towards cross-instrumental collaboration

Different stakeholder groups prioritised very different governance instruments: state institutions → planning & monitoring; municipalities → spatial planning and institutional capacities; farmers/businesses → financial & technical support; NGOs/mediators → communication & participation. All six governance instrument groups are necessary: legal–political, planning, institutional–administrative, economic–financial, technological, and communication & collaboration instruments.

Representatives from state institutions primarily highlighted the significance of institutional coordination mechanisms, planning instruments, and monitoring systems as crucial elements in floodplain management; however, they also acknowledged the limitations imposed by the fragmented nature of ministerial responsibilities and collaboration limitations.

Municipal officials underscored the necessity of more explicit delineation of responsibilities and the enhanced incorporation of environmental goals within spatial planning and local development initiatives, as well as the growth of municipal capacities (esp. territorial administrative and management units). Local business owners and land managers/farmers, conversely, often prioritise pragmatic and economic considerations, specifically the demand for dependable financial instruments and enduring funding strategies that would facilitate the implementation of environmentally focused land and water management practices, which also require necessary infrastructure - technological instruments (also NWRSM) as well as related information and training instruments. Simultaneously, mediators and representatives of the local communities stressed the importance of communication, stakeholder engagement, and collaborative platforms designed to foster improved cooperation between governmental bodies and local communities.

Communication and the dissemination of knowledge instruments are definitively crucial elements affecting the efficacy of policy implementation. In Latvia, policy communication tends to be predominantly reactive, and the information provided frequently presents navigational challenges for its intended audience. Consequently, this situation hinders the acknowledgement of the prospective economic and environmental benefits linked to NSWRM, thus contributing to restricted engagement in funding endeavours. Prior European research also underscores that improved communication strategies, advisory frameworks, and knowledge-sharing networks are crucial for augmenting farmer participation and facilitating the implementation of sustainable land and water management practices (Glavan et al., 2022).

2.5. Governance: triple governance dimensions frame

These governance challenges are also reflected in the comparison between the two interviews and other studies' stages conducted in this study. The initial interview stage employed a top-down methodology, engaging primarily with representatives from national and regional public institutions and municipalities. The interviewees highlighted challenges related to structural policy and governance, such as policy fragmentation, administrative difficulties, and insufficient coordination between different sectors. In contrast, the following second interview stage took a bottom-up approach, focusing on the perspectives of local stakeholders. Here, these structural issues manifested practically through ambiguous responsibilities, restricted communication, and fragmented collaboration at the local level.

Effective governance requires an integrated application of the triple governance dimensions: cross-sectoral, cross-level, and multi-stakeholder governance, supported by communication and monitoring.

These findings are also consistent with the conclusions of the environmental governance audit of the Dviete

River Basin conducted previously (Ernsteins et al., 2025), which similarly identified fragmented governance, weak horizontal and vertical integration, limited monitoring, and insufficient stakeholder coordination as key barriers to effective environmental governance management. Both studies emphasise that improving governance effectiveness requires stronger integration and complementary application of governance instruments, a SES approach, enhanced environmental communication, and the development of collaborative platforms that support both bottom-up engagement and coordinated top-down support.

The results, in summary, also corroborate several pivotal conclusions presented in OPTAIN Project Deliverable 6.2. Successful execution of water and nutrient retention strategies necessitates more robust horizontal policy integration across various sectors, improved coordination among different governance tiers, and more effective support systems for agricultural producers and landholders. Furthermore, translating policy goals into tangible environmental improvements require enhanced monitoring, communication, and stakeholder collaboration. Strengthening these governance dimensions would support more integrated and effective water and agricultural policy implementation in Latvia and across Europe.

Conclusions

1. Water and agriculture governance harmonization imperative. The results of policy and document analysis, stakeholder mapping and interviews highlight key challenges and opportunities related to policy arrangements and practice implementation, pointing to water and agriculture governance harmonisation as imperative in Latvia. While perceptions of governance effectiveness, regulatory burden, and sectoral responsibilities vary across stakeholder groups, the interviews collectively highlight several key structural issues in cross-sectoral cooperation and environmental governance.

2. Fragmented water and agriculture governance. The agriculture-water governance framing landscape could currently be characterised by systemic deficiencies within existing policy frameworks, encompassing fragmented and inconsistent legislation, inadequate cross-sectoral collaboration, and a lack of administrative capacity, expertise, and technical assistance. Funding mechanisms frequently prove insufficient or misdirected, and awareness-raising and communication initiatives are often restricted, thereby impeding the effective integration of water and agricultural governance.

3. Horizontal and vertical integration dependency. Effective implementation depends on stronger horizontal integration between water, agriculture, biodiversity and climate policies, together with improved vertical coordination across national, regional and local governance levels. Despite existing coordination mechanisms (e.g., between the Ministries of Agriculture and Environment), cross-sectoral and vertical cooperation remains insufficient for coherent policy arrangements.

4. Imperative: overarching water and agriculture governance framework. Overall, the findings indicate that improving individual policy instruments alone is insufficient. Effective implementation of NSWRM and general river water basin management requires an overarching governance framework, and for this role, stakeholders qualitatively tested governance framework integrating the triple governance dimensions - multi-stakeholder, cross-sectorial, multi-instrumental governance process across all governance levels.

5. Stakeholder engagement and tailored communication instrumentarium. Although advisory actors and support structures are present, access to information and knowledge, particularly for water retention practices, remains limited for farmers, constraining effective practice implementation in agricultural systems. Information exchange alone is insufficient, and it must be complemented by targeted training, participatory approaches, and practical demonstrations and behaviours, e.g., the all-quadruple communication instruments. And instruments shall be selectively adjusted and tailored to each stakeholder's core grouping and subgroups, which is essential for improving knowledge exchange, increasing awareness and supporting bottom-up implementation.

6. The whole set of governance instruments. Stakeholders prioritise each different governance instrument group according to their public functions and roles: state institutions focus on coordination and planning instruments, municipalities on clearer responsibilities and spatial integration, businesses on financial instruments and stability, and civil society on communication and cooperation instruments.

Achieving effective governance and local implementation, potential harmonisation requires not only a balanced combination of the whole set of complementary governance instruments (legal-political, planning, institutional-administrative, economic-financial, infrastructure-technological, and communication & collaboration instruments) but also their coordinated development, planning, and implementation rather than fragmented application.

7. Innovation, technical and financial support programs. Although advisory structures exist, access to knowledge, innovation and technical support remains limited, particularly for farmers implementing water retention measures. Increased financial support, together with improved information exchange, informal education and digital tools, was identified as the highest priority for strengthening implementation capacity.

8. Governance sectors and socio-ecological systems approach. Stakeholders identified excess water as the main agricultural thematic challenge, whereas water scarcity, in-field water retention, and nutrient recovery receive comparatively limited attention. Also, the SES

approach is not only known for traditional environmental pollution and infrastructure sectors, biodiversity and nature resources sectors, but also non-traditional environmental health, communication and, particularly, climate change governance sectors, as well as integrated linkages with socio-economic sectors.

9. Imperative policy coherence for integrated water resources and agriculture governance and management practice. Effective implementation of water retention and general water-agricultural harmonisation towards policy coherence in Latvia is constrained less by the legislation limitations than by fragmented governance – weak cross-sectoral coordination, insufficient stakeholder collaboration, and poor integration of complementary governance instruments across governance levels. Furthermore, administrative complexity, weak enforcement, voluntary implementation, and unfavourable cost-benefit ratios further constrain practice implementation. At the same time, bottom-up initiatives increasingly contribute to practice implementation and even local policy coherence developments, especially where institutional capacity is limited.

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DYNAMICS OF BUILT-UP AREA DEVELOPMENT IN LITHUANIA IN 2005-2025

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Abstract
This study analyses the development and spatial transformation of built-up areas in Lithuania and its counties over the period from 2005 to 2025. A combination of quantitative, comparative, grouping, categorization, and classification methods were applied to systematically examine patterns of urban expansion. Statistical data from the Land Fund of the Republic of Lithuania (2005–2025) and Eurostat (2022, 2025) were used to assess changes in the extent of built-up areas at both national and county levels, alongside demographic indicators such as population number. The results indicate that in 2025, built-up areas in Lithuania covered a total of 248,550.05 ha, corresponding to 3.81% of the national territory, with the largest proportions recorded in Vilnius (5.13%) and Kaunas (5.08%) counties, and the smallest in Tauragė (2.74%) and Utena (3.01%) counties. Analysis of population density and compactness demonstrated that the highest values occurred in Vilnius, Kaunas, and Klaipėda counties, reflecting concentrated and intensive urbanisation, while peripheral counties exhibited more dispersed, low-density development. The overall compactness of built-up areas in Lithuania in 2025 was 12.29 inhabitants/ha, indicating medium-density urbanisation and a mixed urban structure. Between 2005 and 2025, the total built-up area in Lithuania increased by 67,966.42 ha (37.64%), with the fastest relative expansion observed in Klaipėda (77.49%) and Utena (46.63%) counties, highlighting regional disparities in urban growth and spatial development patterns.
Key words: built-up area, change in built-up area, compactness of built-up areas.

Introduction

The expansion of built-up areas and urbanization in major cities and regions is a key topic in contemporary urban studies. Urban growth is influenced by population dynamics, planning priorities, and long-term economic trends, and it significantly transforms landscapes in ways that are often long-lasting and difficult to reverse (Seto et al., 2011; Angel et al., 2011; Liu et al., 2020; Chen et al., 2024).

Urbanization does not occur uniformly. In some cities, expansion spreads at low density into suburban areas, while in others, construction intensifies within existing urban zones, increasing population density. These processes are driven not only by housing demand and the need for services but also by broader factors such as economic development, market distribution, and population mobility (Batty, 2024; Frolking et al., 2024).

Advances in technology have greatly enhanced the monitoring of built-up areas. High-resolution satellite imagery (Sentinel, Landsat, PlanetScope), remote-sensing tools, and advanced data-processing methods now provide precise insights into the dynamics and trends of urban expansion. Large-scale geospatial platforms allow for long-term analyses and comparative studies of urban transformations across cities, regions, and countries (Gorelick et al., 2017; Li et al., 2020, 2024).

The environmental impacts of urban growth are increasingly evident. Expansion disrupts natural landscapes, degrades soil quality, threatens biodiversity, and alters hydrological patterns, particularly in sensitive areas such as wetlands and natural meadows (Grimm et al., 2008; McKinney, 2009; Alberti et al., 2016). These changes often lead to increased flood risk, higher local temperatures, and altered microclimates, with effects that are long-term and frequently irreversible (Zhou et al., 2016; European Environment Agency, 2016).

Climate change mitigation has become an increasingly important issue today. Climate change affects the natural environment, rural areas, and urban systems, making it essential to understand how urbanization influences environmental conditions. Previous studies indicate that the expansion of built-up areas has significant impacts on ecosystems, physical structures, and the social environment. Therefore, development management decisions must be comprehensive and directed toward the sustainable development of territories (Ramanauskas et al., 2024).

Urbanization occurs at varying rates and under different regulatory frameworks worldwide. Rapid, loosely regulated growth is common in parts of Africa and Asia, often linked to new infrastructure development (Cobbinah & Aboagye, 2017). Conversely, European and North American cities tend to emphasize compact urban layouts, redevelopment of underused land, and more intensive land use (Schneider et al., 2010; Haaland & van den Bosch, 2015).

In the Baltic countries, suburban expansion frequently converts agricultural land into residential areas, creating fragmented and uneven landscapes (Feranec et al., 2017; Listauskas & Valčiukienė, 2018). Capitals such as Vilnius and Riga illustrate this trend, where development often outpaces the capacity of planning systems, altering spatial structures and local environments (Bardauskienė & Pakalnis, 2012; Krišjāne at el., 2012).

According to Pereira et al. (2025), both population changes and territorial planning issues are evident in Lithuania and its suburban areas. An analysis of land-use changes in the country's major cities—Vilnius, Kaunas, and Klaipėda—reveals a decline in

agricultural land and an increase in forested and built-up areas. These trends highlight the particularly complex transformation of urban territories and the landscape structure across the country.

Rapid urbanization has led to various territorial planning challenges, particularly when green or natural infrastructure is not effectively integrated into urban spatial frameworks. Ramanauskas et al. (2025) highlight that high-density development and extensive surface sealing adversely affect quality of life. Therefore, the expansion of built-up areas must be accompanied by deliberate planning measures that prioritize the incorporation and development of green spaces.

The development of natural infrastructure, such as green spaces, is an objective achieved through the sustainable planning and management of territories. It also underscores the critical interrelationship between society, the environment, and the economy. In highly urbanized areas with limited or no green space, the impacts of climate change and related challenges become particularly pronounced, including frequent and intense storms, heat waves, and excessive or insufficient precipitation (Aslanoğlu et al., 2025).

Long-term land-cover studies show a steady increase in urbanized areas, particularly in suburban zones. Effective planning and institutional oversight are essential to ensure that urban expansion occurs in ways that protect environmental quality, maintain landscape integrity, and benefit local communities (UN-Habitat, 2020).

Growing concerns about uncontrolled urbanization have highlighted the importance of planning principles that promote environmental protection, green infrastructure, and compact urban forms (Kabisch et al., 2017; Keskin et al., 2013). Cities investing in interconnected green and natural systems benefit from improved microclimates, reduced flood risk, and other positive outcomes (Feltynowski et al., 2018). Scenario modeling is increasingly used to evaluate potential development trajectories under varying demographic, economic, and climate conditions (van Vliet et al., 2009).

Not all urban areas are expanding; some experience population decline, resulting in abandoned buildings and underused infrastructure (Haase et al., 2013; Martínez-Fernández et al., 2012). These contrasting trends require context-specific strategies. In rapidly growing regions with limited planning capacity, informal or unauthorized construction can further complicate environmental management (UN-Habitat, 2020).

As can be seen from the analysis above, the expansion of built-up areas is driven by interconnected demographic, economic, technological, governance, and environmental factors. Ensuring sustainable urban growth that benefits society while minimizing environmental risks requires continuous spatial monitoring, effective planning, and adaptive policy frameworks (Liu et al., 2014; Wei et al., 2022).

The chosen topic is relevant because analysing changes in the extent of built-up areas helps to reveal ongoing urbanisation processes in the country and its counties. This, in turn, makes it possible to anticipate future trends, prevent emerging planning and environmental challenges, and ensure sustainable territorial development, a high quality of life, and effective environmental management. However, despite the importance of understanding urban expansion dynamics, there is still a lack of detailed, spatially consistent, and up-to-date analyses of how built-up areas have changed over time across different administrative levels in the study region. This gap limits the ability to accurately assess the scale and rate of urbanisation needed for informed planning and decision-making.

The object of this study is the built-up areas of Lithuania.

The aim of the study is to analyse the dynamics of built-up area expansion in Lithuania from 2005 to 2025.

Research objectives:

1. To analyse the current state of built-up areas across Lithuania and its counties.
2. To calculate population density, built-up density, intensity, and urban compactness using standardized spatial formulas.
3. To evaluate the changes in built-up area extent between 2005 and 2025.

Materials and Methods

In order to assess changes in built-up areas from 2005 to 2025, the following statistical data were used: data from the Land Fund of the Republic of Lithuania for the period 2005–2025 (Nacionalinė…, 2005–2025) on built-up areas in Lithuania and its counties, as well as Eurostat data from 2022 and 2025 (Eurostat, 2022, 2025) on built-up areas and demographic indicators in the EU. The study covered the period from 2005 to 2025. Changes in built-up areas and other indicators were analyzed not only at the national level but also across ten Lithuanian counties.

Quantitative analysis methods were employed in the study. Changes in built-up areas were calculated for the country as a whole and for individual counties. During the preparation of the article, population density, the share of built-up areas, and the built-up area compactness index (population per hectare) were also calculated.

The compactness of built-up areas reflects the number of inhabitants per hectare of built-up land, Formula 1.

$$BC = \frac{P}{Ab} \quad (1)$$

where: BC is built-up area compactness (population per hectare, people/ha), P – population (number of inhabitants) and Ab – area of built-up land (hectares).

For the analysis, grouping, categorization, and classification methods were used. *Grouping* was used to organize the statistical data by key analytical

dimensions, including time periods (2005–2010, 2010–2015, 2015–2025), territorial units (Lithuania and ten counties), and thematic indicators (built-up area extent, population, population density, and compactness index). This approach allowed for the identification of temporal trends and spatial patterns in a structured manner.

Categorization was applied to transform continuous quantitative variables into meaningful analytical classes. For instance, built-up area compactness values were categorized into three interpretative levels: low, medium, and high compactness. This procedure facilitated the interpretation of spatial urban structure by simplifying complex numerical distributions into conceptually clear categories that reflect different stages and forms of urban development.

Classification was used to assign observed values and calculated indicators into predefined typologies based on defined threshold values. In particular, the intensity of built-up area change was classified into three development types: intensive (>40%), medium (20–40%), and passive (<20%). This classification enabled the assessment of the magnitude of spatial change and supported comparative evaluation between counties and time periods.

Built-up area compactness data were classified into three categories: low, medium, and high compactness. Low compactness of built-up areas is a spatial characteristic of urban structure that describes low building density and a fragmented, dispersed distribution of buildings within a territory. Such a spatial pattern is often associated with peri-urban zones, suburban expansion, or a dispersed type of urbanisation, and may indicate the dispersion of urbanisation processes and increasing territorial fragmentation.

Medium-density urbanization represents a transitional urban structure in which the city core is relatively dense but is surrounded by lower-density residential and functional zones.

High compactness reflects efficient use of urbanized areas and can facilitate infrastructure development and service planning.

In analyzing changes in built-up areas from 2005 to 2025, three phases were distinguished: 2005–2010 – stagnation, 2010–2015 – rapid increase, and 2015 – 2025 – stabilization with slow growth. The temporal segmentation was based on changes in the rate of built-up area growth identified through comparative trend analysis across sub-periods.

Based on calculations of area changes in hectares and percentages, types of built-up area development intensity were identified: intensive (>40%), medium (20–40%), and passive (<20%). The thresholds between low, medium, and high intensity of built-up area expansion were determined based on land cover change analysis methodologies widely applied in remote sensing and GIS studies (Coppin et al., 2004), as well as in urban expansion assessment research (Seto et al., 2011; Angel et al., 2011), and the European Environment Agency's CORINE Land Cover methodology (EEA, 2019).

A descriptive and comparative statistical analysis was conducted, including comparisons of built-up areas (ha and %), population density, compactness indices, and temporal changes in built-up areas across counties between 2005 and 2025, using Land Fund statistical data (Nacionalinė…, 2005–2025) and Eurostat data (2022, 2025).

In addition to quantitative and comparative statistical methods, the study employed analytical and logical reasoning approaches to interpret spatial and temporal patterns of built-up area change. The analytical approach involved the systematic decomposition of complex spatial datasets into key variables (e.g., built-up area, population density, and compactness indices) in order to identify relationships, trends, and structural differences across counties over the study period (2005–2025). This approach is consistent with spatial analysis principles commonly applied in GIS-based land use research, where multivariate datasets are interpreted to reveal underlying spatial processes (Longley et al., 2015; O'Sullivan & Unwin, 2010).

The logical reasoning approach was applied to interpret results and to derive coherent explanations, such as differences in urban growth intensity among counties. This involved inductive reasoning, where general patterns were inferred from observed data trends, and deductive reasoning, where theoretical concepts of urban expansion and land-use change were used to interpret empirical findings. Such reasoning is widely recognized as a fundamental component of geographic and environmental research, particularly in studies of land-use dynamics and urbanization processes (Lambin & Geist, 2006; Seto et al., 2011).

Results and Discussion

Analysis of Built-Up Area Extent in 2025

According to 2025 data, built-up areas in Lithuania covered 248,550.05 ha, representing 3.81% of the country's total area. Including roads, built-up areas account for 5.45% of the national territory. According to Eurostat (2022), in 2022 man-made or built-up areas represented 4.4 % of the total area of the EU, with variations across individual member states (Eurostat, 2022).

The analysis of the share of built-up areas across ten Lithuanian counties reveals significant regional differences in urbanization. The largest built-up areas were recorded in Vilnius County (49,953.55 ha, or 5.1%) and Kaunas County (41,059.83 ha, or 5.08%), Table 1. In three counties – Vilnius, Kaunas, and Klaipėda – built-up areas account for more than 4.5% of the total county area. These territories represent the main cores of Lithuania, where concentration of population, services, infrastructure, and economic activities drives continuous land conversion from agricultural and natural land to built-up land. The average built-up share in these counties is approximately 5.0%, which is significantly above the

national average of 3.81%, indicating a clear core–periphery urban structure.

In contrast, the lowest values are recorded in Tauragė (2.74%) and Utena (3.01%) counties, which are characterized by dispersed settlement structures and predominantly rural land use. These counties also show a higher proportion of agricultural and forest land, reflecting a less intensive transformation of natural landscapes into urban fabric. Urbanization processes in Tauragė County are not intensive, as the landscape is predominantly agricultural. In 2025, agricultural land in the county covered 246,781.22 ha, or 55.98%, compared to the Lithuanian average of 51.55%. In contrast, forests in Utena County covered 248,691.56 ha, or 34.59% (the national average is 32.86%). The density of built-up areas in these counties is low, reflecting a predominantly rural landscape structure. In the remaining six counties, the share of built-up areas ranges from 3.10% to 3.67%, indicating a medium density of built-up areas.

So, the share of built-up areas varies from 2.74% to 5.13%, indicating moderate but clearly differentiated levels of urbanization intensity across the country.

Table 1

Built-Up area of Lithuanian counties in 2025 (ha and %)

Counties	Built-up area (ha)	Built-up area as a percentage of total territory (%)
Alytus	16,700.78	3.08
Kaunas	41,059.83	5.08
Klaipėda	24,898.94	4.77
Marijampolė	16,367.09	3.67
Panevėžys	24,949.51	3.17
Šiauliai	26,439.20	3.10
Tauragė	12,098.51	2.74
Telšiai	14,466.05	3.33
Utena	21,616.59	3.01
Vilnius	49,953.55	5.13

(Nacionaline…, 2005–2025).

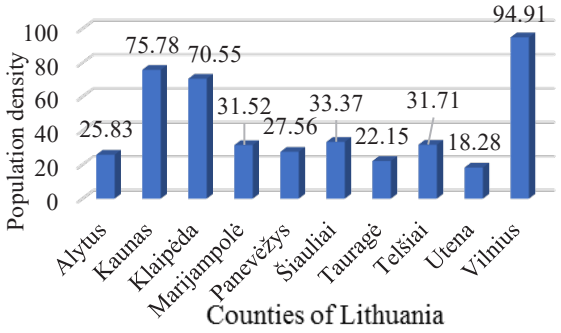
From a statistical perspective, the distribution of built-up areas shows a positively skewed pattern, where a few highly urbanized counties (Vilnius, Kaunas, Klaipėda) concentrate significantly higher built-up shares, while the majority of counties cluster around the lower and medium range (3.0–3.7%). This supports a polycentric but uneven urban structure, dominated by strong centers.

Relationship between built-up area share and population density

The analysis of built-up area shares in relation to population density shows that urbanization intensity depends on demographic conditions. The highest population densities were recorded in Vilnius (94.92 inhabitants/km²), Kaunas (75.78 inhabitants/km²), and Klaipėda (70.55 inhabitants/km²) counties, see Figure 1. From this analysis, it is evident that these counties also have the largest shares of built-up areas. Therefore, in counties with the highest populations, economic activities are more developed, and the expansion of built-up areas occurs more rapidly. This confirms a strong positive spatial association between demographic concentration and land conversion intensity.

Figure 1

Population density of Lithuanian counties in 2025 (inhabitants/km²)



Peripheral counties (Utena, Tauragė, Alytus, and Marijampolė) exhibit lower urbanization intensity and have smaller populations, resulting in dispersed built-up areas and lower land-use efficiency. This spatial pattern is closely related to the structure of land cover, particularly the balance between agricultural land and forests.

In these regions, land-use composition shows a dual tendency: while Marijampolė retains a highly agricultural character with 66.5% agricultural land and relatively low forest cover (21.42%), Utena and Alytus demonstrate the opposite pattern, with significantly higher proportions of forested areas (34.59% and 48.09%, respectively) and lower shares of agricultural land (43.73% and 34.9%). Tauragė represents a more balanced but still relatively forest-influenced structure, where forests occupy 32.94% and agricultural land 56.01%.

This distribution suggests that peripheral counties are characterized not only by lower urbanization but also by more heterogeneous land-use systems, where natural and semi-natural landscapes (forests) play a more dominant role compared to intensively cultivated agricultural land. In contrast to central Lithuanian regions, where agricultural land dominates and supports more intensive land management systems, peripheral areas reflect a transition toward less intensive land exploitation and greater ecological continuity.

In the country, the population in 2025 was three million fifty-four thousand five hundred forty-nine (Registrų centras, 2025). In Lithuania, with a population density of 46.79 inhabitants/km² and a 3.81% share of built-up areas, the intensity of urbanization is relatively low.

In 2023, the average population density across the EU was 109 inhabitants per km² although this figure varied

widely among member states. Malta had the highest density, with 1,766 inhabitants per km², followed by the Netherlands (526) and Belgium (387). In contrast, Finland (18) and Sweden (26) recorded the lowest population densities (Eurostat, 2025).

Thus, the analysis indicates that urbanization intensity in Lithuania is lower than the EU average, meaning that residents are less densely settled in built-up areas compared to the European average. In this context, Lithuania occupies an intermediate but low-intensity urbanization position, characterized by dispersed settlement patterns and relatively large shares of agricultural and natural land.

Built-up Area Compactness. The data analysis shows that Vilnius County is characterized by the most compact settlement structure, with the highest built-up area density (18.5 inhabitants per hectare), the greatest overall population density (94.91 inhabitants per km²), and the largest share of built-up land (5.13%), distinguishing it from all other counties in terms of urban concentration and land-use intensity.

At the national level, Kaunas and Klaipėda counties also exhibit relatively high compactness, at 14.93 inhabitants/ha and 14.79 inhabitants/ha, respectively.

Medium compactness of built-up areas was recorded in Marijampolė (8.60), Panevėžys (8.70), Telšiai (9.53), and Šiauliai (10.78) counties, Table 2.

Table 2

Distribution of counties by built-up area compactness categories

Built-up area compactness category	Counties and built-up area compactness (inh/ hectare)	Urban form type	Nature of transformation
Low compactness	Utena (6.08)	Low-density urbanization	Dispersed structure, dominated by single-family houses, weak concentration of urban centers
	Tauragė (8.07)	Low-density urbanization	Sparse, fragmented development with a limited urban structure
	Alytus (8.38)	Low-density urbanization	Dispersed development, dominated by residential houses and homestead-style settlement patterns
Medium compactness	Marijam-polė (8.60)	Mixed-density urbanization	Urban core with low and medium-density zones
	Panevėžys (8.70)	Mixed-density urbanization	Functionally differentiated structure with dominance of the city center
	Telšiai (9.53)	Mixed-density urbanization	Historically formed urban structure
	Šiauliai (10.78)	Mixed-density urbanization	Balanced structure with medium-density built-up areas and peripheral zones
High compactness	Klaipėda (14.79)	High-density urbanization	Compact, multifunctional structure with integrated port and industrial functions
	Kaunas (14.93)	High-density urbanization	Compact urban fabric with active suburban densification
	Vilnius (18.49)	High-density urbanization	Metropolitan structure, highly intensive, with strong functional concentration

The lowest compactness of built-up areas was observed in Utena County, at 6.1 inhabitants/ha. In 2025, built-up areas in Utena County covered 21,616.59 ha, representing 3.01% of the county, with a low population density of 18.28 inhabitants/km². This indicates that Utena County has a low population density and a dispersed urban structure. Low-density urbanization is a form of urban development characterized by a small population spread over a large built-up area, resulting in a scattered and minimally compact urban structure. After carrying out the calculations, it was found that the overall compactness of built-up areas in Lithuania is 12.29 inhabitants per hectare. This value indicates medium-density urbanisation, suggesting that urbanised areas are not excessively dispersed. An analysis of built-up compactness and population density shows a mixed urban structure: concentrated in major cities and their surroundings, and fragmented in peripheral counties.

In Vilnius, Kaunas, and Klaipėda counties, apartment buildings dominate the housing stock. This is associated with a high level of urbanization, strong population concentration, and the Soviet-era development pattern of apartment housing, which has persisted to the present day.

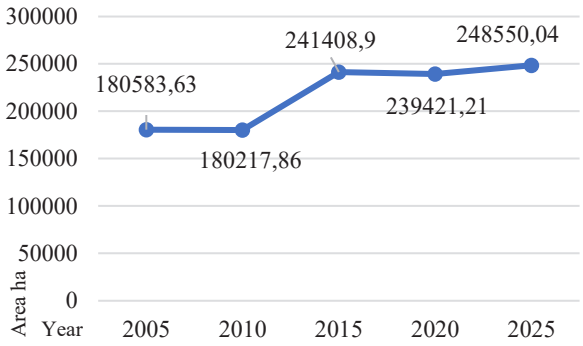
In contrast, in peripheral counties such as Utena, Tauragė, Telšiai, Alytus, and Marijampolė, single-family houses are predominant. In these regions, single-family dwellings typically account for 65–85% of the total housing stock, while the share of apartment buildings is significantly lower.

For example, in Utena and Alytus regions, single-family houses often exceed the 70% threshold.

Changes in the extent of built-up areas in Lithuanian counties, 2005–2025

An analysis of changes in the extent of built-up areas in Lithuanian counties between 2005 and 2025 (in hectares) shows that counties containing major cities – Vilnius, Kaunas, and Klaipėda – experienced the most consistent and greatest expansion of built-up areas. In Šiauliai, Panevėžys, and Telšiai counties, the expansion of built-up areas was uneven: the area increased rapidly until 2015 and then stabilized, Figure 2.

Figure 2
Changes in the extent of built-up areas in Lithuania, 2005–2025 (ha)



Source: (Nacionalinė…, 2005–2025).

Although demographic indicators declined throughout the entire period in Utena and Alytus counties, intensive development still occurred, indicating inefficiencies in territorial structure and a tendency towards urban fragmentation.

As shown in Figure 2, changes in built-up areas in Lithuania during 2005–2025 were uneven, and three distinct stages can be identified: 2005–2010 – stagnation; 2010–2015 – rapid growth; and 2015–2025 – relative equilibrium with slow growth.

This pattern is supported by the data: built-up areas accounted for 180,583.63 ha in 2005 and remained nearly unchanged in 2010 (180,217.86 ha). A sharp increase was observed in 2015, reaching 241,408.90 ha, followed by a slight decrease and stabilization in 2020 (239,421.21 ha), and a modest increase again in 2025 (248,550.04 ha).

Interval-based data analysis indicates that the most rapid expansion of built-up areas in Lithuania occurred during 2010–2025, amounting to 61,191.04 ha, or 33.95%. Overall, analysis of changes in the extent of built-up areas in Lithuania between 2005 and 2025 shows that the analysed area increased by 67,966.42 ha, or 37.64%.

The analysis of changes in the extent of built-up areas (ha) revealed that Vilnius County experienced the largest increase, amounting to 14,744.87 ha.

In contrast, the smallest absolute expansion occurred in Tauragė County, where built-up areas increased by 2,797.18 ha, Figure 3.

Figure 3
Changes in the extent of built-up areas in Lithuanian counties, 2005–2025 (ha)



	Alytus	Kaunas	Klaipėda	Marijamp	Panevėžys	Šiauliai	Tauragė	Telšiai	Utena	Vilnius
2005	11107.53	33477.38	14028.63	11662.42	19939.62	21120.36	9301.33	9995.02	14742.66	35208.68
2010	11149.53	33919.51	13333.45	11579.71	19215.9	21529.05	9301.32	9968.46	14755.46	35465.47
2015	16055.19	40217.07	23134.97	16675.7	25620.29	26571.25	12285.98	14203.23	21037.86	45607.36
2020	16064.12	40352.73	23266.04	16259.84	24692.22	25718.58	11811.16	14029.63	20913.55	46313.34
2025	16700.78	41059.83	24898.94	16367.09	24949.51	26439.2	12098.51	14466.05	21616.59	49953.55

Source: (Nacionalinė…, 2005–2025).

Analysis of the data presented in Table 3, expressed as percentages, shows that during 2005–2025 the extent of built-up areas increased by 77.49% in Klaipėda County and by 50.36% in Alytus County. These represent the highest urbanisation indicators in the country over the analysed period.
The lowest percentage growth in built-up areas was recorded in Kaunas County (22.65%) and Panevėžys County (25.13%).

Table 3
Changes in the extent of built-up areas in Lithuanian counties, 2005–2025 (ha and %)

Counties	Changes in built-up areas (ha)	Changes in built-up areas (%)
Alytus	+5,593.25	+50.36
Kaunas	+7,582.45	+22.65
Klaipėda	+10,870.31	+77.49
Marijampolė	+4,704.67	+40.34
Panevėžys	+5,009.89	+25.13
Šiauliai	+5,318.84	+25.18
Tauragė	+2,797.18	+30.07
Telšiai	+4,471.03	+44.73
Utena	+6,873.93	+46.63
Vilnius	+14,744.87	+41.88

Based on the observed changes in built-up area extent during 2005–2025, the author of this study identified the following types of change.

- >40% – intensive change (Vilnius, Klaipėda, Alytus, Marijampolė, Telšiai, Utena counties);
- 20–40% – moderate change (Kaunas, Šiauliai, Panevėžys, Tauragė counties);
- <20% – passive change.

The study found that intensive and moderate expansion of built-up areas predominated across Lithuanian counties.
The analysis revealed that the expansion of built-up areas in Lithuania during 2005–2025 was uneven. Vilnius, Kaunas, and Klaipėda counties experienced the highest intensity of development and exhibited high compactness, while in other counties urbanisation increased in relative terms but the areas remained more dispersed.
Future expansion of built-up areas will depend on political factors (taxation, subsidies, development strategies), economic factors (job creation, investments in real estate and infrastructure, demographic growth), social factors (population needs, standard of living), and planning factors (legal framework, including laws and building permits, as well as territorial planning documents).
Based on the data and analysis of changes in built-up area extent during 2005–2025, it can be expected that counties containing major cities – Vilnius, Kaunas, and Klaipėda – will remain the primary centres of urbanisation. Expansion is likely to occur both within the cities themselves and in suburban areas and surrounding county districts. In other counties (Utena, Telšiai, Alytus, Marijampolė), development will also continue, with growth in residential quarters and suburban areas. Therefore, future development is expected to involve both residential and commercial areas, along with supporting infrastructure.

Conclusions

1. In 2025, built-up areas covered 248,550.05 ha, accounting for 3.81% of the national territory. The largest built-up areas were recorded in Vilnius County (49,953.55 ha or 5.13%) and Kaunas County (41,059.83 ha or 5.08%), while Tauragė (2.74%) and Utena (3.01%) counties had the smallest share.
2. The highest population densities were observed in Vilnius (94.92 inhabitants/km²), Kaunas (75.78 inhabitants/km²), and Klaipėda (70.55 inhabitants/km²) counties, where built-up area expansion was also the fastest. Utena (18.28 inhabitants/km²), Tauragė (22.15 inhabitants/km²), and Alytus (25.83 inhabitants/km²) counties had low population densities and a dispersed urban structure.
3. The analysis of built-up area compactness revealed that Vilnius County stands out with the highest compactness at 18.5 inhabitants/ha. Kaunas and Klaipėda counties also exhibit high density (14.93 and 14.79 inhabitants/ha, respectively). The lowest population densities per hectare were recorded in Utena (6.08 inhabitants/ha) and Tauragė (8.07 inhabitants/ha), while the national average compactness is 12.29 inhabitants/ha, indicating medium-density urbanisation.
4. Analysis of changes in built-up area extent during 2005–2025 reveals that the total built-up area in Lithuania increased by 67,966.42 ha, or 37.64%. The largest absolute increase occurred in Vilnius County (14,744.87 ha), but the smallest in Tauragė County (2,797.18 ha). In percentage terms, the fastest urbanisation took place in Klaipėda (77.49%) and Utena (46.63%) counties.

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AGRICULTURAL LAND CHANGE IN LITHUANIA AND ITS COUNTIES (2005–2025)

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Abstract
This study examines changes in agricultural land areas in Lithuania between 2005 and 2025, focusing on their spatial distribution, dynamics, and structural characteristics across all ten counties. The main objectives were to evaluate the current state of agricultural land, analyze its temporal changes over two decades, and identify the main factors influencing these transformations. The study is based on data from the National Land Service of Lithuania covering the period 2005–2025. Both absolute values (hectares) and relative shares (%) of agricultural land by county were analyzed. Agricultural land dynamics were assessed for the years 2005, 2010, 2015, 2020, 2025. Counties were classified according to the intensity of agricultural land change: rapid decrease, moderate change, or relative stability. In 2025, agricultural land in Lithuania covered 3,365.699.61 ha, representing 51.55% of the national territory. The largest shares of agricultural land were recorded in Marijampolė (66.49%), Šiauliai (61.46%), and Panevėžys (60.23%) counties, while the smallest shares were observed in Alytus (34.89%), Vilnius (38.55%), and Utena (43.73%) counties. During the period 2005–2025, the total agricultural land area decreased by 117,246.88 ha (3.37%). The most significant reductions occurred in Vilnius, Utena, and Alytus counties. Structurally stable agricultural land patterns were observed in Kaunas, Marijampolė, Tauragė, and Telšiai counties. The decline of agricultural land is driven by urbanization, suburban expansion, infrastructure development, land-use changes, economic factors, decreasing agricultural intensity, ecological conditions, and regional characteristics. The results indicate that intensive agrarian landscapes are likely to persist in structurally stable regions, whereas more urbanized and environmentally constrained areas may continue to experience agricultural land loss.
Key words: agricultural land, the intensity of change, area changes.

Introduction

The European landscape is shaped by various factors, among which agriculture plays a significant role (Jerrentrup et al., 2017), encompassing agricultural land such as arable land, meadows, natural pastures, and orchards. These areas are used for crop and livestock production as well as other agricultural activities. Agricultural practices include soil preparation, irrigation, sowing, planting, crop management, pest control, harvesting, and other related activities (Farmonaut, 2025b).

Research on changes in the structure of agricultural land is an important field of study (Yan-gang, 2009). Land-use changes are driven by economic, social, legal, biophysical, and various environmental factors. These changes have a significant impact on landscape structure and function (Yan-gang, 2009; Baessler & Klotz, 2005; Xian-jin, 2002; Chun-me, 2014; Reulier et al., 2018). Assessing land-use change trends helps to identify patterns of transformation in agricultural areas and supports the development of sustainable land-use policies (Yan-gang, 2009; Gniadek et al., 2019; Yazdanpanah et al., 2025).

Scientific literature indicates that changes in agricultural land use are driven by a complex interplay of economic, social, and environmental factors, with economic development, urbanization, and climate change identified as particularly influential (Food and Agriculture Organization, 2017; Intergovernmental Panel on Climate Change, 2022). Land use and land cover change studies emphasize that these processes extend beyond purely agrarian transformations and reflect broader landscape dynamics closely linked to socio-economic development (Lambin et al., 2001; Foley et al., 2005; Verburg et al., 2013). Agricultural land is frequently converted into urban areas, forests, or natural habitats depending on regional political priorities, economic conditions, and planning frameworks. Economic growth and market demand play a central role, as land is often reallocated to more profitable uses or adapted to changing consumption patterns and population dynamics. In addition, structural changes such as labor migration, farm consolidation, and shifts in agricultural practices significantly reshape land-use patterns. These transformations increasingly occur at multiple spatial scales, including the global level, with important implications for food security, ecosystem functioning, and the sustainability of landscapes (Rong & Fu, 2023).

Economic factors are among the primary drivers of changes in agricultural land use (Chun-me, 2014). Key influences include low productivity, declining farm profitability, and the conversion of agricultural land into urbanized areas in pursuit of higher economic returns. These processes are further shaped by limited financial capacity to develop farming activities, the effects of economic sanctions and inflation, unemployment, and insufficient income from agricultural production. Income disparities among low-income farmers may encourage their withdrawal from the agricultural sector and a transition toward alternative economic activities. Research indicates that farming costs, gross income, land ownership structure, labor allocation, access to capital, infrastructure quality, and market accessibility are critical economic factors influencing changes in agricultural land use

(Agricultural…, 2025).

Climate change and natural environmental processes also exert a significant influence on the structure of agricultural land. Scientific studies demonstrate that variability in climatic conditions alters land suitability for agricultural activities, compelling farmers to reallocate land to different crops or abandon portions of cultivated land altogether. Such decisions often represent adaptive responses to changing climatic conditions (Tahmasebi et al., 2020).

Processes of farm intensification and diversification are evident in the use of agricultural land (Xian-jin, 2002; Li & Wang, 2002). For example, in China, between 1988 and 2009, the area of arable land decreased significantly, while orchards and forested land became concentrated in more favorable locations (Sha-sha et al., 2013). Globally, since 2001, the total area of arable land has increased by approximately 80 million hectares (5%), whereas permanent meadows and pastures have decreased by 150 million hectares (Food…, 2025). The intensive use of agricultural land depletes natural resources, alters landscapes, contributes to deforestation, and increases greenhouse gas emissions.

Urban expansion is a major factor contributing to the loss and fragmentation of agricultural land (Farmonaut, 2025a). Driven by population growth and economic development, productive agricultural areas are increasingly converted to other land uses, including residential zones, industrial facilities, and urbanized spaces (Xian-jin, 2002; Yazdanpanah et al., 2025).

The structure of land ownership has changed significantly, particularly in post-socialist countries (Lerman et al., 2003; Rusu & Simionescu, 2014; Moravcová et al., 2016; Valtenbergs et al., 2018). In Latvia, an increasing share of agricultural land is owned by legal entities, often with foreign capital, whereas land owned by foreign individuals represents only a small proportion (Valtenbergs et al., 2018). Land reforms and the restoration of property rights, as in other former socialist countries, aim to adapt agricultural structures to current needs (Moravcová et al., 2016). Farm sizes have also changed; in some regions, such as Poland, the number of very small and very large farms has increased (Sikorska et al., 2008).

Transformations in land use have significant impacts on ecosystem services. For instance, the conversion of agricultural land to non-agricultural areas, such as urbanized zones, or the reduction of pastures can negatively affect biodiversity and disrupt natural ecosystem processes. This is highlighted in several review studies analyzing the environmental impacts of land-cover changes (Foley et al., 2005; Newbold et al., 2015; Hasan et al., 2020).

Long-term agricultural practices, including the application of organic and chemical inputs, significantly influence soil properties by altering the structure and functioning of microbial communities. Research shows that ecologically managed land tends to support greater microbial diversity than chemically intensive systems, leading to improved soil quality characterized by higher levels of organic carbon, nitrogen, and microbial biomass (Chaudhry et al., 2011). Nevertheless, soil degradation—manifested through compaction, loss of structure, nutrient depletion, and salinization—remains a major challenge for sustainable agriculture (World…, 2024).

In addition to environmental impacts, changes in agricultural land structure are closely linked to social and economic processes. These transformations often contribute to population migration, shifts in rural employment, and the restructuring of farming practices. Such changes can have significant implications for food security and the economic resilience of farmers. Comparable land-use transformations are observed globally, ranging from structural changes within European Union countries to intensive land-use dynamics in Southeast Asia. Together, these studies demonstrate the complex and interrelated nature of social, economic, and environmental drivers that shape and continuously modify agricultural land-use structures (Appelt et al., 2022).

However, despite the growing body of research, there remains a clear knowledge gap regarding the integrated assessment of how these interacting drivers jointly influence medium- and long-term spatial patterns of agricultural land structure at regional scales. Most existing studies tend to focus on individual drivers (e.g., economic, climatic, or urbanization processes) in isolation or emphasize either global-scale assessments or localized case studies, limiting the ability to generalize results across different socio-spatial contexts. Furthermore, fewer studies explicitly link land-use structural changes with combined socio-economic outcomes and ecosystem responses within a unified analytical framework. Addressing this gap is essential for improving understanding of the multi-dimensional processes shaping agricultural landscapes and for supporting more coherent and sustainable land-use policy development.

Research object is agricultural land.

Objective of the study is to analyze changes in agricultural land areas in the Republic of Lithuania between 2005 and 2025.

Study tasks:

1. To analyze the current state of agricultural land areas;
2. To examine changes in agricultural land areas in Lithuania and its counties from 2005 to 2025;
3. To assess the causes of changes in agricultural land areas.

Materials and Methods

The study focuses on the distribution and dynamics of agricultural land in the Republic of Lithuania, covering all ten counties. The analysis considers both absolute areas (hectares) and relative shares (%) of agricultural land within each county, as well as changes over the period 2005–2025.

The primary data were obtained from the National Land Service of Lithuania (Nacionalinė…, 2005–2025), which provides comprehensive records on agricultural land areas. Absolute agricultural land areas and relative shares were tabulated by county for 2025, and counties were ranked according to both absolute agricultural land and its share of the total area.
To assess spatial differences in agricultural land use across Lithuanian counties in 2025, a descriptive statistical analysis was applied. The analysis included calculation of:

- relative share (%) of agricultural land in each county,
- absolute values (hectares) of agricultural land,
- ranking of counties based on both indicators,
- range analysis (max–min variation between counties),
- comparative classification of counties into land-use intensity groups based on percentile distribution (high, medium, and low agricultural land share).

For interpretative purposes, counties were grouped using a quantile-based classification approach, where:

- high agricultural land use corresponds to upper quantile values,
- medium use corresponds to interquartile range values,
- low use corresponds to lower quantile values.

This approach allows identification of spatial differentiation patterns in land-use structure and supports interpretation of landscape heterogeneity across Lithuania.
Agricultural land areas for 2005, 2010, 2015, 2020, and 2025 were compared to determine trends. Annual changes were calculated to assess the intensity of agricultural land loss or stability. Based on the magnitude of change, counties were classified into three categories:

- rapid decrease: counties with high annual losses of agricultural land (Vilnius, Utena, Alytus);
- moderate change: counties with intermediate losses (Klaipėda, Šiauliai, Panevėžys);
- relatively stable: counties with minimal annual changes (Kaunas, Marijampolė, Tauragė, Telšiai).

The classification of counties according to the magnitude of agricultural land change was based on the calculated annual rate of change in agricultural land area over the study period. For each county, change values were derived from temporal differences in agricultural land extent and expressed as annual percentage change. To ensure comparability across spatial units, a threshold-based classification approach was applied, which is commonly used in spatial and land-use change analysis for grouping continuous variables into meaningful categories (Slocum et al., 2009). Thresholds were defined based on the distribution of observed values in the dataset, allowing the identification of natural breaks between different levels of change intensity. Accordingly, counties were assigned to three categories: rapid decrease (high negative annual change values), moderate change (intermediate negative values), and relatively stable conditions (minimal or near-zero annual change). This approach enables a simplified interpretation of spatial heterogeneity in land-use dynamics while preserving the underlying variability of the data and facilitating comparative regional analysis.
The relationship between agricultural land, urbanization, and population density in 2025 was examined using typological analysis and scatterplots. The relationship between agricultural land, urbanization, and population density in 2025 was analyzed using typological analysis and scatterplot visualization. Typological analysis classified spatial units (e.g., counties or municipalities) into categories based on agricultural land extent, urbanization level, and population density, identifying homogeneous groups such as highly urbanized high-density and predominantly agricultural low-density areas. Scatterplots were used to explore pairwise relationships, with agricultural land share plotted against urbanization and population density to assess trends, correlations, and potential nonlinear patterns. Together, these methods provided both a structured spatial classification and an exploratory quantitative assessment of land-use–population relationships.
To assess temporal and spatial changes in agricultural land area between 2005 and 2025, a time-series descriptive statistical and change analysis was applied. The method included calculation of absolute and relative changes in agricultural land area at both national and county levels.
To evaluate differences among counties and across time periods, a percentage change comparison approach was used, allowing identification of spatial heterogeneity in land-use dynamics. The results were visualized using a time-series trend diagram.
After conducting an analysis of changes in agricultural land areas, the causes of these changes were identified. Based on observed trends from 2005–2025, projections were made regarding the persistence or reduction of agricultural land in each county, taking into account urbanization pressure, suburban expansion, and demographic characteristics.
The estimated average annual decrease in agricultural land was determined by dividing the total change in area from 2005 to 2025 by the 20-year interval.
To estimate future agricultural land-use dynamics, a second-degree polynomial trend model was applied. The model was used to capture potential non-linear patterns in land-use change over time, allowing for the representation of accelerating or decelerating trends. The general form of the model is expressed as, Formula 1:

$$Y_t = at^2 + bt + c \quad (1)$$

where: Y_t – agricultural land area (ha) at time t; t – time variable (year or sequential time index); a, b, c – coefficients estimated from observed data.
The model was fitted separately for each county to

account for spatial heterogeneity in land-use dynamics. Model parameters were estimated based on observed 2005–2025 data using polynomial trend fitting. The resulting county-specific functions were then used for extrapolation beyond the observed period. Forecasts were generated for the years 2030, 2035, and 2040 by extending the fitted polynomial trend lines. In addition to county-level projections, national-level values for Lithuania were obtained by aggregating the projected county estimates. The modelling approach allows identification of long-term tendencies in agricultural land-use change and differences between regions. The polynomial structure captures non-linear trend behavior, which is particularly relevant for areas affected by urban expansion and land-use conversion processes. The resulting projections are interpreted as trend-based scenario estimates rather than exact predictions. They reflect the continuation of historical dynamics under the assumption that observed patterns persist into the future without abrupt structural changes.

Figures and tables were generated to present the spatial distribution and temporal dynamics of agricultural land.

Results and Discussion

Analysis of agricultural land areas in 2025

In 2025, agricultural land in the Republic of Lithuania covered an area of 3,365,699.61 ha, accounting for 51.55% of the country's territory. This indicates that more than half of Lithuania's land area is used for agricultural activities. The data presented in Table 1 demonstrate substantial differences in agricultural land areas among the country's counties.

Table 1

Agricultural land area in Lithuanian counties in 2025 (ha and %)

Counties	Agricultural land area in 2025 (ha)	Share of agricultural land (%)
Alytus	189,022.42	34.89
Kaunas	450,355.52	55.69
Klaipėda	270,289.10	51.76
Marijampolė	296,902.01	66.49
Panevėžys	474,520.40	60.23
Šiauliai	524,731.29	61.46
Tauragė	246,781.22	55.98
Telšiai	223,523.37	51.39
Utena	314,486.43	43.73
Vilnius	375,087.85	38.55

Source: (Nacionalinė…, 2005–2025).

A county-level analysis reveals a clear spatial gradient in agricultural land use intensity. The highest proportions of agricultural land were observed in Marijampolė County (66.49%), Šiauliai County (61.46%), and Panevėžys County (60.23%). These territories form a coherent high-intensity agricultural core of Lithuania, characterized by fertile soils, favorable relief conditions, and long-established agrarian specialization, which collectively support extensive agricultural production systems.

A second group of counties, including Tauragė (55.98%), Kaunas (55.69%), Klaipėda (51.76%), and Telšiai (51.39%), demonstrates a more balanced land-use structure. In these regions, agricultural land remains a dominant component; however, it coexists with significant urban, forested, and semi-natural areas. This indicates a transitional landscape type where agricultural functions are integrated within more heterogeneous spatial systems.

The lowest shares of agricultural land were identified in Alytus (34.89%), Vilnius (38.55%), and Utena (43.73%) counties, where a larger proportion of the territory is occupied by forests, lakes, protected areas, and urbanized zones – particularly in Vilnius County. Consequently, the share of agricultural land in these counties is comparatively smaller.

When agricultural land areas are examined in absolute terms (hectares), the largest areas were recorded in Šiauliai (524,731.29 ha), Panevėžys (474,520.40 ha), and Kaunas (450,355.52 ha) counties.

Although Vilnius County is the largest in terms of total area, it is characterized by a relatively low share of agricultural land (375,087.85 ha or 38.55%), reflecting the strong influence of urbanization and infrastructure development.

Marijampolė County stands out not only for having the highest proportion of agricultural land (66.49%), but also for its clear agrarian specialization within the national context.

Overall, in 2025, Lithuanian counties show clear differentiation in terms of agricultural land use intensity and landscape diversity. Central and northern Lithuania (Marijampolė, Šiauliai, and Panevėžys counties) is characterized by intensively agrarian landscapes, while southern and eastern Lithuania (Alytus, Utena, and Vilnius counties) exhibits a predominantly natural–urbanized landscape type. Kaunas, Tauragė, Klaipėda, and Telšiai counties occupy an intermediate position, with mixed landscapes reflecting a more balanced land-use structure.

To broaden the analysis, the interrelationships between agricultural land, urbanization, and population density in 2025 were examined. The typological analysis presented in Figure 1 reveals several important relationships between agricultural land share, population density, and the extent of urbanized areas. Intensively agrarian counties (Marijampolė, Šiauliai, and Panevėžys) are characterized by a high share of agricultural land (60.23–66.49%) and medium population density (approximately 28–61 inhabitants/km²). This indicates that agriculture dominates in these territories, while urbanization pressure remains relatively low.

In counties where agricultural land occupies a large proportion of the territory, the level of urbanization is generally lower. Šiauliai, Panevėžys, and Marijampolė counties contain some of the largest agricultural land areas (ranging from 296,902.01 ha to 524,731.29 ha), yet the share of built-up areas does not exceed 3.7%. This reflects the predominantly agrarian character of these regions and the limited intensity of urban development.

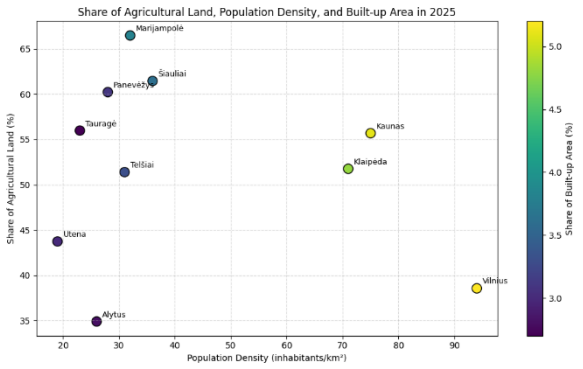
In counties with low population density – Utena (18.28 inhabitants/km²), Tauragė (22.15 inhabitants/km²), and Alytus (25.83 inhabitants/km²) – agricultural land areas in 2025 ranged from low to moderate (189,022.42 ha to 246,781.22 ha), while the share of urbanized areas remained small (approximately 2.7–3.1%). This suggests that low population density creates favorable conditions for more extensive land use and slower urbanization processes.

In 2025, agricultural land accounted for 38.55% of Vilnius County, which also recorded a high population density (95 inhabitants/km²) and the largest share of built-up areas among all ten counties (5.13%). These indicators point to strong urbanization pressure, suggesting that a portion of agricultural land may be converted into urbanized areas in the future.

Overall, Figure 1 illustrates a clear negative relationship: as population density and the extent of built-up areas increase, the share of agricultural land decreases. Larger extents of built-up areas are concentrated in more urbanized counties, such as Vilnius and Kaunas, while smaller extents prevail mainly in agrarian regions.

Figure 1

The Interrelation of Agricultural Land, Urbanization, and Population Density in 2025



The analysis of agricultural land in 2025 shows that Lithuania's counties are clearly differentiated in terms of agrarian landscape intensity, urbanization pressure, and landscape heterogeneity. This assessment enables a systematic evaluation of the territorial agrarian structure and supports the planning of land-use policies that consider the interactions between urbanization and the natural environment.

Analysis of Changes in Agricultural Land in Lithuania, 2005–2025

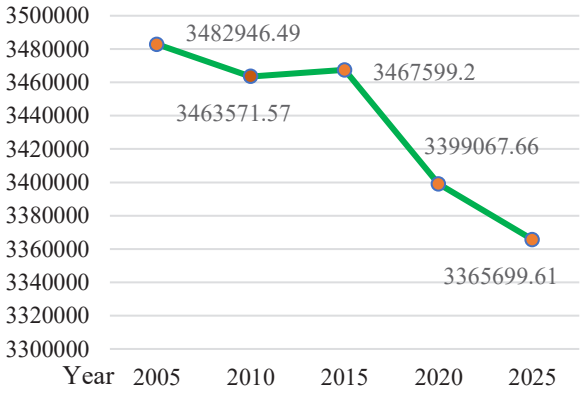
Between 2005 and 2025, the area of agricultural land in Lithuania steadily declined. Nationally, agricultural land decreased from 3,482,946.49 ha in 2005 to 3,463,571.57 ha in 2010, corresponding to a reduction of 0.56%. In 2015, the area slightly increased to 3,467,599.2 ha, but it remained below 2005 level. By 2020, agricultural land had fallen to 3,399,067.66 ha, and in 2025 it reached 3,365,699.61 ha, approximately 0.98% less than in 2020. Over the entire 2005–2025 period, Lithuania's agricultural land declined by 117,246.88 ha, or 3.37%, Figure 2.

The analysis of agricultural land from 2005 to 2025 shows that its area decreased in all counties of the Republic of Lithuania, indicating a nationwide and persistent trend of agricultural land contraction over the past two decades. However, the magnitude of change varied considerably between counties, indicating strong spatial heterogeneity. These differences reflect varying intensities of urbanization pressure, demographic dynamics, and regional land-use policies.

The results demonstrate that although agricultural land remains a dominant land-use category in Lithuania, its gradual decline and uneven spatial distribution indicate ongoing structural transformation of the national landscape system.

Figure 2

Changes in Agricultural Land Areas in Lithuania, 2005–2025 (ha)



Source: (Nacionalinė…, 2005–2025).

Between 2005 and 2025, the largest decreases in agricultural land were observed in Vilnius (38,068.39 ha or 9.22%), Utena (23,149.01 ha or 6.86%), and Alytus (14,523.58 ha or 7.14%) counties. The smallest percentage changes were recorded in Tauragė (0.60%) and Kaunas (0.82%) counties, Table 2.

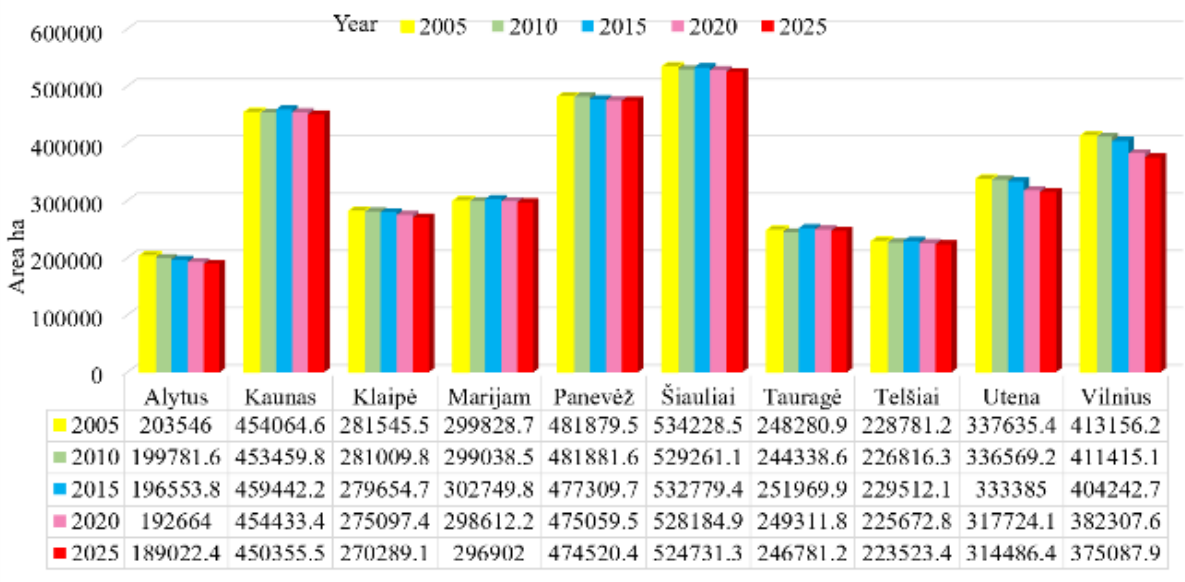
According to data on changes in agricultural land from 2005 to 2025, Lithuanian counties can be divided into three main groups based on the scale and intensity of changes: rapidly decreasing agricultural land, moderate change, and relatively stable.

This regional typology allows for a systematic assessment of territorial differences and highlights the prevailing land-use processes.

The estimated average annual decrease in agricultural land, calculated as the total change between 2005 and 2025 divided by the 20-year period, was highest in Vilnius County, where approximately 1,903 ha per year were lost. This indicates a strong long-term tendency of agricultural land conversion driven by urbanization, suburban expansion, and infrastructure development.

Figure 3

Changes in Agricultural Land Areas of Lithuanian Counties, 2005–2025 (ha)



	Alytus	Kaunas	Klaipė	Marijam	Panevėž	Šiauliai	Tauragė	Telšiai	Utena	Vilnius
2005	203546	454064.6	281545.5	299828.7	481879.5	534228.5	248280.9	228781.2	337635.4	413156.2
2010	199781.6	453459.8	281009.8	299038.5	481881.6	529261.1	244338.6	226816.3	336569.2	411415.1
2015	196553.8	459442.2	279654.7	302749.8	477309.7	532779.4	251969.9	229512.1	333385	404242.7
2020	192664	454433.4	275097.4	298612.2	475059.5	528184.9	249311.8	225672.8	317724.1	382307.6
2025	189022.4	450355.5	270289.1	296902	474520.4	524731.3	246781.2	223523.4	314486.4	375087.9

Source: (Nacionaline…, 2005–2025).

In Utena county, the average annual decrease was about 1,157 ha, and in Alytus county about 726 ha per year, also indicating significant and long-term contraction of agricultural land.

Table 2

Changes in Agricultural Land Areas of Lithuanian Counties, 2005–2025 (ha and %)

Counties	Change ha	Change %
Alytus	–14,523.58	–7.14
Kaunas	–3,709.09	–0.82
Klaipėda	–11,256.39	–4.00
Marijampolė	–2,926.70	–0.98
Panevėžys	–7,359.05	–1.53
Šiauliai	–9,497.21	–1.78
Tauragė	–1,499.67	–0.60
Telšiai	– 257.84	–2.30
Utena	–23,149.01	–6.86
Vilnius	–38,068.39	–9.22

Moderate changes were recorded in Klaipėda, Šiauliai, and Panevėžys counties, where the annual decrease ranged from approximately 368 to 563 ha per year. In these counties, the decline in agricultural land was consistent but less intensive than in the eastern and southern regions of Lithuania. The changes occurred gradually, often integrating agricultural activities with other functions such as urban development, industrial expansion, or transport infrastructure.

Meanwhile, Kaunas, Marijampolė, Tauragė, and Telšiai counties showed the greatest structural stability. In Tauragė County, the average annual decrease was 75 ha; in Kaunas, 185 ha; and in Marijampolė, 146 ha per year. This indicates that the agricultural land structure in these territories remained relatively stable, with agriculture continuing to play an important role in the regional land-use system.

In summary, based on land-area dynamics, the counties can be clearly differentiated into structurally stable (Tauragė, Kaunas, Marijampolė, Telšiai) and high-change (Vilnius, Utena, Alytus) territories.

Causes of agricultural land decline in Lithuania and its Counties

The decline of agricultural land in Lithuania over the past 20 years is a complex process influenced by several interrelated factors, including urbanization and suburban expansion, changes in land use and infrastructure development, economic factors and decreasing agricultural intensity, natural and ecological factors, and regional characteristics (Antrop, 2004; Foley et al., 2025). These factors affect counties differently: in intensively agrarian counties, the reduction of agricultural land has been slower, whereas in urbanized or naturally constrained counties, the decline has been more rapid.

Urbanization in major cities and their surrounding areas alters land use, with portions of agricultural land being converted into residential, commercial, or industrial areas. This impact is most pronounced in Vilnius, Kaunas, and Klaipėda counties, where population density is rising and urban infrastructure is expanding.

In some counties, such as Alytus and Utena, agricultural land is decreasing due to conversion into forests, natural pastures, or protected areas. This process is linked to biodiversity conservation, environmental policies, and forest expansion programs.

Intensively agrarian counties, including Marijampolė, Šiauliai, and Panevėžys, retain a large share of agricultural land, although minor reductions are still observed due to infrastructure development and land consolidation.

Trends

Based on the above analysis, it can be predicted that in Vilnius, Utena, and Alytus counties – where the largest reductions in agricultural land were observed over the past 20 years – urbanization pressure and suburban expansion are likely to continue reducing agricultural areas. This is especially relevant for Vilnius county, where population density and the proportion of urbanized areas are the highest. Consequently, agricultural land is expected to continue declining in urbanized and environmentally constrained counties.

Kaunas, Marijampolė, Tauragė, and Telšiai counties maintained a relatively large area of agricultural land and structural stability during 2005–2025, indicating that agriculture will remain a dominant function in these territories. This suggests that these counties will continue to form intensive agrarian landscapes.

A second-degree polynomial trend model was applied to 2005–2025 time-series data in order to project agricultural land-use dynamics across Lithuanian counties for the period 2030–2040, Table 3. The results indicate a non-linear and spatially heterogeneous decline in agricultural land, with an overall tendency toward accelerated reduction in more urbanized and economically dynamic regions.

In 2030, the largest agricultural land areas are projected in Šiauliai, Panevėžys, and Kaunas counties, reflecting their historically strong agricultural structure. However, even in these regions a gradual decline is evident. More pronounced reductions are observed in Vilnius, Klaipėda, and Utena counties, where land-use conversion processes are more intensive due to urban expansion, infrastructure development, and peri-urban land fragmentation.

By 2035 and especially by 2040, the polynomial model suggests a strengthening of the downward trend, with differences between counties becoming more pronounced. Vilnius County demonstrates the most substantial relative decrease, indicating strong pressure from urbanization and land conversion to non-agricultural uses. Similar, though slightly less intensive, patterns are observed in Klaipėda, Utena, and Tauragė counties. In contrast, Kaunas and Panevėžys counties exhibit a more gradual and stable decline, suggesting a comparatively slower pace of land-use transformation.

Table 3

Polynomial forecasting of agricultural land-use dynamics in Lithuania (ha)

County	2030	2035	2040
Alytus	185,256	181,431	177,547
Kaunas	443,449	433,836	421,660
Klaipėda	266,182	255,848	243,739
Marijampolė	292,139	285,507	276,991
Panevėžys	472,401	469,389	465,351
Šiauliai	513,064	502,702	490,504
Tauragė	241,621	235,373	227,801
Telšiai	219,343	214,254	208,345
Utena	296 610	282,890	267,311
Vilnius	352,809	329,424	302,366
Lithuania	3,295,805	3,215,633	3,121,096

At the national level, total agricultural land is projected to decrease from approximately 3.30 million ha in 2030 to about 3.12 million ha in 2040. This corresponds to a reduction of roughly 5–7% over the 10-year period, with a clear indication that the decline is not linear but accelerates over time.

Agricultural land dynamics in Lithuania generally follow the declining trend observed across the European Union; however, the scale, spatial differentiation, and underlying drivers of change are notably distinct. While agricultural land in the EU is projected to decrease modestly (approximately 1–2% per decade) (European Commission, 2021), the results of this study indicate a substantially steeper decline in Lithuania, reaching about 5–7% over the period 2030–2040. Moreover, land-use change in Lithuania is characterized by pronounced intra-national variability. In contrast, agricultural land change across Europe tends to exhibit broader regional patterns with comparatively lower internal disparities (Eurostat, 2023). The identified non-linear (polynomial) trajectory of agricultural land change in Lithuania further suggests a transitional land-use system shaped by post-socialist restructuring, demographic shifts, and uneven economic development, consistent with patterns observed in Central and Eastern Europe (Joint Research Centre, 2019). Conversely, most EU countries demonstrate more stable and gradually evolving land-use patterns, largely regulated by policy frameworks and environmental constraints (European Environment Agency, 2020). Overall, these findings indicate that Lithuania represents a more dynamic and spatially heterogeneous system of agricultural land transformation, whereas the European context reflects a relatively mature and stabilized land-use regime.

Conclusions

1. In 2025, Lithuania's agricultural land covered 51.55% of the country's territory, indicating that more than half of Lithuania's area is used for agricultural activities. The highest proportion of agricultural land was recorded in Marijampolė (66.49%), Šiauliai (61.46%), and Panevėžys (60.23%) counties, while the lowest was in Alytus (34.89%), Vilnius (38.55%), and Utena (43.73%) counties.
2. Between 2005 and 2025, Lithuania's agricultural land decreased by 117,246.88 ha, or 3.37%.
Agricultural land decreased in all counties, with the largest reductions in Vilnius (9.22%), Utena (6.86%), and Alytus (7.14%) counties. The smallest percentage changes were recorded in Tauragė (0.60%) and Kaunas (0.82%) counties.
3. Based on agricultural land dynamics, Lithuanian counties can be clearly divided into structurally stable (Tauragė, Kaunas, Marijampolė, Telšiai) and high-structural-change territories (Vilnius, Utena, Alytus). This differentiation reflects the uneven impact of urbanization, demographic processes, and land-use transformations across the counties.
4. The reduction of agricultural land in Lithuania over the last two decades is a multifaceted process driven by a combination of interconnected factors, such as urban and suburban growth, shifts in land use and infrastructure development, economic influences, ecological and natural conditions, as well as regional-specific features.
5. According to the polynomial projection, national agricultural land is expected to decrease from about 3.30 million ha in 2030 to 3.12 million ha in 2040 (−174,000 ha; ~5–7%). The largest losses are projected in Vilnius (−50,443 ha), followed by Utena (−29,299 ha) and Klaipėda (−22,443 ha), reflecting strong urbanization pressure. Smaller decreases are observed in Kaunas (−21,789 ha), Šiauliai (−22,560 ha), and Panevėžys (−7,050 ha), indicating relatively higher landscape stability.

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GREENHOUSE GAS EMISSION REDUCTION POTENTIAL ASSESSMENT FROM LAND-USE CHANGE IN AGRICULTURE

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Abstract
This study analyses the potential greenhouse gas emission reduction of land-use change interventions in agricultural land with organic soil in the district of Kuldiga, Latvia. Using the Land-use and Land-use Change and Forestry (LULUCF) decision-making support tool, three nature-based interventions were selected: agricultural land afforestation with native tree species, with monoculture of fast-growing tree species, and natural wetland forest ecosystem conversion to agricultural land. A dataset of 152 valid entries was created to analyze intervention combinations across three factors: location, agricultural use and field management. Each entry estimates the potential emission reductions that a specific combination would contribute. Non-parametric statistical methods (Kruskal-Wallis and Dunn test) were applied to determine the most influential factors of intervention efficiency, and Gamma generalized linear model was used as a basis for the prediction proposal. Results indicate that afforestation with fast-growing species offers the highest median emission reduction potential (607 t $CO_{2\text{-eq}}$ ha^{-1}), significantly exceeding other interventions. However, the most influential factor is the agricultural land-use with 26.2% effect size and landscape characteristics with 15.4%, leaving the intervention itself only the third factor in terms of greenhouse gas saving. Grasslands exhibit the highest potential across all scenarios, while field management has no significant effect. The LULUCF decision-making support tool is ideal for preliminary site selection for nature-based climate mitigation interventions, but a combination with actual land-use and baseline emission amounts would improve the user experience and strengthen spatial planning in rural areas.
Keywords: organic soil, afforestation, climate neutrality, decision support tool, spatial planning.

Introduction

Growing concern about climate adaptation and mitigation has been reflected throughout European, national, and municipal-level planning documents. As the Sustainable Energy and Climate Adaptation plan for Kuldiga district 2021 – 2030 is entering its second half, a clear path forward for the climate adaptation sector has yet to be defined. Nature-based solutions are considered essential for land-use management due to the soil potential as a carbon sink. Regarding the climate, there are dual expectations of soil: to capture and store as much carbon as possible, and to remain healthy and capable of producing food and timber yields by maintaining its structural stability and erosion resilience. Recommendations for achieving the planned emission reduction of 6 Gt CO_2 ha^{-1} across agricultural and land-use change sectors, with a focus on afforestation of organic soils (EU Strategy for Adaptation to Climate Change, 2021; National Energy and Climate Plan of Latvia, 2021; Lazdiņš, 2023; Kuldīgas novada pašvaldība, 2021).

The largest potential greenhouse gas (GHG) emission reduction potential in agricultural lands in Latvia is afforestation and agroforestry (Licite, 2024). Especially in organic soils, as they are said to contribute 3.1 million tonnes of GHG emission to the atmosphere (Lazdiņš et al., 2023). Afforestation as a carbon dioxide removal strategy and sustainable agriculture are recognized as two effective tools for increasing carbon *sinks* (MéNard et al., 2023). A set measurement of CO_2 equivalent is used when assessing climate adaptation and mitigation, including the land-use and land-use change contribution to the emission amount (Calvin et al., 2023). The focus of this article is nature-based mitigation that narrows down to carbon flux between the atmosphere, soil and biomass, while the information available as well as the measurements used in the literature and decision support tool is CO_2 equivalent of greenhouse gases (GHG).

Nature-based solutions have been implemented and studied in other European countries, showing the emission reduction effect. It is important to emphasize that the carbon sink consists of soil and biomass growing from it. Depending on the land-use type, a larger part of stored carbon can be either soil or biomass, and it can transfer during the aging process of a forest stand. Despite the rapid carbon intake and GHG retention during the initial phase of afforestation (Baumgarten et al., 2021; Pilli et al., 2016), it does not always result in net ecological carbon gains during a decadal timespan (Strand et al., 2020). For example, early age Scots pine (*Pinus sylvestris*) stand in Latvia absorbs 0.69 t C ha^{-1} in biomass and deposits soil organic carbon by 0.08 ± 0.33 t C ha^{-1} in the 0-40 cm soil layer during one year, and a juvenile Norway spruce (*Picea abies*) stand absorbs 1.05 ± 0.23 t C ha^{-1} in biomass, while soil organic carbon is reduced by 0.54 ± 0.16 t C ha^{-1}, and biomass carbon increase in Silver birch (*Betula pendula*) stand is 1.05 ± 0.23 t C ha^{-1} with a SOC extraction 0.66 ± 0.15 t C ha^{-1} (Petaja et al., 2023). The full life span of a spruce stand can offer a 1600 t C ha^{-1} accumulation during 120 year period, without mentioning of the amount stored in soil (Lazdiņš, 2023). Researchers in the United Kingdom discovered that the conversion of meadow into a forest caused a reduction in soil organic carbon. Functional shift of mycorrhizal community connected with the tree roots causes nutrient mining, where trees allocate their photosynthetic carbon into roots. It stimulates microbial growth, and by increased respiration, also increases carbon release into the atmosphere (Friggens et al., 2020).

While afforestation offers an immediate effect on climate mitigation, it does compete with agricultural land-use for food production. This leads to a careful site selection requirement for both climate farming and food production, and local criteria are needed for sustainable spatial planning in rural areas.

Since an empirical observation of all the carbon and greenhouse gas flux is too expensive, a mathematical approximation model has been developed – the Land-use and Land-use Change and Forestry (LULUCF) decision support tool. It combines 17 interventions, of which 9 consider forestry and 8 agricultural, and gives a calculated amount of GHG emission reduction in case an intervention would be implemented, together with a territory suitable for it (Nipers, 2025).

The main question that drives this research is which land-based parameters prove to be the most influential for the emission reduction in land-use change sector. What conclusions can this tool offer in order to enhance data-based decision-making process for nature-based solutions for climate mitigation in Kuldiga district?

Materials and Methods

Land-Use, Land-Use Change and Forestry (LULUCF) decision Support Tool provides potential greenhouse gas flux calculations for a collection of 17 nature-based interventions: 9 forestry and 8 agricultural land-use change. Chosen for data analysis are the following three: 1) Afforestation of agricultural land on organic soils (AGRI-FOR), 2) Restoration of natural, waterlogged forest ecosystems on organic soils in agricultural lands (FOR-AGRI), 3) Monoculture plantations of fast-growing tree species on agricultural land as an alternative to afforestation with native tree species (AGRI-MONOFOR). This selection of nature-based interventions comprises an ongoing process of rural depopulation and afforestation due to natural succession (Vinogradovs et al., 2017), which is considered a negative side effect, overtaking possibly productive territories. Therefore, a prognosis on climate mitigation effect and the most suitable implementation territories for intentional afforestation with either native or fast-growing tree species can lead to possible solutions for a site-specific and more valuable land-use. Intervention of returning wet natural forest ecosystems into agricultural land mainly is a comparison, as well as a long-term speculation, in case local food production in the future could be limited due to vast forested territories.

After an intervention is chosen, the Tool provides seven filters from which five are used as qualitative factors in an ordinal scale to determine their effect on the potential GHG emission reduction results in case they were implemented. The district of Kuldiga municipality is the experimental area. Intervention itself is the first factor, as its effect and dependence from other factors is the focus of this research. Landscape is the factor as there are four different landscape zones within the district of Kuldiga, and they differ by terrain genesis, main deposit mineral that is also soil parent material, and main land-use, as well as by their size. Agricultural management system is the third factor – either conventional (includes intensive crop production, mechanization, mineral fertilizer and chemical pesticide use, focus on productivity) or organic (extensive production that values natural processes, natural fertilizer and no chemical pesticide use, focused on soil protection). The size of a single field is the fourth factor (<20 ha or 20 – 100 ha). As the fifth factor, a filter is selected for agricultural use – Grains, oil seeds and legumes (as the widest use of arable land), Temporary cultivated grassland (mixture of grasses, forages including protein crops sown in arable land and declared for less than five consecutive years), Fallow land (green manure) and Other crops (all other agricultural production that is not vegetables, orchards and none of the abovementioned sown pure in arable land). Filters of land-use restriction and land quality based on potential productivity are not considered in this analysis.

Landscape zones (Figure 1) within the Kuldiga district are:

1) The East Kurland upland (East-up) – a slightly wavy terrain of moraine with arable land in the highest parts, and grasslands, pastures and meadows in the lowest parts, with tree and shrub intersections. Several hills in this landscape are covered with forest (mostly pine and birch with large areas of black alder tree stands – species not specified). Soil parent material is formed by various proportions of clay and sand, lowest parts of the terrain hold peat deposits. The eastern part of this landscape's agricultural land tends to overgrow with trees and shrubs.

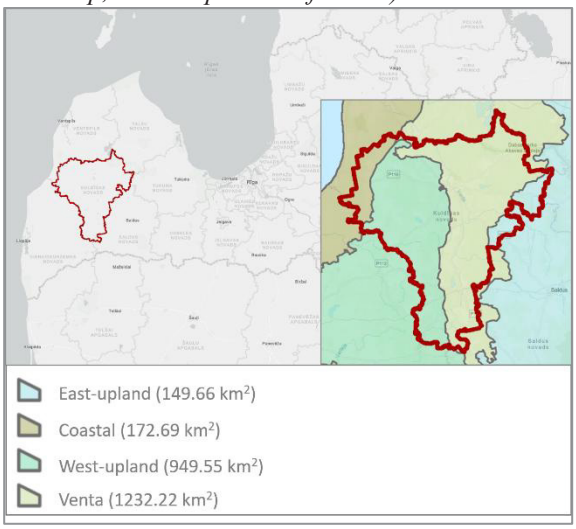
2) The West Kurland upland (West-up) – a flat, slightly wavy terrain of glaciofluvial and glacigenic deposits. Forest areas are fragmented, scattered patches of drained agricultural land are located on the highest places of this landscape zone. High heterogeneity of soil types, moisture, microclimate, and vegetation.

3) The Baltic sea coastal and former coastline area of different Baltic sea development stages (Coastal) – soil parent material is formed by Littorina sea sands and Baltic Ice lake sandy sediments. Intensive forestry is the predominant land-use with unspecified pine, spruce, and birch species stands of various ages, afforested both intentionally and naturally. Small rivers are often straightened for the drainage of valleys that are used in agriculture as pastures and grasslands. Besides the intensive forestry and extensive agriculture, an active process of land abandonment and afforestation by natural succession takes place.

4) The Venta River Valley (Venta) – sits on Baltic Ice lake sandy sediments and a glaciolacustrine plain, with occasional aeolian dunes and glacigenic tills. Main land-uses are agriculture on drained soils (intensive and extensive) and forestry (with spruce, birch, pine, distinct places with oak and ash tree dominance). Much of this landscape is of aesthetic quality, where intentional afforestation is not recommended in several

places due to scenic open views. Rivers are meandering through dolomite and often create deep valleys in the upper sediments, resulting in biodiversity hubs and tourist attractions. Landscape is a mosaic with high sensitivity to land-use change (Nikodemus et al., 2025).

Figure 1
Kuldiga district and Landscape zones (ArcGIS Online base map, Landscape atlas of Latvia)



Above-mentioned agricultural land-uses were chosen due to their abundance in results extracted in the Tool, while the 'vegetables', 'potatoes', and 'orchards' for the selected interventions showed no suitable territories for the selected interventions within the district of Kuldiga. The type of agricultural use can indicate the already existing GHG emission variability. Three interventions filtered by four landscape zones, two management types, two field size groups and four types of agricultural use either before afforestation or after deforestation with which the emission difference is set, together make a 192 sample size database, including a range of 64 digits per intervention, 48 per each landscape zone and agricultural use types. Several filter combinations yielded null results, meaning no applicable territory was found, because each intervention requires organic soil by default (Nipers, 2025). For example, AGRI-FOR intervention for organic management type on field size 20-100 ha has results for such agricultural uses as Grains, oils and legumes, and Fallow land on organic soil, while Grassland and Other are not agricultural land-use types on organic soils within the landscape of East Kurland upland; therefore, the conversion from agricultural to forestry land-use on organic soils does not apply and creates a null data entry. Most of the null values are for organically managed fields of 20-100 ha, indicating that existing agricultural use of organic soils dominate in smaller fields. Valid results remained in 152 rows and altered the initial set of data into an unbalanced design database, which is considered for the selection of data analysis methods.

D*ata analysis*. After selecting each intervention and rendering every filter combination, the GHG emission reduction value and suitable area for the respective combination are collected into a database for further analysis in *RStudio.* Skewness of the preliminary scatter plot declines the hypothesis of normal distribution. Statistical analysis begins with the impact assessment of each factor (intervention, landscape, management type, field size, and agricultural use) on the possible emission reduction by using the *Kruskal-Wallis* test. Factors with significant impact on emission values are selected for further analysis for the calculation of inner rank differences with the post-hoc pairwise comparisons *Dunn* test. For example, not only can we know that agricultural use has a significant effect on emission reduction by the land-use change, but also that temporary cultivated grassland exceeds all of the other agricultural use types. Detecting factors with significant impact on the GHG reduction potential, as well as knowing the inner group differences, a prediction for the most effective intervention, location and management combination can be clarified. In order to create a prediction, the Generalized linear model (GLM) with Gamma error distribution and logarithmic function is used to reveal the combined effect of the most influential factors. From these results, an estimated marginal means prediction heatmap is created to visualize potential GHG emission reduction for each combination.

Results and Discussion

The primary descriptive results delineate the intervention of afforestation on agricultural land with organic soils as the most effective, with median values of 607.0 t $CO_{2\text{-eq}}$ ha^{-1} potential reduction by using monoculture fast-growing tree species, and 319.5 t $CO_{2\text{-eq}}$ ha^{-1} with native species, while the reverse intervention of turning a natural wetland forest ecosystem into agricultural land-use can offer an emission reduction potential of 132.0 t $CO_{2\ eq}$ ha^{-1} (Table 1).

In terms of landscape zone, the West Kurland upland and the Venta Valley dominate the factorial impact by their similar median values (578.5 and 577.0 t $CO_{2\ eq}$ ha^{-1}). The maximum potential emission reduction possible in the West Kurland upland shows 9,596 t $CO_{2\ eq}$ ha^{-1} and the Venta Valley – 5,995.0 t $CO_{2\ eq}$ ha^{-1}. Interestingly, the very small Coastal landscape zone equals the Venta River valley by its maximum values and sums, while the median is nearly eight times smaller. The data variability with few high-value entries indicates the possibility that Coastal landscape holds more organic soil areas that are currently in agricultural use.

Land-use conversion to and from the four types of agricultural uses distinguishes Grasslands, with the highest minimal value achievable in the case of afforestation intervention, as well as the total sum and median. The only exception is the maximum value (that is second to Grains, oils and legumes).

Interestingly, the same value of 9,596.0 t $CO_{2\ eq}$ ha^{-1} occurs in all factors, leading to a thought that it is one filter combination selected in the decision-making tool. It illustrates the potential GHG emission reductions if the AGRI-MONOFOR intervention - afforestation of fast-growing monoculture tree species on arable land – were applied to conventionally managed grains, oilseeds, and legumes in fields up to 20 ha. Total area suitable for this exact factor combination is 799.7 ha. In other landscapes, this combination would be suitable for 35 ha in East-upland, 115 ha in the Venta Valley, and 6 ha in Coastal landscape zones.

Table 1
Total greenhouse gas emission reduction potential by the factor

Factor	Ordinal classes*	GHG seq. t $CO_{2\ eq}$ ha^{-1}				
		min	max	sum	median	*p-value total**
Intervention	AGRI-MONOFOR[a]	7.0	9,596.0	58,036.0	607.0	<0.001
	AGRI-FOR[a]	4.0	5,672.0	46,183.0	319.5	
	FOR-AGRI[b]	2.0	2,326.0	18,907.0	132.0	
Landscape	East-high[a]	2.0	798.0	6,004.0	81.0	<0.001
	West-high[c]	8.0	9,596.0	54,490.0	578.5	
	Coastal[ab]	3.0	5,672.0	28,742.0	74.0	
	VentaValley[bc]	17.0	5,995.0	32,931.0	577.0	
Management system**	Conventional[a]	3.0	9,596.0	74,177.0	334.0	>0.05
	Organic[a]	2.0	5,672.0	48,949.0	252.0	
Individual field size	<20 ha[a]	2.0	9,596.0	91,759.0	336.0	>0.05
	20-100 ha[a]	3.0	3,146.0	31,367.0	232.0	
Agricultural land-use	Grain-Oil[b]	9.0	9,596.0	33,534.0	418.0	<0.001
	Grassland[c]	103.0	6,825.0	70,155.0	1,003.0	
	Fallow[a]	2.0	2,457.0	11,824.0	81.0	
	Other[a]	2.0	1,826.0	7,613.0	81.0	

**P-value total* indicates the factorial impact on emission reduction potential. Different superscript letters distinguish significant inner variability of the ordinal groups within each factor.
***A conventional management system is productivity-based and includes the use of mineral fertilizers and chemical pesticides. An organic management focuses on soil health, uses natural fertilizers, and does not use chemical pesticides.

The factors of Intervention, Landscape and Agricultural use have a significant impact on the emission reduction potential, and ordinal groups within these factors show significant differences within factors, but there must be selective combinations more effective than others that the Decision-making tool is not able to filter out.

Land-use change into a forest has a potential emission reduction range of 2.2 –13.3 t CO_2 eq ha^{-1} (Lazdiņš, 2023; Strauss et al., 2024), but the carbon sink tends to slow down after 10 – 15 years (Black et al., 2025). Vast differences between our results in potential emission reduction differ from the ones stated in the literature, possibly because the values extracted from the Tool are mathematically calculated instead of the actual measurements taken from the above-mentioned sources. Also, precise soil properties and tree species are not defined and may cause the gap.

The effect size percentage for both GHG and suitable area, and total corresponding area for each factor, is shown in Table 2. Agricultural use has the largest effect and determines 26.2 % of the emission reduction potential as well as the total suitable area. The other large effect size is created by the Landscape zone – 15.4%.

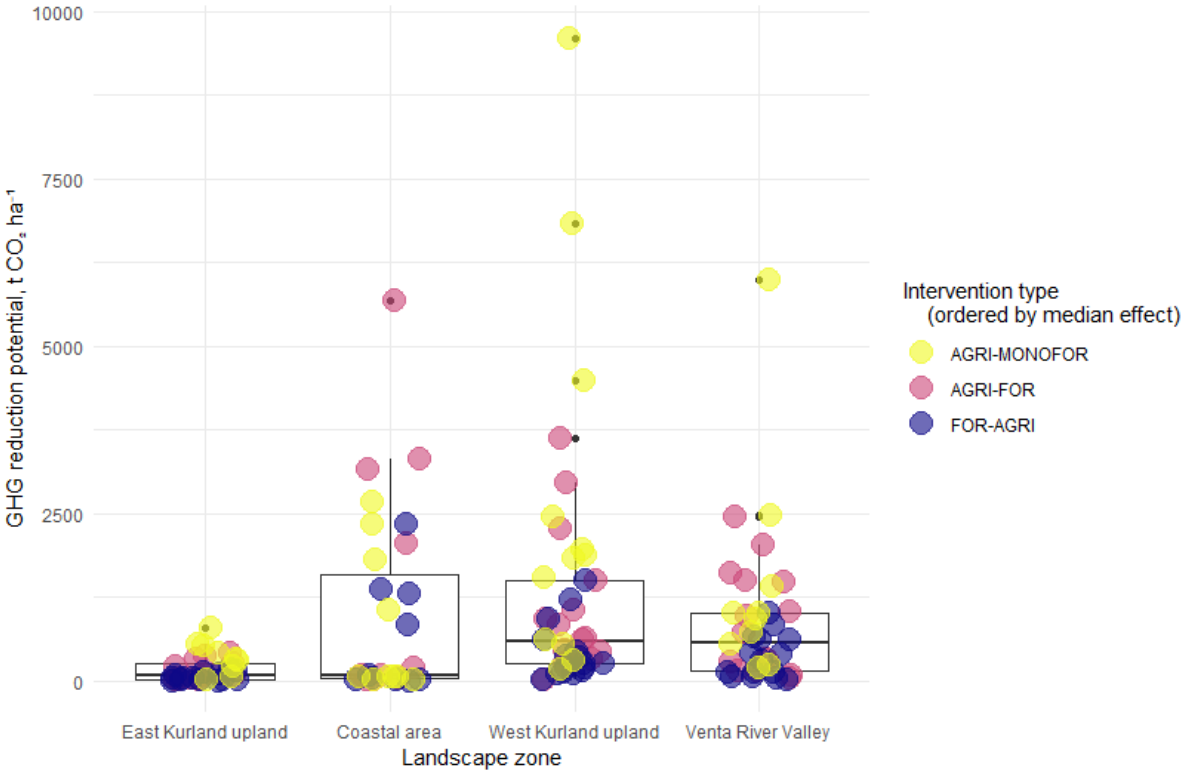
Table 2
Factorial effect size for GHG reduction potential and total corresponding area

Factor	GHG red, %	Total area, %
Agricultural use	26.2	28.0
Landscape	15.4	16.5
Intervention	7.4	0.9
Field size	0.5	0.3
Management	0.2	0.2

The management system and field size do not create a significant impact on the potential GHG reduction amount and show no factorial effect size; therefore, they are excluded from further analysis. Researchers in Lithuania have discovered that the variation component of soil type is 29.5%, and land-use contributes 45.9% (Muraškienė et al., 2023) to the

emission reduction effect.
Secondary analysis is the visual assessment of the factorial impact on potential emission reduction based on landscape and agricultural use (Figure 2 and 3).
A narrow distribution of potential values is in the East Kurland upland, with each filter combination resulting in less than one thousand tonnes of carbon equivalent reduction per hectare. Regardless of its size being similar to the East-upland landscape, the range resembles the district's largest Venta Valley landscape, which is seven times larger. It is also the only landscape in which afforestation with native tree species (AGRI-FOR) dominates the highest potential values, and not the intervention of monoculture fast-growing tree species. It stands out with high potential GHG savings from natural wetland forest ecosystem conversion into agricultural land-use (FOR-AGRI).

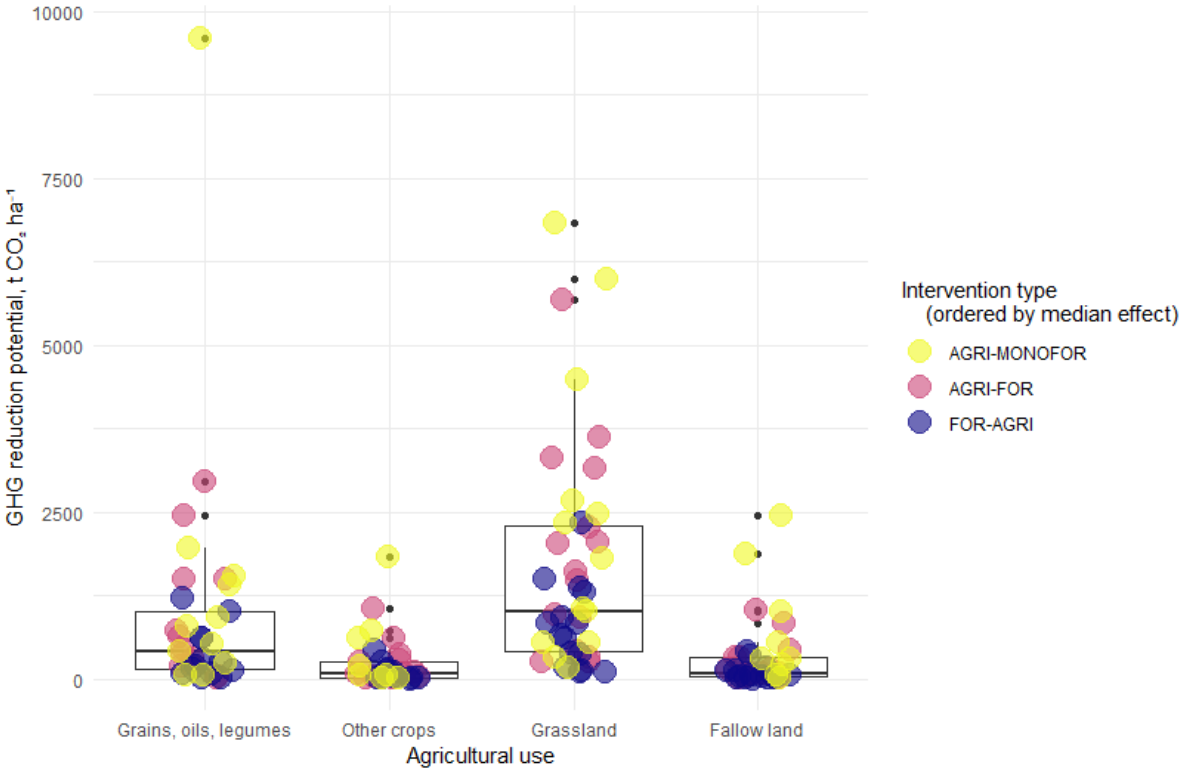
Figure 2
GHG emission reduction potential by intervention and landscape



The West Kurland upland and the Venta Valley exhibit the highest potential values from afforestation with fast-growing tree species (AGRI-MONOFOR) The third intervention of natural wetland forest ecosystem conversion into agricultural land-use (FOR-AGRI) shows comparatively low emission reduction potential, except for the Coastal landscape, in which it even exceeds some agricultural land conversion to a forest.
Regarding the similarities between the Coastal and Venta valley landscapes, the visualization in Figure 2 confirms the extensive distribution of extreme values in the Coastal landscape. In terms of maximum and cumulative values, the potential GHG reduction varies widely between regions; the median value is 74 t $CO_{2\,eq}$ ha^{-1}, for the Coastal landscape to 577 t $CO_{2\,eq}$ ha^{-1} for the Venta Valley The only outlier in Venta cluster is Grassland on field size <20 ha for the AGRI-MONOFOR intervention, and it is suitable for 499 ha. Comparing these results with the Landscape plan of Kuldiga, Coastal landscape is already predominantly used for intensive forestry and has a fragmented character. Exceptions are two small river valleys that are historically used as meadows and pastures, and their preservation is a recommended quality goal where afforestation would disrupt the biologically valuable grasslands. This landscape offers exceptional potential in natural wetland forest ecosystem conversion into agricultural land, especially to Grassland and still contribute to climate mitigation. The decision-making process for the afforestation licensing that determines if it coincides with the municipal spatial plan, should include the scenic value of the landscape into consideration in order to balance out the climate, biodiversity, and scenic objectives. The West Kurland upland is described as a typical agricultural landscape on drained land and well-cultivated soils that are still actively used for production, including intensive forest areas. Abandonment and natural afforestation take place, but scarcely.
The Venta River Valley is actively used for agriculture and forestry, while recreation and nature tourism are also major activities. These two largest landscapes are

mosaic and evaluated as distinctly aesthetic.
Both hold widespread visual and culturally historic values, and are intertwined with high aesthetic value roads. To maintain the landscape quality goal and climate mitigation balance, it would require careful site selection for afforestation interventions where distinct views are not closed. The East Kurland upland is small by area and its low-value emission reductions are formed by small-scale areas, yet it can be considered for climate mitigation interventions as long as the mosaic character is retained (Nikodemus et al., 2025).

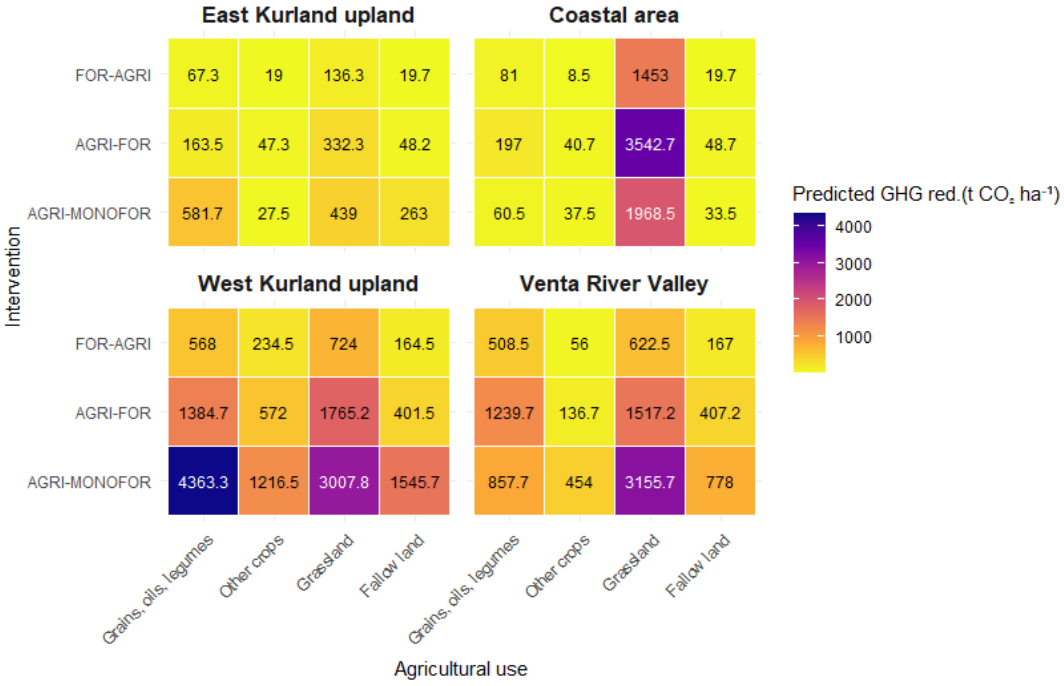
Figure 3
GHG emission reduction potential by intervention and agricultural use



The type of agricultural use impact on intervention effect is visualized in Figure 3. The highest average values can be achieved in Grassland agricultural land-use. Fallow land and Other crops offer similarly low emission amounts; therefore, the emission reduction potential is slight.
Previous agricultural use is considered a strong influential factor also in other research, especially for maintaining soil organic carbon (SOC) – grassland tends to accumulate, and arable land releases carbon through mechanical disturbance. Even the plant variety in grasslands can determine the amount of SOC – mixed plant composition show 10.7% higher amount of SOC than in monocultures (Wang et al., 2020). In an experimental pasture afforestation in Norway, soil organic carbon transfers from soil to biomass in the early years of the tree stand. Both these land-uses have a significant impact on bulk density that changes the soil carbon content in various depths (Strand et al., 2020). Carbon stock transfers from the upper soil horizon to the tree biomass and begins leaching into deeper horizons due to acidification. Carbon removal from the atmosphere is not necessarily an addition to the total ecological carbon after the tree stand is utilized (Friggens et al., 2020; Pilli et al., 2016).
Research from Spain states the opposite, that the labile carbon from the litter layer is also incorporated within soil mineral layers after the land-use change. Higher carbon content in soil was in a floodplain site on humic fluvisol, and its previous land-use was a grassland with no change of SOC after the afforestation. In the second experimental site, which was a maize crop arable land-use, afforestation added carbon to the soil (Priano et al., 2023) although Kravchenko & Roberts (2017) emphasize that only a whole soil profile analysis can ensure the carbon dislocation and transformation within soil.
The focus at hand is the nature-based climate mitigation. By recognizing the potential side-effects of greenhouse gas reduction interventions, the rural spatial planning process should simultaneously aim to achieve climate neutrality, protect biodiversity, and preserve soil health and landscape quality. Therefore, an easily understandable prognosis is needed. The cumulative effect of agricultural use and landscape can be taken into account before suggesting, supporting or stimulating land-use change, especially afforestation of agricultural land. A prediction based on Gamma Generalized Linear Model is visualized in Figure 4.
All three factors influence the potential GHG emission

amount significantly when analysed separately, but the model highlights that 31% of the outcome is influenced by the agricultural use and 25% by the landscape area. Landscape and agricultural use have a very strong factorial interaction and together determine 56% of GHG emission reduction potential (<0.001), but the model shows no significant interaction between intervention and agricultural use.
Grassland is the dominating agricultural land-use type across all interventions, stating also that it is already the most common agricultural use on organic soil. Afforestation with a monoculture of fast-growing tree species in European experience with using afforestation as a climate mitigation tool has shown that it works as a carbon farming, while the natural quality of the ecosystem may be compromised (Hamidov et al., 2018; Jost et al., 2021). General caution is recommended in choosing areas for afforestation interventions, so that climate incentives do not compete with other environmental goals or food security (Hua et al., 2025). Often, carbon exchange and pricing are mentioned, but soil recovery costs after carbon depletion, acidification, and bulk density reduction are not.

Figure 4
Predicted GHG emission reduction by landscape and intervention, t CO_2 ha^{-1}



In the prognosis heatmap, the highest possible emission savings can be expected from the fast-growing monoculture forest intervention (AGRI-MONOFOR). In the West-upland landscape, the largest saving of 4,363.3 t $CO_{2\ eq}$ ha^{-1} are predicted for the afforestation of Grain, oil seed and legume arable land. Meanwhile, in the Venta River Valley an emission reduction of 3,155.7 t $CO_{2\ eq}$ ha^{-1} is predicted from afforesting Grassland. Coastal area potential of the highest emission reduction of 3,542.7 t $CO_{2\ eq}$ ha^{-1} can be achieved not by fast-growing tree species afforestation, but from native species forest on Grassland agricultural land-use.
The East Kurland upland is the least effective landscape for any of the interventions and can be left out of large-scale carbon farming driven afforestation. The West-upland and Venta landscapes are the largest ones; therefore, they show the most potential for emission reduction interventions. Meanwhile, these territories are also valuable for food production, their ecological importance and recreational function.

These findings coincide with other research and show that land-use is the dominant factor determining carbon sink. Grassland conversion into arable land creates the largest depletion of SOC in comparison with arable land converted into grassland or forest and grassland to forest (Jost et al., 2021; Muraškiene et al., 2023; Priano et al., 2023). Afforestation can cause SOC depletion as it transfers to biomass, leaving the soil with reduced amount of organic carbon, that is extracted, leached, mineralized or lost due to soil respiration, and the most vulnerable are grasslands (Friggens et al., 2020; Strand et al., 2020). Crop rotation, drainage, change of arable land into grassland and vice versa are established as effective climate adaptation interventions that reduce soil threats and improve soil functions (Hamidov et al., 2018).
One threat that afforestation can counteract is soil compaction, as root system development significantly reduces bulk density (Hamidov et al., 2018). Consequently, this intervention is highly suitable for areas of moderate productivity, provided tree species

are selected that do not cause soil acidification. Even the below-ground habitats are damaged in site preparation phase for afforestation, a new ecosystem will evolve over time. Therefore, intervention of agricultural land afforestation with native tree species in small-scale is advisable in mosaic landscapes with high biodiversity.

Even though afforestation may not always be the most sustainable land-use change in terms of food security and soil health, it could add value to abandoned agriculture lands where natural succession has begun to take place (Thibault et al., 2022).

Research done in Austria used three land-use intensities: land spearing – where productive and nature protection areas are separated, land sharing – agricultural and biodiversity share the same landscape, and balanced land-use – a combination of spearing and sharing. These land-use intensities, together with climate change scenarios, were modelled to estimate soil characteristics, including soil organic carbon sink in three different land-use change experiments between arable, grassland, and forest. A combination of land-use and climate change scenarios proved that land sparing is the most vulnerable and contributes the least to carbon sink capacity due to its intensive arable use. Their finding strengthens this research by stating that mosaic and mixed-use landscapes can be 'carbon-neutral enough' with soil cultivation and agronomic methods, while large arable territories can be considered for use in carbon farming. Areas with organic soils, situated in flat, homogeneous landscapes with arable land-use and already depleted biodiversity, are well-suited for intentional afforestation - even with the fast-growing tree species. Leaving more diverse areas for medium and small-scale food production, landscape, soil health and biodiversity preservation (Jost et al., 2021).

Irish researchers, who tested Canadian land-use models for forest and agricultural areas, discovered that empirical field sampling provides lower emission and sequestration values than the satellite-image and carbon estimation of the model (Ituen & Hu, 2024). This is supported by Kravchenko and Robertson (2010) who proved that a whole soil profile analysis can reveal contradicting carbon cycle processes.

Identifying the largest uncertainty elements of an emission estimation model is suggested by McGlynn and her research team (McGlynn et al., 2022), possibly narrowing down the supplementary data needed for decision-making. Uncertainty discovered in this research is yet an unknown quantitative balance between landscape quality, soil health, and long-term soil organic carbon deposit, as well as food production. The cumulative effect of these territorial qualities ought to be evaluated equally within the decision-making process. As the research team of MéNard (2023) suggests, an analytical framework is needed and coincides with the results of this research. The intervention itself is only the third in its effect size for emission reduction impact, and an analytical framework would best work when used together with soil data, forest stand placement and development phase, as well as with the agricultural use and landscape. A qualitative and balanced approach is recommended for the Sustainable Energy and Climate Adaptation plan of Kuldiga district.

The carbon flux is not continuously observable, thus, not entirely reliable. Model deviation can be up to 10% (MéNard et al., 2023), signifying that it is most useful for preliminary analysis in site selection for climate mitigation interventions. Since the LULUCF Decision-making support tool offers a mathematical calculation for possible emission reduction and not the actual amount of real-time GHG flux, a direct connection with agricultural use and afforestation activities is advisable. Additional data of soil type and land-use are welcome to secure the calculation. Further research in soil profile analysis according to the intervention and agricultural use combination could solidify the prediction model and support the decision-making process at municipality level.

Conclusions

1. Monoculture forests with fast-growing tree species can offer the largest greenhouse gas sequestration, compared to other intervention types.
2. The majority of the potential emission reduction potential derives from low-effect applications.
3. The largest effect size on GHG sequestration from land-use change is created by agricultural use to or from the conversion is implemented, exceeding the effect size of the intervention itself.
4. The LULUCF tool offers estimation of potential emission change provided by land-use change, ideal for preliminary site selection.
5. Soil analysis in areas of highest emission reduction potential is suggested to ensure soil health and climate mitigation balance.

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THERAPEUTIC LANDSCAPES AS A PUBLIC HEALTH RESOURCE

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Abstract
Increasing rates of stress-related disorders, mental health challenges, and population ageing have intensified the need to reconsider the role of outdoor environments in supporting public health and well-being. Recent studies combining knowledge from various fields show that everyday contact with nature and thoughtfully designed outdoor spaces can significantly contribute to psychological restoration, stress reduction, and improved quality of life across different age groups. Therapeutic landscapes represent an approach that bridges landscape architecture, environmental psychology, and health-related research, focusing on the interaction between people and their surrounding environments. While this concept has been widely explored within clinical and rehabilitation settings, its potential application as a preventive and supportive element within everyday living environments remains insufficiently systematized. The aim of this paper is to examine the theoretical foundations and key planning principles of therapeutic landscapes, with particular attention to their relevance for mental health support in an ageing society. The study combines a qualitative literature review with a comparative case study analysis of three rehabilitation institutions in Latvia – *Līgatne*, *Tērvete*, and *Vaivari* – evaluating the implementation of therapeutic landscape planning principles in practice. The paper identifies and systematizes core principles of therapeutic landscape design, including sensory engagement, spatial diversity, accessibility, safety, and the role of universal design in creating inclusive environments. The findings highlight the importance of integrating therapeutic landscape principles into contemporary outdoor environment design as a long-term strategy for enhancing public health and mental well-being.
Keywords: therapeutic landscapes, healing environments, mental well-being, landscape architecture, universal design.

Introduction

Modern society faces a range of global challenges that directly affect human health and quality of life. Increasing levels of urbanisation, socio-economic instability, and changes in lifestyle have contributed to the growing prevalence of stress-related illnesses and mental health disorders. Studies indicate that stress is one of the most significant health problems in Europe, affecting a considerable proportion of the population. At the same time, demographic trends point to a rapidly ageing society, which increases the demand for health-promoting living environments and rehabilitation opportunities (Mental health at work, n.d.; Mental health in Latvia, 2022).

In this context, increasing attention is being paid to the quality of the living environment and its impact on human physical and psychological well-being. Landscape architecture and urban planning can serve as important tools for promoting public health, as well-designed outdoor environments can help reduce stress, improve mental well-being, and encourage social interaction (Souter-Brown, 2015).

The theoretical foundations of therapeutic landscape planning principles can be traced to health geography, where Gesler first introduced the concept of therapeutic landscapes in 1992 while investigating why certain environments evoke a sense of healing and contribute to well-being. These environments were defined as therapeutic landscapes – spaces in which the physical and built environment, social conditions, and human perception interact to create an atmosphere conducive to healing (Gesler, 1992).

The concept of therapeutic landscapes is based on the assumption that natural environments and landscape elements can positively influence human psychological and physical conditions. Historically, people have long associated natural environments with healing properties, and in many cultures natural settings have been used for both spiritual and physical restoration (Pouya et al., 2015). Gesler also emphasised that the healing process is not determined by a single element but rather by a combination of environmental components, including physical, social, and symbolic dimensions (Gesler, 1992).

In the literature, several terms are used within the context of therapeutic landscapes, such as healing gardens, therapeutic gardens, sensory gardens, and rehabilitation landscapes. Although these terms are often used interchangeably, they share a common goal—to create environments that support human health, well-being, and recovery processes (Belčáková et al., 2018; Cooper Marcus & Sachs, 2013). Previous studies have largely focused on the use of therapeutic gardens in healthcare institutions such as hospitals, sanatoriums, and rehabilitation centres. However, increasing attention is being given to the potential integration of therapeutic landscape principles into broader living environments, including public outdoor spaces and urban settings (Souter-Brown, 2015).

Considering the growing challenges related to public health, as well as the needs of an ageing population, the integration of therapeutic landscapes into contemporary outdoor planning is becoming increasingly relevant. The aim of this paper is to analyse the theoretical foundations of therapeutic landscapes and to identify key planning principles that contribute to the development of health-supportive outdoor environments.

In addition to the theoretical analysis, the study includes a comparative assessment of three rehabilitation institutions in Latvia – *Līgatne*, *Tērvete*, and *Vaivari*. These case studies were selected because they represent different geographical contexts, rehabilitation environments, and levels of outdoor spatial development, allowing evaluation of therapeutic landscape principles in real-life settings.

Materials and Methods

The study is based on a qualitative analysis of scientific literature aimed at identifying and systematising the planning principles of therapeutic landscapes and their significance in the context of public health. The analysis included scientific articles, monographs, and international studies examining the interaction between natural environments, landscape architecture, and human health. Particular attention was given to research on therapeutic landscapes, healing gardens, and rehabilitation landscapes that analyse the impact of these environmental types on physical and mental health.

During the literature analysis, the main theoretical concepts and approaches characterising therapeutic landscapes across different disciplines were identified, including landscape architecture, environmental psychology, and public health research. Based on the collected information, a conceptual analysis was conducted to identify and systematise the key principles of therapeutic landscape design, including spatial diversity, sensory engagement, safety, accessibility, universal design, and opportunities for social interaction in outdoor environments.

To evaluate how the therapeutic landscape planning principles identified in the literature are implemented in practice, a comparative assessment of three rehabilitation institution territories in Latvia was conducted. The selected case-study sites included the rehabilitation centres Līgatne and *Tērvete*, as well as the National Rehabilitation Centre *Vaivari*.

The selected institutions also differ in terms of accessibility, surrounding natural conditions, spatial organisation, and functional structure, providing a broader understanding of rehabilitation landscape development opportunities in Latvia.

The assessment of the territories focused on spatial structure, accessibility, diversity of outdoor functions and activities, environmental quality, natural elements, and the overall suitability of the outdoor environment for rehabilitation and psychological restoration.

To evaluate the outdoor environments of the selected rehabilitation institutions, developed evaluation matrix of therapeutic landscape planning principles was created based on the theoretical findings identified in the literature analysis. The matrix enabled a structured and comparative assessment of the analysed territories according to key therapeutic landscape criteria (Table 1).

The matrix included several environmental and spatial quality criteria, including spatial diversity, functional zoning, safety and orientation, accessibility and universal design, physical and emotional comfort, availability of activities, and the presence of natural elements within the landscape. Each criterion was evaluated using a qualitative five-point Likert scale, where 1 indicated insufficient integration of therapeutic landscape principles and 5 indicated a high-quality and well-integrated therapeutic environment.

The evaluation matrix was applied to all three rehabilitation institution territories in order to identify strengths, deficiencies, and development opportunities in relation to therapeutic landscape planning principles. This approach allowed the comparison of different rehabilitation environments and provided a practical application of the theoretical principles identified during the literature analysis.

Table 1

Basic principles of therapeutic landscape planning assessment matrix (authors table, 2023)

Criterion	1	2	3	4	5
Variety of spaces	1-3 different rooms		Up to five different rooms		Eight different rooms
Variety of activities	Uniform activities dominate (e.g. walking areas)		Both active and passive activities. Ability to choose from at least three activities (e.g., walking, some sport, gardening)		A wide range of activities, the ability to operate in any weather and season. There is lighting to use the outdoor area in the dark.
Physical and emotional comfort	Rarely placed benches, resting places are not inviting (physically, emotionally outdated elements). Elements create a reluctance to stay		There are areas that create negative emotions (e.g., outdated, questionable elements), but most of the territory is clean, organized, and pleasant to stay in.		Enough space for recreation, harmony between the architecture and the surrounding environment, it is not heavy. There are no aspects that cause emotional doubts (old, withered trees, overgrown water bodies, untidy environment)
Accessibility	Accessibility of the environment is not ensured, visitors with physical disabilities can only get into the premises with the help of an assistant		Partially accessible. There are rooms that anyone can visit without assistance. Other rooms require the assistance of an assistant.		Everyone, regardless of age, physical and emotional abilities, has the opportunity to access all spaces
Sensory stimulation elements	Uniform materials, greenery, no safe way to touch plants, elements, etc.		There is a variety of vegetation or materials. There are valuable views, but they are not highlighted.		Ample opportunities for sensory stimulation. Variety of materials/textures in both elements and greenery. Emphasizes valuable views, includes water features
Vegetation diversity	No greenery groups have been created, naturally formed vegetation (trees, shrubs) dominates.		Existing vegetation dominates, but separate groups of greenery have been created, which include flowering plants.		Diverse greenery (flowering, of different colors, textures, sizes, foliage). Existing vegetation preserved (large trees, shrubs, ground cover)

Criterion	1	2	3	4	5
Entrance quality	No specific entrance to the territory can be read. The entrance overlaps with the flow of cars.		There are readable entrances. There are several of them - it is difficult to distinguish which is the main entrance, which will lead to the goal		A clearly defined entrance is highlighted, accentuated, inviting.
Safety	No fencing, several aspects that create a feeling of insecurity (e.g. traffic flow)		Partially fenced area. There is no physical fence, but the boundary is formed by other aspects (greenery, forest, etc.)		The territory is completely fenced, there are several components that create psychological and emotional security
Accessibility	There are no memorable elements in the area, on the contrary, negative associations are formed.		Partially recognizable, there are spaces, elements that are associated positively, as well as spaces, elements that create a negative experience		The territory has several elements, zones, views, etc. that create positive emotions, thus remaining in the memory.
Legibility and orientation	Incomprehensible movement spaces make you ask the question - would you dare go there?		Easy-to-read walking routes, but not all trails lead to destinations or building entrances		Fully understandable and readable pedestrian paths, all paths lead to a specific destination or building entrance. No abstract elements

Results and Discussion

The literature analysis on the concept of therapeutic landscapes and related studies allows the identification of several key planning and design principles that contribute to human psychological and physical well-being in outdoor environments. These principles are based on an interdisciplinary approach that integrates research from landscape architecture, environmental psychology, and public health (Belčáková et al., 2018; Souter-Brown, 2015).

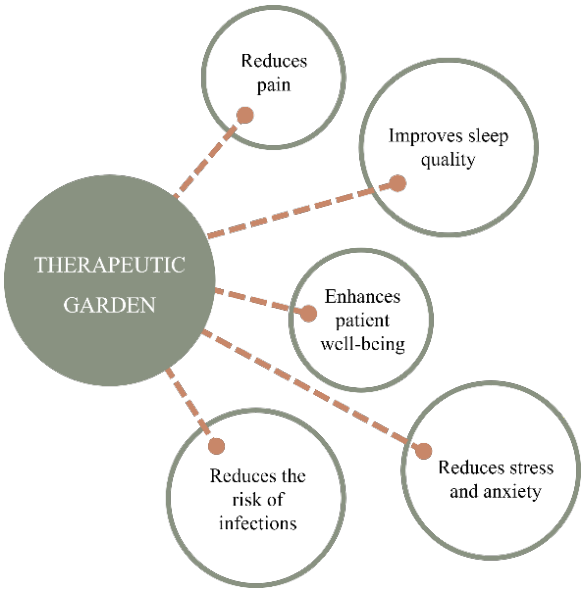
The analysed sources emphasise that therapeutic landscapes are not merely aesthetically designed green areas but carefully planned environments in which natural elements, spatial structure, and user needs interact to create spaces that support psychological restoration, stress reduction, and social well-being (Ulrich, 1999; Cooper Marcus & Sachs, 2013).

Rehabilitation landscapes, which in the context of healthcare institutions' outdoor environments can be viewed through the concept of healing gardens, provide important support in challenging life situations and can complement traditional medical treatment methods. They do not replace medical care or therapeutic procedures but rather function as a supportive mechanism that contributes to faster and higher-quality recovery outcomes (Figure 1). When discussing health, it is essential to consider the interrelationship between physical and psychological factors, which influence one another. Based on this principle, natural environments or environments dominated by natural elements can affect not only physical health but also psychological well-being (Belčáková et al., 2018; Constitution, n.d.).

The results of the study identified several key components that characterise successful therapeutic landscape design. These include spatial diversity and functional zoning, the provision of safety and orientation within the environment, the creation of sensory experiences, accessibility and the integration of universal design principles, as well as the presence of natural elements, particularly water, within the landscape (Pouya et al., 2015; Thaneshwari et al., 2018; Souter-Brown, 2015). The interaction of these principles creates an environment that can support both physical activity and psychological restoration.

Figure 1

Benefits of healing gardens (authors scheme, 2023)

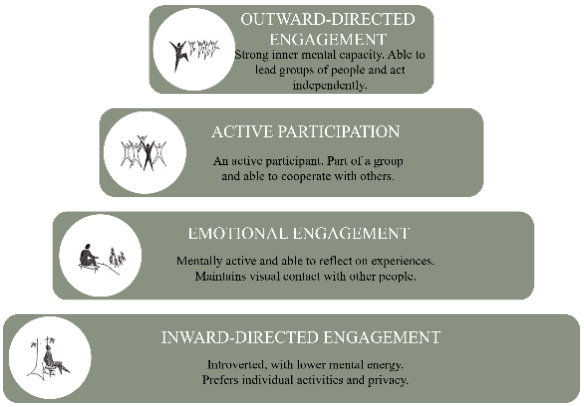


Creating a healing environment requires the combination of two essential aspects: the creation of place and the facilitation of the healing process. Understanding how people perceive their environment and how they respond to it is one of the most important components of therapeutic design. A key aspect involves recognising the relationship between the physical and social environment and human functioning. The pyramid model (Figure 2) illustrates how individuals may have different environmental preferences depending on their mental and physical condition at a given moment (Shahrad, 2012; Stigsdotter & Grahn, 2002).

At the base of the pyramid is inward-directed engagement, where individuals prefer solitude. At this level, mental capacity is relatively low, and activities tend to be private, such as walking or quietly observing

the surroundings. As mental energy increases, individuals may begin to prefer more active engagement with their environment. The second level represents emotional participation, where visual contact with other people becomes important. The next level is active participation, in which individuals seek to be involved in a specific group and engage in shared activities with others, demonstrating a willingness to interact, share experiences, and express creativity. At the top of the pyramid is outward-directed engagement, where individuals possess high mental energy and may take on leadership roles within a group. At this level, people can act independently without requiring external support.

Figure 2
Pyramid of Engagement (authors scheme, 2023, based on Shahrad, 2012)



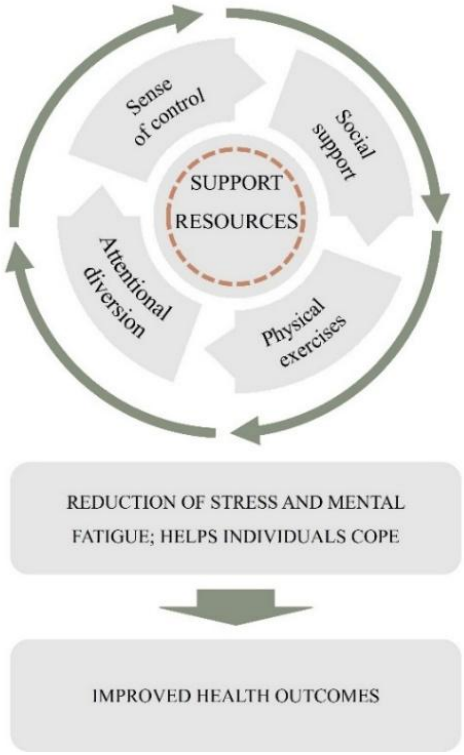
A therapeutic garden should therefore be able to interact with its users at different levels of engagement. When mental energy is low, individuals may require greater privacy and a less demanding environment. As mental capacity increases, the level of engagement with the environment also increases, enabling more active and socially oriented activities (Ottosson, 2001; Shahrad, 2012).

Considering the impact of stress on human health, it can be argued that gardens within healthcare institutions can improve health outcomes to the extent that they effectively support recovery from stress. The concept of stress provides a foundation for developing scientifically grounded theories of supportive garden design, which conceptualise environmental characteristics and design approaches in relation to their potential impact on health. In this context, the term supportive refers to outdoor environments with environmental features that help patients, visitors, and healthcare staff cope with stress (Ulrich, 1999).

Considering both the impact of stress and the varying levels of human engagement in surrounding activities depending on mental and physical conditions, the surrounding landscape or garden should be able to provide four main supportive resources (Figure 3).

Sense of control – an important factor influencing an individual's ability to cope with stressful events or situations. By helping patients regain a sense of personal control and capability, the recovery process can be accelerated. Visitors to the garden should be aware of its existence, be able to find it easily, and understand how to use the space either actively or passively. Therefore, wayfinding and accessibility are important considerations in garden planning and design (Pouya et al., 2015; Ulrich, 1999).

Figure 3
Support resources provided by the gardens (authors scheme, 2023)



Social support – the garden can serve as an environment that promotes social and emotional support. Group activities, shared physical exercises, horticultural therapy, and informal conversations encourage users to meet others, share experiences, and receive emotional or practical support. Such interactions can help restore self-confidence and support the healing process. Garden design should provide convenient access to different spaces while avoiding layouts that excessively encourage interaction to the extent that it compromises personal privacy (Pouya et al., 2015; Ulrich, 1999).

Physical activity – strengthens both the body and the mind. The garden should motivate individuals to leave indoor environments and encourage them to spend as much time outdoors as possible. It should also provide opportunities to participate in various activities offered within the garden environment (Pouya et al., 2015).

Positive distraction – refers to environmental features that attract visitors' attention and help divert them from negative thoughts or emotions. Such elements can contribute to improved physiological and

psychological responses, including reduced stress levels and improved blood pressure. Examples include water features, flowers, and natural sounds that stimulate sensory engagement (Pouya et al., 2015).

A prerequisite for these previously mentioned stress-reducing resources to be effective is that the garden must create a sense of safety. If the garden design or its location generates a feeling of insecurity or risk, the environment will produce stress and negative experiences rather than promote restoration, and patients may avoid using the garden altogether (Ulrich, 1999).

Based on certain interpretations and viewpoints, any natural garden or park could be considered a healing environment. However, the design of therapeutic gardens is intentionally developed so that their healing and restorative effects can be utilised as effectively and sustainably as possible (Belčáková et al., 2018).

When planning such specialised gardens, it is important to understand the key development processes before initiating the design phase, as well as during the planning process itself (Figure 4). Two main aspects must be considered prior to the planning stage: first, identifying and understanding the potential users of the garden, and second, assessing the physical site where the garden is intended to be developed. Equally important is the recognition of key factors that influence the design during the planning process (Shahrad, 2012).

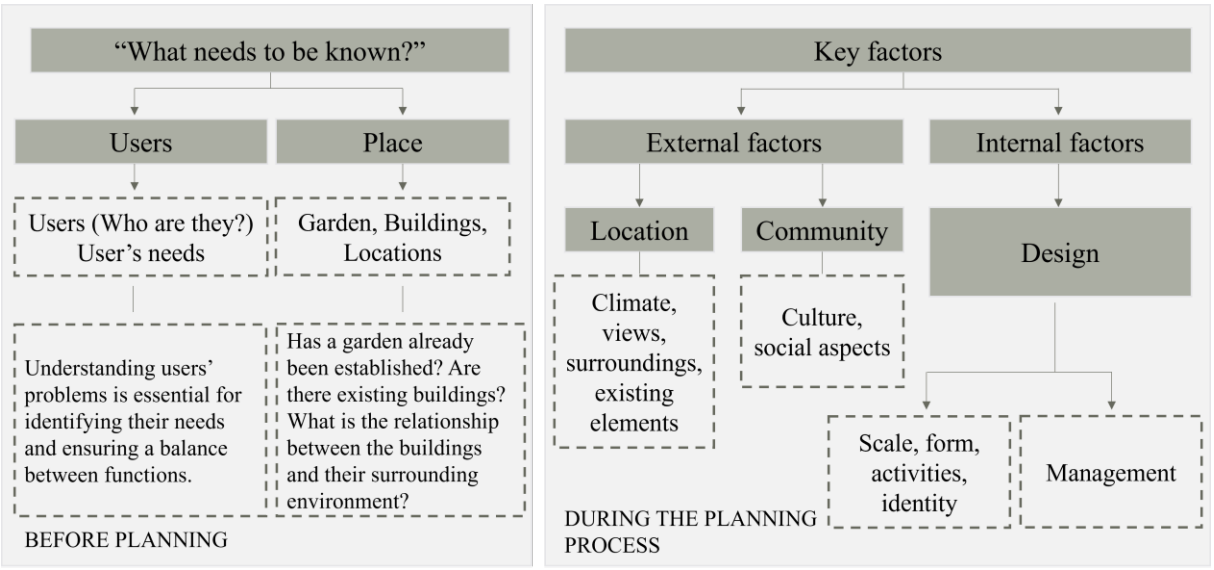
Understanding user groups and their needs

Before initiating the design process, it is essential to identify the potential user groups. In the planning of therapeutic gardens, primary attention should be given to the people who will use the garden, and this theoretical aspect should serve as a guiding framework for design decisions. To determine the needs of potential users, it is necessary to understand the problems they experience and, accordingly, identify the types of interventions and solutions required.

Depending on the target user groups, a balance should be maintained between opportunities for physical activity and possibilities for passive engagement with the garden environment. Essentially, it is necessary to understand which groups of people will use the garden by addressing questions such as: Who are they? What activities do they engage in? Understanding how individuals perceive their surrounding environment, how they respond to it, what they observe, and how they interpret it is one of the key factors in therapeutic design (Shahrad, 2012; Stigsdotter & Grahn, 2002).

Figure 4

Progress of the rehabilitation landscape planning process (authors scheme, 2023, based on Shahrad, 2012)



At the initial stage, it is also necessary to obtain comprehensive information about the physical location of the garden. All relevant baseline information about the site should be collected. One important aspect of site analysis is accessibility and transportation, ensuring that the area can be conveniently reached not only by private vehicles but also by public transport. It is important to understand where the site is located, what surrounds it, and what specific characteristics define the place. The analysis should identify which site components are valuable and which are less significant. Climatic conditions, prevailing winds, and sun exposure are also important factors. Additionally, it is necessary to determine whether a garden already exists within the site and assess its development potential. Another important consideration is whether there are existing buildings within the territory and how these buildings interact with the surrounding environment (Shahrad, 2012).

During the planning process, two types of key aspects must be considered: external factors and internal factors. External factors mainly originate from the broader social context and the characteristics of the site, while internal factors are directly related to the specific design approach of each individual garden.

A significant portion of design concepts and their

implementation is influenced by external factors. Location is one of the primary aspects of site analysis, as it is shaped by the surrounding environment, climate, and existing landscape elements. There is a substantial difference between a garden located in an urban environment and one situated in a rural area outside the city. Views and the surrounding landscape are important elements that can either enhance or diminish the overall value of the garden. Therefore, perspectives that offer attractive views throughout different seasons should be emphasised, while less appealing views should be visually screened. A therapeutic garden should also provide a variety of activities.

The surrounding environment plays an important role in encouraging visitors to engage in different types of activities, ranging from sitting, resting, and observing the landscape to walking or listening to natural sounds (Shahrad, 2012).

The task of the garden designer is to select the most appropriate locations for different activities to encourage visitors to spend more time outdoors. The surrounding environment should be utilised both physically and visually. Designing gardens within natural settings, incorporating natural sounds and locations outside densely populated areas, helps create a sense of being ʻaway' from everyday routines, which is one of the key qualities sought in healing environments. In this sense, a garden may function as a simple place that contrasts with the complexity of modern society (Shahrad, 2012).

Existing elements within the site are just as important as the surrounding environment. These values may vary considerably—for example, a garden with mature trees and shrubs has a different character compared to an empty plot of land. Integrating existing elements into the emerging design concept is an important aspect of therapeutic garden planning, as it reflects the identity, values, and historical context of the place. The geographical and historical context of a site is particularly important, as it demonstrates how the place has evolved over time and explains why it appears as it does today (Shahrad, 2012; Stigsdotter & Grahn, 2003).

Society, through cultural and social aspects, forms the second component of external factors. It is important to understand the social context in which the garden is being developed and the characteristics of horticultural culture within that society. This includes understanding how well the society recognises the relationship between nature and health, the healing potential of natural environments, and the role of gardening in supporting well-being (Shahrad, 2012).

Internal factors, on the other hand, reflect the specific **design** and development approach of each individual garden. A therapeutic garden should be both functional and aesthetically appealing to attract visitors and effectively respond to users' needs. Maintenance considerations also play an important role in the design process. From a management perspective, factors such as the appropriate size of the garden, the types of vegetation, and the landscape elements to be included should be carefully evaluated (Shahrad, 2012).

To evaluate how the therapeutic landscape planning principles identified in the literature are implemented in practice, three existing rehabilitation facility territories in Latvia were analysed in this study. The assessment of such territories makes it possible not only to evaluate the application of theoretical principles in real environments but also to identify potential challenges and development opportunities in the creation of health-promoting outdoor spaces. Outdoor environments in rehabilitation institutions are particularly important, as they serve as part of the treatment and recovery process, providing patients with opportunities to spend time in natural surroundings, engage in physical activities, and experience psychological restoration.

Within the framework of the study, three rehabilitation facility territories in Latvia were analysed: the rehabilitation centre *Līgatne*, the rehabilitation centre *Tērvete*, and the National Rehabilitation Centre *Vaivari*. The characterisation of these territories is based on an assessment of the existing conditions, with particular attention given to spatial structure, the presence of natural elements, accessibility, and the potential use of outdoor spaces within the rehabilitation process.

To evaluate the outdoor environments of the aforementioned healthcare institutions according to therapeutic landscape planning principles, an evaluation matrix of planning principles was developed. The matrix analysed several key environmental aspects, including spatial structure, functional diversity, sense of safety, physical and emotional comfort, availability of activities, and environmental accessibility. Such an approach enables a systematic comparison of outdoor environments in different rehabilitation institutions and allows the assessment of their compliance with therapeutic landscape planning principles.

The analysis shows that the rehabilitation centres *Līgatne* (Figure 5) and *Tērvete* (Figure 6) are in relatively similar situations, where certain environmental components reveal deficiencies or are insufficiently developed. In the territory of the rehabilitation centre *Līgatne*, the lowest-rated components were physical and emotional comfort, as well as the limited diversity of available activities. In contrast, the outdoor environment of the rehabilitation centre *Tērvete* received the lowest evaluation in terms of spatial diversity and the sense of safety within the territory. In both institutions, a lack of universal design and environmental accessibility was also observed, which may limit the full use of the territory by different user groups.

A different situation can be observed at the National Rehabilitation Centre Vaivari, which is considered one of the most successful examples of rehabilitation landscapes in Latvia. The evaluation of the territory

based on the planning principles matrix showed that many of the analysed components in this territory received the highest scores (Figure 7).

Figure 5
RC Līgatne assessment (authors scheme, 2023)

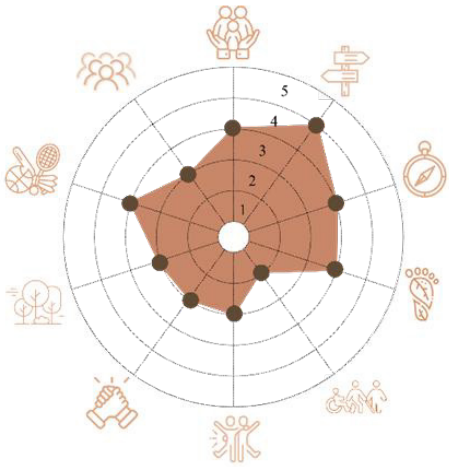


Figure 6
RC Tērvete assessment (authors scheme, 2023)

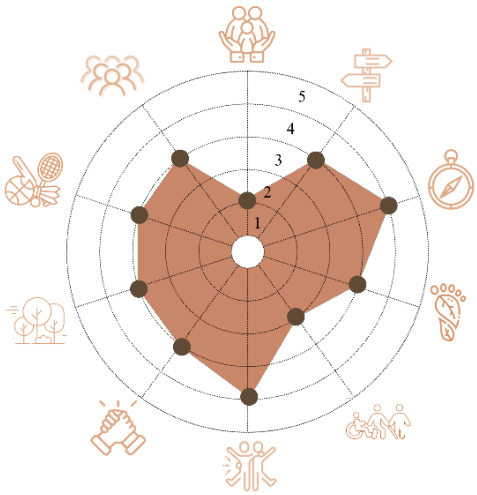
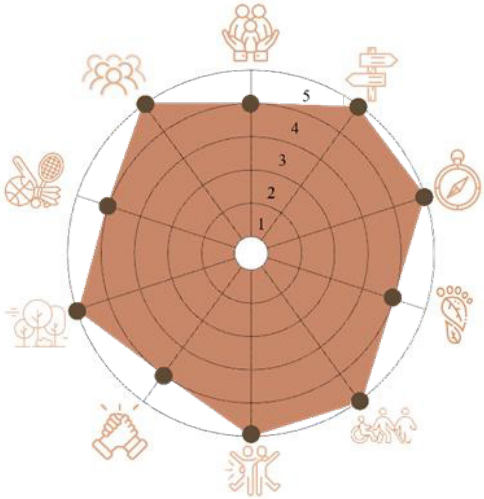
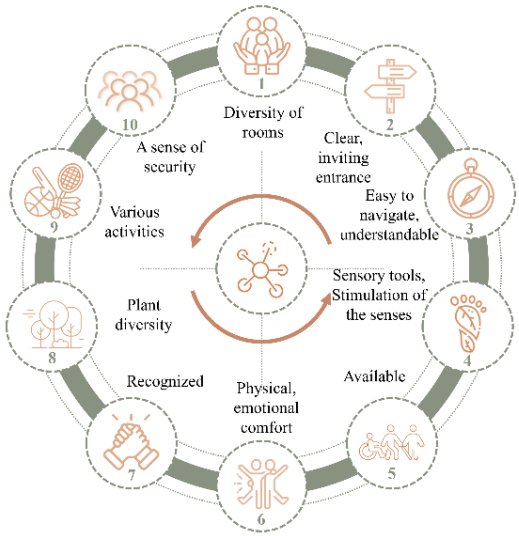


Figure 7
NRC Vaivari assessment (authors scheme, 2023)



An important factor in the development of the centre is its location—it is easily accessible and situated in a resort town, where tourism also contributes significantly to the development and use of the territory. In addition, the high environmental quality of the area is supported by natural factors, particularly the proximity to the sea, which creates favourable conditions for the rehabilitation process. Basic principles of rehabilitation landscape planning their evaluation within the analysed territories are illustrated in Figure 8.

Figure 8
Basic principles of rehabilitation landscape planning (authors scheme, 2023)



The spatial and functional quality of a healing garden is closely related to a complex set of interrelated planning principles (Stokmane & Graudina, 2024) that determine the therapeutic potential of the environment and the psychophysiological responses of its users.

1. Sensory experience and environmental diversity

The quality of a healing environment is significantly determined by its ability to engage all human senses. The diversity of materials and vegetation – various textures, forms, colours, and scents – supports mindfulness practices and fosters a stronger connection with the surrounding environment (Shahrad, 2012). In plant selection, preference should be given to a wide variety of species, including those that create sound in the wind, attract birds and butterflies, and mark seasonal changes, thereby creating a sense of cyclical rhythm and continuity (Pouya et al., 2015). Water elements are particularly valuable: moving water acts as a natural sound buffer and calming visual stimulus, while still water promotes meditation and psychological tranquillity (Pouya et al., 2015).

2. Sense of safety, orientation, and accessibility

A healing environment must ensure both physical and psychological safety for its users. A clear spatial structure – including legible pathways, landmarks, and signage that consistently lead back to building

entrances – reduces the risk of disorientation, which can otherwise trigger anxiety (Pouya et al., 2015). In addition to clear orientation, the environment should evoke familiarity and a sense of security. Recognisable elements, distinctive planting compositions, or water structures can stimulate positive memories and foster a sense of belonging (Erbino et al., 2015; Pouya et al., 2015). The principle of universal design ensures that the garden is accessible to all users regardless of age or physical ability. This includes appropriate pathway widths, suitable surface materials, and seating areas systematically placed approximately every 25 metres (Cooper Marcus & Sachs, 2013; Pouya et al., 2015).

3. Spatial diversity and opportunities for choice

A high-quality healing outdoor environment provides a variety of spaces that correspond to different user needs and emotional states. Secluded and quiet areas for individual rest and reflection, alongside socially active spaces for small or larger groups, provide users with a sense of control over their environment – a factor closely associated with stress reduction (Pouya et al., 2015; Ulrich, 1999). The balance between active and passive zones should be adapted to the specific user group and their capacity and willingness to engage in activities (Shahrad, 2012). Another important aspect is the usability of the garden throughout different seasons and weather conditions. Shelters, semi-enclosed areas near entrances, and appropriate lighting can ensure year-round accessibility (Belčáková et al., 2018; Pouya et al., 2015).

4. Aesthetic quality and positive emotional messaging

The entrance area of a garden forms the first impression and plays a crucial role in shaping the visitor's psychological readiness. It should therefore be representative, welcoming, and evoke a sense of safety (Pouya et al., 2015; Shahrad, 2012). The architecture of buildings, artistic elements, and the overall composition of the garden should create a harmonious and non-oppressive environment, as negative visual associations may intensify feelings of distress among vulnerable users (Shahrad, 2012). Reducing the proportion of hard surfaces and emphasising green vegetation enhances the perceived naturalness of the environment, which – according to the stress recovery theory – is one of the key factors supporting restoration and recovery (Ulrich, 1984).

5. Integration of biophilic design

In contemporary therapeutic landscape planning, increasing importance is placed on the principles of biophilic design, which expand the concept of sensory experience by providing a more systematic framework for strengthening the human–nature relationship. Biophilic design elements – such as natural lighting, natural ventilation, organic materials, and access to green areas – have been associated with reduced stress levels, shorter recovery times, and improved patient engagement (Kellert & Calabrese, 2015). Kellert identified three primary ways in which nature is experienced within built environments: direct contact with natural elements, indirect representations of nature, and spatial relationships that reflect natural forms and structures (Kellert & Calabrese, 2015). Biophilic design has the potential to reduce stress, improve cognitive functioning and creativity, enhance well-being, and accelerate recovery (Browning et al., 2014). Therefore, integrating biophilic design in healing gardens is not merely an aesthetic decision but also a scientifically supported therapeutic strategy.

6. Cultural identity, intergenerational interaction, and community engagement

The effectiveness of healing environments depends not only on their physical and sensory qualities but also on their ability to reflect the social and cultural identity of their users. Successful therapeutic landscapes integrate principles of biophilic design, adaptive resilience, sensory calibration, social granularity, and cultural resonance, offering solutions that promote public health and community resilience. Culturally relevant plantings, design motifs, and spatial arrangements create environments that strengthen a sense of belonging and enrich user interaction with the therapeutic space.

A particularly important aspect is the inclusion of elements that encourage intergenerational interaction. Spaces intentionally designed for contact between different generations not only strengthen social connections but also address the diverse needs of different user groups. Community participation in the design process – through participatory strategies during diagnostic and planning phases – is also a prerequisite for ensuring that healing outdoor environments truly respond to the needs of the specific community and produce long-term therapeutic outcomes (Quiroz Saavedra & Cruz Covarrubias, 2026).

Conclusions

1. The conducted literature analysis confirmed that therapeutic landscapes represent an interdisciplinary approach that combines principles of landscape architecture, environmental psychology, and public health. The analysed studies demonstrated that natural environments can support psychological restoration, reduce stress, and contribute to overall well-being, particularly within healthcare and rehabilitation settings.

2. The study identified several key therapeutic landscape planning principles that are essential for creating health-supportive outdoor environments. The most significant components include spatial diversity, accessibility, safety and orientation, sensory engagement, universal design, and the integration of natural elements such as vegetation and water features. The interaction of these components creates environments that support physical activity, psychological restoration, and social interaction.

3. The comparative assessment of rehabilitation institutions in Latvia revealed considerable differences in the implementation of therapeutic landscape principles. The evaluation matrix demonstrated that

the National Rehabilitation Centre *Vaivari* showed the highest level of integration of therapeutic landscape planning principles, particularly in terms of accessibility, spatial quality, and environmental functionality. In contrast, rehabilitation centres *Līgatne* and *Tērvete* showed deficiencies related to spatial diversity, accessibility, activity opportunities, and emotional comfort, which may limit the therapeutic potential of these outdoor environments.

4. The results of the study indicate that many rehabilitation institutions in Latvia possess high natural landscape potential; however, this potential is not always fully utilised in the development of health-promoting outdoor environments. The findings highlight the importance of integrating therapeutic landscape principles into the planning and redevelopment of rehabilitation territories in order to improve the quality and functionality of outdoor spaces within the rehabilitation process.

5. The developed evaluation matrix proved to be an effective tool for assessing therapeutic landscape quality in rehabilitation environments. The matrix enabled a structured comparison of outdoor spatial characteristics and helped identify both strengths and deficiencies within the analysed territories. The study findings indicate that accessibility, spatial organisation, and diversity of activities are among the most critical factors influencing the usability and restorative potential of rehabilitation landscapes.

6. Considering the increasing prevalence of mental health challenges and the demographic trend of population ageing, the integration of therapeutic landscape principles into healthcare environments, public spaces, and residential areas is becoming increasingly important. Future research could further investigate the application of therapeutic landscape principles within broader urban environments and evaluate their long-term contribution to public health and well-being.

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FROM PAPER TO PIXELS: DIGITAL DELEGATE BADGES AND CONFERENCE COMPETITIVENESS

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Abstract
Digital solutions and innovative technologies are among key drivers of destination competitiveness, rising awareness, and enhancing attractiveness. This is particularly visible in the meeting and conference industries where place and venue are not sufficient factors any longer to define competitive advantage to attract local and international conference tenders. While sector has been defined as priority export area in Latvia as well application of contemporary digital solutions is among tasks still to be completed to appreciate possible results. Participant delegate cards (badges) are among key features of any business event, conference or meeting, allowing to identify each other and gather valuable attendance statistics. This is also one of areas with high potential to digitalize exiting print-based solutions, though choosing the most appropriate one is an issue with polarized opinions among event organizers, venues and delegates. Digital and reusable conference delegate badge as a competitive advantage has been defined as priority area of development by the conference organizers though service suppliers and in particular smaller event organizers and regional players with lower level of direct involvement in the international business travel may see this as another obstacle to overcome. This article summarizes results of digital badge implementation related research following focus group discussions with industry meeting and event industry representatives and provides in-depth analysis of business environment. Results provide recommendations and a road map to implement what has been defined as 'D-Badge' – an innovative and technologically advanced solution. Research results disclose nuances summarized in scenarios as a framework for further individual actions.
Keywords: digital delegate badges, conference competitiveness.

Introduction

In recent years, conferences and business events have been increasingly influenced by two interrelated developments – the growing emphasis on sustainability and the rapid spread of digital technologies. Conferences are events that generate significant material waste, particularly in the form of single-use participant badges and lanyards, which are often discarded immediately after the event (Mair & Jago, 2010; Getz & Page, 2016). At the same time, conference organisers operate in a highly competitive environment where advantage is achieved through service quality, operational efficiency, and reputational value (Rogers, 2013).

Digital and reusable conference participant badges have been developed as a potential solution addressing both challenges simultaneously. These badges, frequently incorporating QR codes, RFID or NFC technologies, enable the use reusable physical components combined with digital functionalities such as access control, networking, and data collection. While such solutions are increasingly adopted in practice, academic research has largely focused on sustainability, environmental impacts, waste reduction strategies and carbon emissions, while and the importance of digital technologies are analysed separately (Laing & Frost, 2010; Jones et al., 2017), whereas event digitalisation is analysed separately and focuses on visitor experience and smart technologies (Neuhofer et al., 2015). Consequently, the strategic role of digital and reusable badges as a source of competitive advantage remains insufficiently examined.

Recent opinions of the resource-based view emphasise that sustainable competitive advantage depends not only on the value of resources, but on the organisation's ability to effectively embed these resources into organisational processes that support consistent value creation (Barney, 2018; Teece, 2018). Digital and reusable badge systems may contribute to value creation by reducing operational costs, improving data accuracy, and enhancing attendee experience. However, as the technologies are becoming increasingly available, their potential to generate sustained competitive advantage depends on complementary organisational capabilities rather than on the technologies themselves.

From a perspective of sustainability, digital and reusable badge systems are in line with the circular economy principles by extending product lifecycles and reducing material waste (Geissdoerfer et al., 2017). Moreover, sustainability-related practices may contribute to reputational benefits and organisational legitimacy, which are increasingly relevant in attendee decision-making. Nevertheless, the existing literature provides limited empirical evidence on how conference participants perceive such initiatives and whether they are interpreted as meaningful sustainability actions or merely as measures aimed at improving operational efficiency. This is another aspect that highlights the need for further research examining the relationship between digital and reusable badge systems and their competitive advantage.

Conferences and business events face concurrent imperatives to advance sustainability by embracing digitalisation to improve service quality and even brand positioning. Recent reviews show that digital transformation can reinforce sustainability objectives by enhancing operational efficiency, data visibility, and stakeholder engagement, particularly within the service industry (Robertsone & Lapiņa, 2023). In this context, transitioning from single-use and even disposable to reusable, digitally enabled badges

address a salient waste stream while aligning with digitalisation's capability to personalize experiences and streamline interactions (Jiang & Phoong, 2023). More broadly, policy and development analyses emphasize that digital tools can reduce environmental impacts across value chains by improving productivity and resource use, reinforcing the strategic case for integrated digital–sustainability initiatives in events (UNCTAD, 2024).

Digital conference badges employing QR, RFID, or NFC, function as identity, access, and data interfaces enabling expedited check-ins, session-level access control, and contact exchange for networking purposes (Veľas et al., 2024).

While much of the events-related literature treats such tools primarily as experience enhancers, integrated assessments of their sustainability impacts and strategic implications remain limited (Parolin et al., 2024; Chen et al., 2025).

Event competitiveness can be developed across several dimensions − operational efficiency, attendee experience quality and data-driven decision making (Busulwa et al., 2022; Chen et al., 2025). Technology facilitated engagement contributes to these outcomes when coherently embedded across the whole procedure of an event. Recent reviews classify event technologies (including smart, consumer-assistive tools such as digital badges) and link them to enhanced engagement and value creation (Chen et al., 2025). Digital participant badges streamline session-level access control, and enable networking exchanges, thereby reducing friction and elevating perceived service quality (Busulwa et al., 2022). The integration of digital services improves the operational efficiency of conferences by reducing administrative processing time per participant, thereby increasing the ratio of achieved outputs to labor and administrative inputs. This means that, with the same staff capacity, it is possible to serve a substantially larger number of participants, thereby enhancing the operational performance of the conference (Paul et al., 2024; Valášková et al., 2025). Competitive effects depend less on the badge technology per se and more on its integration into organisational routines and complementary assets, consistent with contemporary resource-based theorising that locates advantage in how resources are configured and deployed (Barney et al., 2021). Extending this logic, dynamic capabilities, like sensing, seizing, and reconfiguring, are prerequisites for converting generic digital tools into context specific service innovations and performance gains. The payoff from digital badges scales with CRM integration, personalization rules, data governance, and post-event analytics that enable iterative improvement (Teece, 2007).

Materials and Methods

This study employed a sequential mixed methods design to examine the functional needs and market availability of digital, reusable, and interactive conference participant identification cards. The empirical study was conducted in three consecutive stages. The first stage combined a qualitative focus group interview with a quantitative survey to define the most frequently required functions among industry stakeholders. The second stage comprised a structured desk review and thematic analysis of software platforms and equipment suppliers in accordance with the results obtained in the first stage of the research. Based on the research results from the first and the second stages, a product development scenario matrix was developed in the third stage.

In the first stage, data were collected using a two-step empirical procedure: (a) a focus group interview was conducted to collaboratively identify target use objectives and key functional requirements; (b) a structured survey instrument was subsequently administered to evaluate the perceived importance of the proposed digital participant badges functionalities derived from the qualitative findings of the first stage. In the second stage of the study, a desk-review protocol was implemented to identify and systematically code vendor offerings – both software platforms and hardware solutions, based on information available on websites. Operational definitions were established to differentiate between digital badges, e-badges, virtual badges, and smart badges, with the latter defined as badges incorporating embedded technologies that enable functions such as access control, attendance tracking, networking, and potential payment solutions. In the third stage, building upon the findings obtained in the previous stages, a 2×2 product development scenario matrix was applied. This method enabled the systematic identification and structuring of plausible development scenarios.

In the first stage, the same cohort of industry managers participated in the focus group and structured survey, ensuring population consistency across methods. A total of 32 respondents (92% of the association's membership), representing the sector's leading organisations for which business events organisation is a primary activity, participated in the study. Entities for which business event organisation represent only occasional line of business were purposively excluded from the sample to ensure sectoral relevance and analytical validity. The focus group interview was analysed using thematic analysis, which enabled the identification of the most important themes emerging from the discussion. The relative importance of each identified theme was subsequently examined in the next stage of the study through a structured survey instrument. In the survey phase, only responses from companies with prior experience in the implementation of digital participant badges were included in the analysis. A total of 24 questionnaires were analysed, representing business event, meeting and conference, organizers representing majority of the industry. Descriptive statistics were used to evaluate the perceived importance of eight predefined

functional domains for digital delegate badge implementation. Respondents ranked the domains from 1 (most important) to 8 (least important). Mean ranks and standard deviations were calculated to determine relative priorities. Lower mean ranks indicate higher importance.

During the second stage, a qualitative desk review was conducted to systematically map existing software and hardware solutions to the six use objectives identified in the first stage. Vendor identification was carried out by means of targeted web-based screening of company websites. Thematic analysis was structured through a deductive coding framework derived from the six predefined objectives. For each reviewed vendor, coders recorded the extent to which the six objectives were covered, the enabling technologies employed, the integrations provided, and any differentiating features (e.g., real-time monitoring, alerts for unauthorised access, depth of analytics). Cross-platform comparative matrices facilitated systematic comparison and gap identification, resulting in an aggregated functional landscape of market offerings and highlighting the most comprehensive solution providers. Overall, the software review encompassed 12 platforms, including both Latvian and international providers. Thematic analysis of publicly available website documents was performed to capture the functional scope, enabling technologies, analytical capabilities, and system integrations.

Table 1
Vendor analysis summary

Functionality	Availability	Notes
Registration	Universal	Core feature
Access control	Widely available	Standard implementation
Analytics	Widely available	Varies in depth
Networking	Highly availably	From basic to advanced
Contactless payments	Rarate	Only 1 platform

During the third stage and based on the findings of the desk review, a scenario analysis was conducted to assess the product's commercialisation potential. Scenario development is a strategic analytical tool employed to explore and prepare for multiple plausible futures, particularly under conditions of uncertainty. Scenario planning was selected as an appropriate method given uncertainty about future pathways for a digital, reusable, interactive conference badge. It constructs goal-oriented narratives that explore how objectives, stakeholders, trends, and critical uncertainties may interact.

To develop the product development scenarios, a 2×2 scenario matrix was applied, following the methodological guidelines proposed by Rhydderch (2017) and Stucki (2022). In determining the key scenario drivers, the research integrated findings from the stakeholder focus group discussions, product readiness assessment, analysis of available software and hardware solutions, evaluation of technical functionalities, competitive positioning, commercialisation prospects, and risk identification. The synthesis of empirical findings enabled the identification of the principal driving forces contributing to high levels of uncertainty surrounding product implementation, as well as the range of unknown variables potentially influencing its future development trajectory.

Results and Discussion

Based on focus group findings, the identified attributes were consolidated into six overarching functional domains for the proposed digital badge solution. First, digital registration and participant administration encompasses the optimisation of on-site registration procedures, digital badge allocation, participant flow coordination, and badge return monitoring, thereby contributing to operational efficiency and process standardisation. Second, access control and security governance includes role-based and zone-specific access management, controlled entry mechanisms, and security monitoring functionalities, supporting both physical venue management and digital system integrity. Third, networking and structured information exchange refers to functionalities enabling digital contact transfer, scanning-based data acquisition, and facilitated interaction among participants, thus enhancing relational capital formation within business events. Fourth, participant engagement and real-time interaction comprise interactive mechanisms such as live polling, moderated Q&A functionalities, feedback submission, and gamification tools designed to increase active participation and experiential involvement. Fifth, data capture, monitoring, and analytical intelligence incorporates attendance tracking, movement pattern analysis, behavioural data aggregation, and post-event performance analytics, thereby enabling evidence-based decision-making and strategic event optimisation. Sixth, personalisation and experiential enhancement include the provision of customised agendas, tailored informational prompts, and targeted networking suggestions, supporting individualised participant pathways and value co-creation. Beyond these primary objectives, several cross-cutting dimensions were identified as critical implementation contingencies, including sustainability considerations, economic feasibility, technological interoperability with existing platforms, and compliance with ethical and data protection frameworks. Collectively, these findings provide a structured functional taxonomy for evaluating the developmental and commercialisation potential of the 'D-Badge' concept within the business events ecosystem.

The survey's forced-ranking task revealed a clear priority structure: registration acceleration and simplification were the foremost objective (M = 3.79), indicating that operational efficiency and data driven

administrative streamlining dominate organizers' strategic considerations. Overall differentiation across objectives was moderate (mean ranks 3.79–4.71), with access control across event zones receiving the lowest relative priority (mean rank 4.71), suggesting that security related segmentation is secondary in near term implementation planning. Consistent with this pattern, respondents primarily associated digital delegate badges with process optimization and administrative enhancement rather than security centric functions. Variability in evaluations was moderate (SD 1.44–2.96), indicating some heterogeneity in priorities while preserving an overall coherent preference structure within the sample.

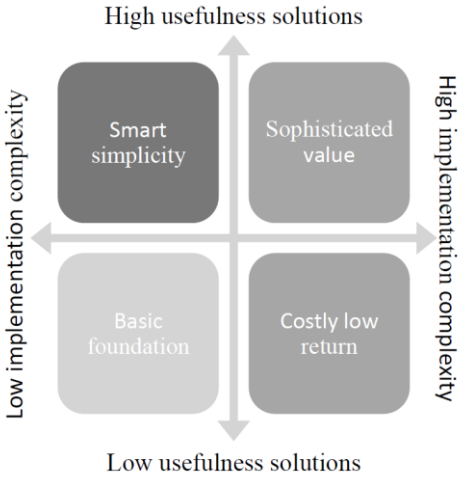
Drawing on a review of vendor website documentation for 12 platforms mapped to six use goals derived from stage one, three main results emerged. First, digital registration was universally supported, and most platforms also offered access control and attendance analytics, typically enabled by QR, RFID, or NFC. Second, networking capabilities varied markedly—from basic in-app messaging to algorithmic matchmaking and NFC-based contact exchange—indicating heterogeneous depth across vendors. Third, contactless payments were rare, identified in only one platform, revealing a pronounced capability gap relative to other domains. Integrations (registration systems, CRM, mobile apps, scanners, and published APIs), analytics features, and enabling technologies were systematically extracted from website materials to characterize functional coverage.

Following the results accomplished in first two stages of research, the results of the third stage focus on the assessment of 'D-Badge' implementation scenarios and related factors which determine an overall digital competitiveness of business travel service providers and destinations which have identified business travel as a part of their strategic tourism development plan. Considering the diversity and complexity of the available technological solutions which can enhance participant experience and boost destination competitiveness suggested scenarios are meant to provide a framework for further implementation activities. Furthermore, there has been emphasis to provide insight into applicable development scenarios as a framework for the strategic development of the business segment.

The scenarios developed provide guidelines for destinations focusing on attracting various business events and provide an outline for their regional competitiveness. They are applicable to business related meetings, conferences and events which require delegate registration, attendance monitoring or interaction with the event itself by accessing program, social program, various important information related to the event. The results are targeted at public and private event organisers, venues and regional business travel stakeholders which have identified business travel and its various forms as a strategic development utilizing available infrastructure.

It was concluded that the main criteria to assess the implementation process of 'D-Badge' and to achieve the overall goal of increased destination competitiveness are the functionality aspect (vertical axis) and implementation complexity (horizontal axis). These two forms also main scenario matrix axis, as illustrated in Figure 1. Based on research results for both axis are defined endpoints.

Figure 1
Scenario matrix



The functionality aspect includes usefulness of commercialisation and added value to user. Applying these to an axis on the one end are comprehensive usefulness solutions with high level of such indicators as information personalisation, exchange, real time feedback and on the other end low usefulness solutions with participant identification and simple access to information, primarily using QR codes as the simplest available version.

On the horizontal axis (implementation), stands technological solutions their complexity and related implementation risks. Risks are related to data privacy, required technical equipment and involved supporting staff, while low risks are related to simple integration with minimal technical support compensated by more affordable costs. This axis focuses on resource, knowledge and required organizational tasks to implement digital solutions in business event services. Following identified values and defined axis endpoints, four scenarios were development and named reflecting functionality, added value and implementation risks and complexity as their key values.

Smart simplicity scenario provides high functionality but low implementation complexity. It is scenario where features offer personalized information, networking and it can be useful for medium-sized events with limited IT resources. However, risks are related to integration between other platforms and external NFC providers.

Sophisticated value scenario provides high user value and advanced functionality, but it requires significant resources, hardware and technical support.

Foundation scenario is a low-cost solution which is usually based on QR codes and simple NFC identifications, but they limit functionality and does not provide high level of participant engagement.
Costly low return scenario has high implementation and development costs and provide litter functional value, and it should be avoided whenever possible.

Conclusions

1. A clear assessment of required functionality and technological appropriateness to the aim of digitalization is the key factor in considering making decisions related to enhancement of business event offerings by integrating digital solutions. This is confirmed by the research results where with a median of 3.79 registration simplification has been ranked as the highest priority. The range of available solutions determines the need to focus on the evaluation of required functions.
2. Sustainability and circularity of business event related materials, devices and supportive tools remain a crucial part in overall destination and supplier competitiveness. 'D-Badge' provides an overview of benefits related to the implementation of such reusable tools while decisions of the solution remain case-based and considering the set of aims.
3. NFC, RFID and QR codes remain to be among the most frequently used solutions in event organizations, as explored by the analysis of possible suppliers. The importance of simple and easy to use QR code solutions is decreasing, being replaced by NFC technologies. This is supported by an increased number of mobile solutions used which have entered into everyday life activities.
4. Digitalisation, user-friendly IT solutions, and functionality have emerged as key driving factors of industry competitiveness. Empirical results also show that event organizers primarily associate digitalization with the process of implementing digital badges while security or advanced engagement features have lower level of prioritization. With the spread of easily accessible technologies, this is now applicable also to event organization and related service providers, venues and other stakeholders throughout the public and private sectors. The ability to offer digital solutions determines success in attractive business events such as conferences and meetings which may serve as revenue streams in tourism ecosystems.
5. While in general tourism development remains as a strategic priority for municipalities in Latvia, there are fewer of them which focus not just on leisure travel but also business travel where focus on digitalisation as a tool for strategic competitiveness is important. Among factors influencing regional competitiveness is also the ability to provide contemporary business event delegate solutions. Even the implementation of 'D-Badge' reveals complexity due to a variety of available solutions; the research results illustrate entry level possibilities to start digitalisation of business events also on regional and small-scale levels.

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UNEVEN DIFFUSION: THE SECTORAL CONTOURS OF DATA CAPITALISM IN A SMALL OPEN ECONOMY

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Abstract
This study investigates the structural penetration of Data Capitalism (DC) within a small open economy, specifically analysing Latvia's 101 most valuable enterprises. Using novel Data-Capitalism Maturity Framework (DCMF), firms are classified into four distinct tiers to determine whether data commodification represents a unified national shift or a phenomenon concentrated in specific sectors. Two hypotheses are tested – first, that the IT & Telecommunications sector exhibits a significantly higher concentration of Primary data capitalists, and second, that data capitalism classification is independent of firm size. Results from non-parametric analyses—specifically Chi-Square, Fisher's Exact, and Cochran-Mantel-Haenszel tests—indicate that the adoption of Data Capitalism (DC) is heavily stratified. Despite comprising only 10.9% of the sample, Primary data capitalists are predominantly located in the IT & Telecommunications sector, which is 35 times more likely to commodify data than other industries. Traditional sectors, such as Manufacturing and trade primarily utilise data for functional efficiency. Additionally, firm size showed no significant association with data maturity tiers, and the IT sector's dominance persisted even after controlling for turnover. The findings conclude that sectoral logic, rather than organisational scale, drives data commodification. Consequently, effective economic policy must be differentiated, prioritising export capabilities for IT firms while enhancing digital integration for traditional sectors.
Keywords: data capitalism, sectoral analysis, firm size.

Introduction

The global economy is undergoing an expansive transition in which the ability to extract, commodify, and exploit data has become a definitive source of competitive advantage (McAfee & Brynjolfsson, 2012; Zuboff, 2022). This shift has given a rise to 'Data Capitalism' (DC). It can be understood as an economic paradigm where data is no longer merely a byproduct of economic activity but a core asset driving value creation (Bolin, 2022). However, this transformation is not a uniform process; its pace and nature are deeply shaped by the unique structural characteristics and technological opportunities of different industrial sectors (Bresnahan et al., 2002). While global technology giants which define the frontier of this new economy are under scrutiny, significantly less is understood about how these dynamics manifest within the diverse industrial contours of small, open economies like Latvia.

Policymakers in regions like Latvia are often tasked to catch up with this new paradigm, yet they lack the granular evidence required to distinguish between sectors that are truly embedded in the data economy and those that are merely undergoing basic digital transformation. Consequently, there is a critical empirical gap in understanding of the actual structural penetration of DC at a sectoral level within a specific national context. It is not quite clear whether the systemic extraction and commodification of data are diffused broadly across the economy or are strictly concentrated within specific industries.

To address this gap, given research empirically assesses the intensity of DC adoption across 101 of Latvia's top enterprises and investigates whether DC represents a unified national shift or it is concentrated in distinct sectoral strongholds.

Furthermore, a critical confounding factor in technology adoption is firm size, as larger firms often possess superior access to capital and talent (Oliveira et al., 2014; Zuboff, 2019). Thus, the research aims to isolate the effect of sector from the effect of size.

With the help of DCMF, the novel framework that categorises firms in four distinct tiers based on their adoption of DC logic, this study is set to determine whether the observed sectoral effects are intrinsic to industry logic or merely artefacts of firms' size. To use turnover as an indicator for firm size is quite a common practice in economic research, used by several scholars previously (e.g. Lestari, 2019; Yasin et al., 2021). To achieve those goals, two specific hypotheses are tested:

H1: The IT & Telecommunications sector exhibits a significantly higher concentration of Primary data capitalists compared to other industrial sectors.

H2: The classification of firms into Data Capitalism tiers is independent of firm size (turnover).

Materials and Methods

The empirical dataset was engineered from the 'TOP 101 of Latvia's Most Valuable Enterprises' list for the year 2024, published by Leading Latvian corporate finance company 'Prudentia' in collaboration with official stock exchange Nasdaq Riga (top101.lv). This list contains a comprehensive cross-section of the 101 economically significant firms operating in Latvia. The sample spans all key economic sectors, such as IT & Telecommunications, Manufacturing & Consumer Trade, Financial Services etc. Financial indicators – including Turnover 2023, EBITDA 2023, and year-over-year Growth – as well as competitive rankings (TOP 2023, TOP 2024), were augmented with the DC tier based on DCMF to provide the quantitative basis for the analysis.

To operationalise the concept of DC, this study employed the DCMF (Mētra, 2026). The framework treats DC not as a binary state but as a continuum

where Primary DC (tier 3) are on the one side and Non-DC (tier 0) on the other with two additional tiers – Secondary DC (tier 2) and Tertiary DC (Tier 1) in the middle.

DCMF assesses firms across four weighted dimensions derived from value creation mechanisms: (1) Data Extraction (20%) – assesses whether data extraction is a core operational activity and a deliberate resource accumulation strategy; (2) Data Commodification (20%) – examines if extracted data is treated as a commodity, through direct monetisation or significant product enhancement; (3) Data Exploitation (30%) – evaluates the use of advanced analytics or AI to exploit data patterns for competitive advantage; and (4) Data Centrality (30%) – determines the extent to which the firm's business model is dependent on data-driven insights for survival.

The classification process involved a mixed-methods approach integrating qualitative analysis with a 'Human-in-the-Loop' (HITL) – AI-assisted methodology. HITL is a procedure in which a person is actively involved in the operation, monitoring or decision-making of an automated system (Stryker, 2025). It is already used in scientific research. For example by Al-Turki et al. regarding RASE tagging in building compliance (Al-Turki et al., 2024) or Umakanth regarding validating GenAI outputs in clinical settings (Umakanth, 2025).

First, the author conducted a systematic review of public documents—corporate websites, annual reports (2021–2023), and press releases for each firm. To ensure reliability and mitigate bias, the classification was validated using two advanced LLMs: Google's Gemini 2.5 Pro and OpenAI's ChatGPT-O3. This validation leveraged the AI's ability to process large text volumes to identify potential anomalies or bias in the human researcher's assessment. In cases of discrepancy, a reconciliation process involving a re-examination of the evidence was triggered. The final classification decision in all cases rested with the human researcher, ensuring that AI remains only as a tool for calibration rather than autonomous decision-maker.

The iteration of DCMF logic proceeded in two blocks. First categorization was performed on random sample data by author and two recruited master level students. First, the author manually analysed the selected companies. For each firm, 'intelligence folders' with annual reports and relevant public documents were created. Subsequently, two independent master-level students were contracted to analyse the same sample using the DCMF (v1.0) protocol. To ensure consistency in the assessment process, the students were given access to 'intelligence folders' together with specific instructions on how to evaluate the firms and calculate the maturity score. Then the same sample data was coded with both LLMs. Both models were provided with the same collated public data and a standardised prompt to perform an independent classification.

The first iteration revealed that earlier version of DCMF overvalued the direct sale of data, underestimating 'walled garden' models where data is exploited internally. Consequently, the final weights prioritise internal transformation and strategic centrality over simple commodification (DCMF v2.0). Each dimension was scored on a four-point ordinal scale (0 = Minimal/None to 3 = Advanced/Extensive), based on verifiable, publicly available information. The scoring protocol is conservative, assigning zero in the absence of clear evidence. The composite DCMF Index Score was calculated as follows:

$$\text{DCMF_Index_Raw} = (Score_{Extraction} \times 0.20) + (Score_{Commodification} \times 0.20) + (Score_{Exploitation} \times 0.30) + (Score_{Centrality} \times 0.30) \quad (1)$$

Firms were then categorised into one of four mutually exclusive tiers based on a sequential logic:

- Tier 0 (Non-Data Capitalist): Data Extraction score is 0 (Gatekeeper Rule).
- Tier 3 (Primary Data Capitalist): (Score ≥ 2 in both Extraction and Commodification) OR (Score = 3 in both Extraction and Exploitation).
- Tier 2 (Secondary Data Capitalist): Remaining entities with DCMF Score ≥ 51.
- Tier 1 (Tertiary Data Capitalist): Remaining entities with DCMF Score ≤ 50.

Integrating the computational efficiency of AI with the critical oversight of a human-in-the-loop framework maximises analytical throughput whilst safeguarding against algorithmic bias and ensuring the contextual validity of the final classifications.

Because of the observed right-skew in financial data, the small sample sizes within certain DC_Tiers, and several missing data points, non-parametric statistical procedures were used. All analyses were performed using the Python programming language (version 3.13.0), with the pandas (1.5.3), numpy (1.24.0), scipy (1.14.1), and matplotlib (3.6.3) libraries.

To control the family-wise error rate across multiple comparisons, the Holm–Bonferroni method was systematically applied. To test H1 (Sectoral Concentration), the sectoral composition of the IT & Telecommunications sector was contrasted against all other industries using a Pearson's χ^2 test on a 4×2 contingency table (Tiers by Sector Group). Effect size was measured using Cramér's V. To identify specific drivers, per-tier contrasts were evaluated using Fisher's exact tests on 2×2 tables, reporting odds ratios (OR) with 95% confidence intervals. To test H2 (Role of Firm Size), independence between DC_Tier and firm size was evaluated using a Pearson's χ^2 test of independence on size quartiles. Given the non-parametric nature of the financial data, a Kruskal-Wallis H-test was also employed to compare raw turnover distributions across the tiers. To ensure that the observed sectoral effects in H1 were not

confounded by firm size, a Cochran–Mantel–Haenszel (CMH) test was conducted. This test pooled the association between IT sector membership and Primary status across the four size strata, yielding a common odds ratio that reflects the relationship independent of firm scale.

These robust statistical methods ensure a reliable foundation for interpreting the complex relationships between data capitalism maturity, industry sector, and firm size.

Results and Discussion

The empirical analysis of Latvia's 101 most valuable enterprises reveals a corporate landscape where data capitalism is not a pervasive, uniform wave, but a stratified phenomenon shaped decisively by sectoral logic. The classification of firms into the DC Tiers using the DCMF yielded a distribution where 'Primary' data capitalists remain a distinct minority, accounting for 10.9% (11 firms) of the sample. However, the economic landscape is not merely binary. The largest segment consists of 'Tertiary' firms (47.5%, n=48). Thus, for almost half of the top enterprises, data remains a supportive resource or functional input rather than a core asset. A significant portion of the sample sits in the intermediate 'Secondary' tier (22.8%, n=23). 'Non-Data Capitalists' comprise the smallest group (18.8%, n=19).

Sectorally, the sample is dominated by Manufacturing & Trade, which represents 45.5% of the firms (46 companies). Next by size is Other Services (20.8%), then Financial Services (10.9%), and IT & Telecommunications (8.9%). Financial profiles across DC tiers reveal a non-linear relationship between size and data strategy. Highest median turnover is found in the Secondary tier (€200.2M). Primary data capitalists (Tier 3) exhibit a robust median turnover of €163.7M. This turnover is substantially higher than €76.4M shown for Non-Data Capitalist tier. Thus, the transition to higher data maturity tiers is generally associated with increased revenue scale.

The first assumption of this research was that the IT and Telecommunications sector would exhibit a significantly higher share of Primary data capitalists than other industries (H1). The analysis provides overwhelming support for this proposition. A 4×2 contingency analysis comparing the tier distribution of the IT & Telecommunications sector against all other industries revealed a statistically significant and strong association ($\chi^2(3) = 32.84$, p <.001, Cramér's V = 0.570). This effect size is substantial, suggesting that sector is a dominant predictor of a firm's data strategy. In contrast to the Financial Services sector ($\chi^2(3) = 5.81$, $p = .121$) or the Manufacturing & Consumer Trade sector ($\chi^2(3) = 8.20$, $p = .042$), which exhibited either no distinction or only modest deviations from the general economic profile, the IT sector stands apart as a distinct 'data-native' ecosystem.

The intensity of this concentration is best illustrated through the odds ratios derived from Fisher's exact tests (Table 1). When isolating the 'Primary' tier, IT & Telecommunications firms are vastly overrepresented.

Table 1

Statistical Association of Sectors with Data Capitalism Tiers

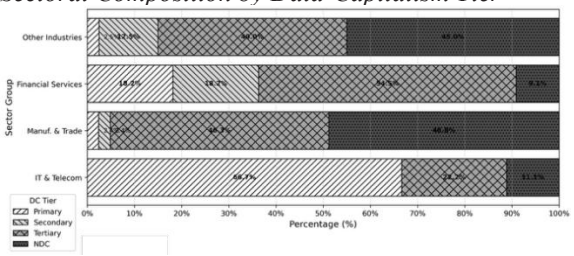
Sector	Focal Tier	Odds Ratio (OR)	95% CI [Low, High]	Fisher's Exact *p* (adj.)
IT & Telecom	**Primary**	**34.80**	**[5.51, 245.05]**	**< .001***
	Tertiary	0.12	[0.01, 0.96]	1.000
Manuf. & Trade	Primary	0.14	[0.02, 1.17]	.182
	Tertiary	1.30	[0.58, 2.89]	.546
Finance	Primary	2.28	[0.42, 12.41]	.596
	Tertiary	1.72	[0.49, 6.05]	.521

Note: *p*-values are Holm–Bonferroni adjusted to control for family-wise error within sectors. Significant results at $\alpha = 0.05$ are bolded.

The analysis yielded an Odds Ratio (OR) of approximately 34.80 (95% CI [5.51, 245.05]; Holm-adjusted p <.001). In practical terms, this indicates that a firm operating in the IT & Telecom sector is nearly 35 times more likely to be a Primary data capitalist than a firm selected at random from the rest of the Latvian economy. Conversely, the sector is numerically underrepresented in the Tertiary tier (OR ≈ 0.12). This finding is reinforcing the binary nature of this divide. It seems that in Latvia IT firms are those that primarily commodify data, whereas firms in other sectors utilise data merely as a functional input. This structural divergence is further illustrated in Figure 1, which details the sectoral composition by tier.

Figure 1

Sectoral Composition by Data-Capitalism Tier



Source: Author's design.

As visualized in Figure 1, the firms in IT & Telecom sector sits dominantly in Primary DC tier (indicated by the darkest shade). They account nearly two-thirds of Primary tier composition (6 out of 9). In sharp contrast, the Manufacturing & Consumer Trade sector is heavyly concentrated in the Tertiary and Non-Data Capitalist tiers (lighter shades).

The visual representation confirms the skew. Figure 1 show that IT sector has internalized data as a core commodity. The traditional sectors remain largely in the value-utilization stages of the data capitalism spectrum.

This finding aligns with the analysis in Andreoni and Roberts, who document pronounced sectoral divergences in digital intensity under platform capitalism, with IT and telecommunications sectors exhibiting high levels of data commodification and digital-native ecosystems, while traditional manufacturing remains largely confined to functional or lower-intensity digital utilization in latecomer economies (Andreoni & Roberts, 2022). In the IT and Telecommunications sector, the core product – whether software code, internet connectivity, or a digital platform—is intrinsically data-based. The marginal cost of duplicating this data for new value streams is near zero, and the infrastructure for data extraction is often pre-integrated into the service delivery mechanism (Parker et al., 2017). For these firms, 'Primary' data capitalism is not a radical pivot; it is a natural result of their existing capabilities.

A critical question in the analysis of technology adoption is whether observed patterns are driven by strategic orientation or simply by resource availability. It is well-established that large firms often have greater access to the financial and human capital required for advanced analytics (Oliveira et al., 2014). Therefore, one might argue that the concentration of Primary data capitalism in the IT sector is merely an artefact of firm size – perhaps the IT firms in the sample are simply larger and thus more capable of investing in data monetisation.

The second assumption of this research was that the classification of firms into Data Capitalism tiers is independent of firm size (H2). For firm size turnover was used as a proxy.

A Pearson Chi-Square test of independence between firm size quartiles and DC tiers yielded a non-significant result ($\chi^2(9) = 16.68$, $p = 0.054$). Similarly, a Kruskal-Wallis H-test comparing the raw turnover distributions across the four tiers failed to reach the threshold of statistical significance ($H = 7.70$, $p = 0.053$. These results indicate that turnover (firm size) is not a deterministic driver of DC maturity.

Looking at the median turnover in each tier further proves that the trend isn't a straight line. While Non-Data Capitalists (Tier 0) exhibited the lowest median turnover (€76.4M), the highest median turnover was actually observed in the Secondary tier (Tier 2) at €200.2M, rather than in the Primary tier (Tier 3), which reported a median of €163.7M. Such distribution indicates that achieving 'Primary' status is not merely a function of economic scale. Many large firms in the sample remain in the Secondary or Tertiary tiers, using data as a support function rather than commodifying it.

To validate H1, determining whether the clustering of Primary data capitalists in the IT sector was an artifact of firm size a Cochran-Mantel-Haenszel (CMH) test was employed. The test assessed the association between sector (IT vs. Other) and Primary status while stratifying firms by size quartiles. The results confirmed that the IT-Primary link is robust and independent of scale. The common odds ratio for being a Primary data capitalist in the IT sector, adjusted for firm size, was 32.56 ($p < .001$). This implies that even when comparing firms of similar size, an IT & Telecommunications firm is nearly 33 times more likely to be a Primary data capitalist than a firm from any other sector. Consequently, sectoral identity, rather than firm size, is the decisive factor in predicting a firm's position at the apex of the data capitalism hierarchy.

This result is of significant theoretical importance. It indicates that when we compare an IT firm and a non-IT firm of the same size, the IT firm is roughly 33 times more likely to adopt a Primary data capitalist model. This confirms that the driver of data capitalism is sectoral logic, not organisational scale. A small IT software provider is structurally more predisposed to monetise data than a massive retail chain or a large manufacturing plant. The retailer may use data to optimise inventory (Tertiary), but the software provider sells the very logic of optimisation (Primary).

The findings of this study offer a corrective to the generalised narratives of the 'Data Economy'. The transition towards data capitalism is often portrayed as a universal imperative—a ladder that all firms must climb to survive (Massa & Tucci, 2013). The empirical results, however, suggest that the ladder exists primarily for specific sectors. The stark concentration of Primary data capitalism in the IT & Telecommunications sector validates the existence of a 'digital native' advantage. These firms possess what Teece describes as dynamic capabilities that are fundamentally aligned with the data economy (Teece, 2018). They do not need to undergo the painful 'digital transformation' that traditional industries face because their assets were digital from birth; their transition to DC is an evolution of their core competency. Conversely, the absence of a statistically distinct profile for the Financial Services sector is a noteworthy 'non-finding'. Despite being an information-intensive industry (Chen et al., 2012), Latvian financial firms do not statistically differ from the general industry baseline in their adoption of Primary data capitalism. This may reflect the 'FinTech paradox': whilst the sector processes immense amounts of data, regulatory constraints (Colangelo, 2024) and legacy infrastructure in established banks often limit their ability to commodify that data directly. They remain high-intensity users (Tertiary) rather than sellers. The lack of a size effect (H2) challenges the Resource-

Based View (RBV) in the context of data strategy (Barney, 1991). Traditional RBV suggests that resources (size, budget) dictate capabilities. However, in the data economy, structural assets (the nature of the product) appear to matter more than financial assets. A small platform company can generate data network effects that a multi-billion-euro manufacturer cannot replicate, simply because the manufacturer's product is rivalrous and physical.

From a theoretical standpoint, these findings support a nuanced view of value creation in the digital age. It is crucial to distinguish between Data-Supported Value Creation (Tertiary), which is applicable across all sectors and involves efficiency and optimisation, and Data-Driven Value Capture (Primary/Secondary), which entails the direct monetisation of data assets. Existing literature frequently conflates these concepts, leading to inflated expectations regarding the transformative potential for traditional industries. The findings suggest that for the Manufacturing and Trade sectors, the 'Tertiary' model does not represent a failure to reach the apex tier, but rather constitutes the appropriate strategic fit for their industrial reality (Kowalkowski et al., 2015). Ultimately, recognising this sectoral dichotomy redefines the trajectory of the digital economy, suggesting that the path to value creation is not a universal ascent towards data commodification, but a strategic alignment with a firm's inherent industrial logic.

DC is neither good nor bad. It is an emerging economic paradigm and must be treated as such. If the national economy can prosper from utilising data as a 'new oil', the government and society might consider it. After all, it is not as if we are sitting on a vast pool of resources, as other nations do. Therefore, from a policy perspective, the implications are distinct. A 'one-size-fits-all' national data strategy is ill-advised; policies designed to foster data driven business models must be differentiated.

For the IT & Telecom sector, policy should prioritise scaling and export: assisting these Primary data capitalists in navigating cross-border data regulations and accessing global markets, given that their product (data or code) possesses global liquidity. Conversely, for the Manufacturing and Trade sectors, the focus should be on adoption and integration: providing incentives for sensor integration, digital twins, and analytics training to maximise efficiency as Tertiary users. Expecting a timber manufacturer to pivot to a data seller model is strategically misaligned; supporting them in utilising data to reduce waste is, however, economically vital.

The independence of data capitalism from firm size suggests that policymakers must not overlook SMEs. Given that smaller IT firms demonstrate a high propensity for Primary tier DC, innovation grants should be accessible to these players, who are often more agile in identifying niche data monetisation opportunities than larger incumbents constrained by legacy models.

Conclusions

1. The empirical analysis of Latvia's 101 most valuable enterprises reveals that Data Capitalism is not a uniform, economy-wide phenomenon, but a highly stratified landscape characterised by distinct sectoral clusters. While nearly half of the sample operates as Tertiary data capitalists, utilising data primarily for operational efficiency, Primary data capitalists remain a distinct minority.
2. The study provides strong support for the hypothesis that sectoral logic is the primary determinant of data capitalism maturity. The IT & Telecommunications sector exhibits a statistically overwhelming concentration of Primary data capitalists; firms in this sector are approximately 35 times more likely to be Primary data capitalists than firms in any other industry.
3. Firm size, measured by turnover, was found to be statistically independent of data capitalism tier. Neither the largest firms nor the smallest are statistically predisposed to achieve Primary status, and the strong association between the IT sector and Primary data capitalism persists even after controlling for firm size.
4. The findings suggest that the structural nature of a firm's core product (whether it is digital or physical) is a more significant driver of data commodification than financial resources or firms' size. Consequently, large traditional firms do not automatically possess superior data strategies compared to smaller technology-focused firms.
5. These results suggest that a 'one-size-fits-all' national data strategy is ill-advised. Policy interventions should be differentiated to support the specific needs of each sector: assisting IT firms with scaling and export capabilities to leverage their global products, whilst supporting Manufacturing and Financial sectors with digital integration tools to maximise efficiency as data users.

Limitations

While these findings offer a robust snapshot of the Latvian economy, they must be interpreted within the constraints of the methodology. The reliance on publicly available data, such as annual reports and websites, means the study captures only publicly disclosed strategic intent. It is possible that some firms, particularly within the competitive financial services sector, employ 'stealth' data monetisation strategies that remain undisclosed to avoid regulatory scrutiny or competitor imitation. Furthermore, as a cross-sectional study of the top 101 firms, this research captures the economic landscape at a single point in time (2023–2024). It does not capture the velocity of change.

Author's note on related work

An extended version of this research is published in scientific peer reviewed journal 'Economics Bulletin' (Mētra, 2026). The present paper should therefore be read as a conference-version contribution from the same research programme. The 'Economics Bulletin' article provides the extended journal treatment of the

sectoral concentration of Data Capitalism in Latvia, including broader hypothesis development and additional performance and mobility tests. The present conference paper retains a narrower focus on the implications of sectoral concentration and firm-size independence for differentiated economic-policy interpretation.

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IOT-BASED AUTONOMOUS MONITORING SYSTEM FOR REAL-TIME WASP DETECTION AT BEEHIVE ENTRANCES

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Abstract
Beekeeping is an established component of agriculture, contributing to both economic output and crop production via pollination services. However, it is increasingly challenged by climate variability, predators, diseases and other stressors. Among these, this study focuses on bee colony protection against predators such as wasps, which can cause substantial colony losses if attacks go undetected. This study develops an IoT-integrated, autonomous three-stage solution intended to detect wasp presence at the beehive entrance and support timely protection. In Stage 1, the Fast Background Subtraction with Adaptive Block Learning (FBS-ABL) model detects motion in downscaled frames extracted from hive-entrance video and produces cropped candidate region. Which will then be processed using a lightweight classifier, MobileOne in stage 2 to label each crop as bee, wasp and background. In this stage, a temporal decision rule then evaluates a short window of consecutive frames and issues an alert that Stage 3 only when multiple wasp occurrences are observed across the window. Finaly in stage 3, YOLO-World v2 performs full-frame detection to localize and confirm wasp presence within the selected window. The beekeeper is alerted only when the Stage 2 indication is corroborated by Stage 3 across multiple frames. This design reduces frequent, expensive calls to the detector and supports low-cost deployment with minimal computational resources, such as a NVIDIA Jetson Nano 4GB, a camera module, a 10 W power supply, and network access. The implemented pipeline achieves near real-time performance at approximately 15 FPS, providing an affordable and reliable near real time warning system against wasp threats at beehive.
Keywords: wasp threat, precision beekeeping, bee colonies, bee hives, autonomous surveillance.

Introduction

Beekeeping has long been practiced in Latvia, as in many other parts of the world, for both food production and medicinal purposes. In 2023, Latvia exported honey worth 1.65 million euros, exceeding the 0.95 million euros spent on imports, reflecting a positive trade balance (Ministry of Agriculture of the Republic of Latvia, 2024). Despite this, the sector demonstrated signs of decline between 2023 and 2024. During this period, honey production fell by 5.4%, the average market price decreased by 3.7%, and the number of bee colonies declined by 2.1% (Central Statistical Bureau of Latvia, 2025). Several factors may explain this downward trend. In 2024, an unusually warm spring caused flowers to bloom earlier and wither more quickly, reducing the period available for nectar collection (Latvian Public Media, 2024). In June, high heat forced bees to spend more energy gathering water to cool their hives, leaving them less time for foraging activity (Zemgale Regional Television, 2024). In addition, although the European Union is the 2nd largest honey producer, it satisfies only about 63% of its internal demand, creating pressure from lower-priced imports (European Commission, 2024). Since honey imported from major external suppliers was sold at a much lower unit value than Latvian honey, this likely intensified market competition and contributed to the decline in Latvia's honey price in 2024 (National Statistical System of Latvia, n.d.). While these external factors are difficult to control, improving internal practices with low-cost solutions could strengthen the resilience and long-term sustainability of the industry. As a member of the European Union, Latvia benefits from access to a large market and already meets quality standards comparing to the external exporters. Moreover, beekeeping plays an essential ecological role, as honeybees are responsible for approximately four-fifths of insect-driven pollination in Latvia, making the sector indispensable to both agriculture and ecosystem stability (Ministry of Agriculture of the Republic of Latvia, 2024).

According to Perichon et al. (2024), the threats affecting beekeeping across European Union countries can be classified into eight categories, one of which is predators, including wasps. This problem has also been observed in Latvia. In 2024, Jelgava Technology Secondary School reported that its bee colonies were frequently exposed to wasp attacks. When such threats are not detected in time, they can have severe effects on colony health and negatively influence honey production. These cases highlight the need for timely predator monitoring. Precision beekeeping offers a practical approach for such early threat detection. Moreover, precision beekeeping has already been introduced in Latvia, which makes further development and application more feasible (Zacepins et al., 2021).

At present, several studies have proposed solutions to address this specific threat, but each has certain limitations. MOG2+CNN and BeePIV were developed mainly for bee counting and estimation of flying direction rather than threat detection, and their performance is affected by shadows and strong dependence on parameter tuning (Kulyukin et al., 2021; Kulyukin & Mukherjee, 2019). This reduces their suitability for real-time threat detection inside hives on low-cost edge devices. DY-RetinaNet was introduced specifically for threat detection; however, it was not designed for low-resource environments, and the study did not provide enough detail to fully assess its computational requirements (Hu et al., 2022). The multimodal system is suitable for edge deployment, but it depends on a specific infrared depth camera and relies heavily on wasp flight paths for

detection (Nasir et al., 2023). While this may be effective for the current task, it limits the adaptability of the system for future extensions. In comparison, image-based features are generally more reliable and more likely to generalize new threats, leaving room for further improvement. The Mask R-CNN with Kalman filtering approach was intended mainly for detecting and tracking individual bees rather than identifying threats, making it computationally expensive and less appropriate for low-cost wasp detection (Kongsilp et al., 2024). YOLO-based approaches have also been used to detect multiple object classes, including wasps (Vdoviak et al., 2025). However, the recommended deployment of hardware, Jetson AGX Orin 64GB, is relatively expensive, which reduces the practicality of this approach for affordable and large-scale deployment.

By analyzing the existing beehive monitoring solutions, it can be observed that motion-based foreground–background separation and object classification or detection are the most commonly used components. However, not all approaches depend on motion-based separation, whereas object classification or detection are used more consistently across the studies. The review of these solutions also shows an extensive use of deep learning models. Although these methods have improved detection performance, they have also increased model complexity, which reduces their suitability for low-cost edge deployment. This is an important consideration for the present research where it aims to provide an affordable solution for autonomous real time detection of wasp threats at the beehive entrance. Another noticeable pattern can be seen in the earlier solutions, such as MOG2 + CNN and BeePIV, which were mainly used for bee counting and traffic direction analysis. These approaches show a link between simpler classifiers, foreground–background separation, and cost-effective deployment. By first separating the foreground from the background, the classifier only needs to process a smaller region of the image, which is sufficient because bees and wasps occupy only a limited part of the frame. Accordingly, this approach could be integrated to develop a viable solution for wasp detection that supports low-cost implementation by reducing computational demand. The proposed solution is therefore divided into three main stages:

1. Use Motion-based object detection techniques to select regions that represent movement between frames extracted from the live video.
2. With a low-cost classifier, search for any appearance of wasp.
3. Use detector on selected frames to localize the threat instead of using such expensive tasks on all frames.

Materials and Methods

a) Stage 1

Following the development of basic architecture, the aim of the first stage is to extract motion regions from consecutive frames in order to identify moving objects at the hive entrance, such as bees and wasps. For this purpose, three categories of methods are considered: traditional background subtraction, optical flow for motion cues, and learned foreground segmentation. To determine the most stable option for the proposed system, one state-of-the-art method from each category is analyzed in Table 1.

Table 1
Analysis of foreground background extraction methods for stage 1

Category	Method	Key Metric	Dataset used	Inference speed	Device	Deep Learning
Traditional background subtraction	FBS-ABL (Montero et al., 2021)	F1 0.6585	Cdnet-2014	277 FPS	I7 3.3 GHz, 16GB RAM	No
				21 FPS	ARM Cortex A9 2-core, 1GB RAM	
Optical flow for motion cues	FastFlowNet (Kong et al., 2021)	EPE 2.08	MPI Sintel clean test set	5.7 FPS	NVIDIA Jetson TX2	CNN
				90 FPS	NVIDIA 1080Ti	
Learned foreground segmentation	Fast BSUV-Net 2.0 (Tezcan et al., 2021)	F1 0.80	Cdnet-2014	29 FPS	NVIDIA Tesla P100 GPU	CNN

Among the evaluated methods, Fast BSUV-Net 2.0 demonstrates higher performance than FBS-ABL when comparing the F1 score. However, this improvement comes with significantly higher computational requirements. Fast BSUV-Net 2.0 achieves an inference speed of around 29 FPS but requires more powerful hardware to operate efficiently. In contrast, FBS-ABL achieves approximately 277 FPS on standard desktop hardware and about 21 FPS on an edge device, making it more suitable for resource-constrained environments. This difference results from the approaches used by the models. Fast BSUV-Net 2.0 belongs to the category of learned foreground segmentation methods, which rely on deep learning architectures to predict foreground masks from video frames. These models generally provide stronger robustness to illumination changes and background dynamics but require greater computational resources and the performance might change based on the training data. On the other hand,

FBS-ABL follows a traditional background subtraction approach, which models a static model and identifies pixels that differ from this model as foreground. While such methods may achieve lower accuracy, sensitive towards changes in environment compared with deep learning approaches, they are significantly more efficient in terms of computational cost and do not depend on the training dataset. Since the objective of this stage is to extract foreground regions while maintaining low computational demand for edge deployment, FBS-ABL represents the most suitable choice. Another method we considered, FastFlowNet, does not report an F1 score, making a direct comparison difficult. Nevertheless, because it is also based on deep learning, it requires higher computational resources similar to Fast BSUV-Net 2.0. For this reason, FBS-ABL is selected as the final method for this stage of the proposed solution.

After selecting FBS-ABL for Stage 1, the method is adapted to better match the requirements of motion extraction at the beehive entrance. Several modifications are introduced to improve its suitability for detecting small moving objects such as bees and wasps. First, the block size is reduced from 16 to 8 to increase sensitivity to small-object motion. Second, instead of linking the background update interval to the frame rate, a fixed update interval is used to provide more stable control over throughput and background adaptation. Third, the smoothing parameters are configured using a 3 × 3 kernel in the background subtraction stage and a 5 × 5 kernel in the foreground mask generation stage to reduce noise while preserving the boundaries of small moving objects. In addition, the hard threshold is lowered from 10% to 8% of the 8-bit grayscale range to improve sensitivity to weak motion.

To further improve detection quality, an optional shadow suppression step is added to reduce false positives caused by rapid lighting changes (Jacques et al., 2005). The resulting binary mask is then refined using a 3 × 3 median filter, morphological closing and opening with a 3 × 3 kernel, and blob filtering based on minimum and maximum area thresholds (St-Charles et al., 2015). After this refinement, candidate regions are extracted from the original frame for Stage 2 classification through a dynamic cropping mechanism. In this process, each detected blob is cropped using a bounding box expanded by 10% in all directions, padded to a square shape, and resized to the fixed input size to match the classifier.

b) Stage 2

Following Stage 1, Stage 2 aims to detect the presence of wasps within the regions represented by the extracted blobs using a classifier. As shown in Table 2, four state-of-the-art classification models designed for low-cost execution were compared for this purpose. Based on Table 2, latency alone cannot be considered a fair basis for comparison when the models are evaluated on different devices.

Table 2
Analysis of classification methods for stage 2

Model	Year	Accuracy	Dataset	Latency (ms)	FLOPs (G)	Parameters (M)	Device
RepViT-M1.0 (Wang et al., 2024)	2023	78.6	ImageNet-1K	1.0	1.1	6.8	iPhone 12
MNv4-Conv-M (Qin et al., 2024)	2024	79.9	ImageNet-1K	1.1	1.0	9.2	iPhone 13
GhostNetV3 (Liu et al., 2024a)	2024	77.1	ImageNet-1K	14.69	0.167	6.1	Huawei Mate 40 Pro
MobileOne-S1(Vasu et al., 2023)	2023	75.9	ImageNet-1K	0.89	0.825	4.8	iPhone 12

Differences in hardware and software configurations can significantly affect performance, and even newer versions from the same manufacturer may achieve lower latency due to hardware improvements. Therefore, directly comparing models tested on devices such as the iPhone 12, Huawei Mate 40 Pro, and iPhone 13 would not be reliable. To ensure a fairer evaluation, the comparison is limited to RepViT-M1.0 and MobileOne-S1, since both were tested on the iPhone 12. Based on the reported results, both models achieve latency below 1 ms and accuracy values of 78.6% and 75.9%, respectively, making them suitable for deployment in edge devices. Among them, MobileOne-S1 appears more suitable because it requires fewer FLOPs and has a smaller number of parameters than RepViT-M1.0. This indicates lower memory usage and reduces computational cost for the overall system, at the expense of only a small drop in accuracy of 2.7%. Given that the main objective of this stage is to classify objects using low computational power, this trade-off is acceptable. Moreover, even when evaluated on more advanced devices, MNv4-Conv-M and GhostNetV3 provide only a small accuracy improvement over MobileOne-S1 while introducing higher latency. Compared with MobileOne-S1, MNv4-Conv-M improves accuracy by 4.0%, while GhostNetV3 improves it by 1.2%. However, their latency increases from 0.89 ms to 1.1 ms and 14.69 ms, respectively despite the lower FLOPs recorded by GhostNetV3. In addition, both models have a higher parameter count than MobileOne-S1.

After selecting MobileOne-S1 for Stage 2, the model is adapted for three-class classification by replacing

the original ImageNet classification head with a new linear layer that outputs logits for bee, background, and wasp. The backbone structure is kept unchanged in order to preserve the model's efficiency for edge deployment. The model is then fine-tuned for 120 epochs using SGD with momentum 0.9 and an initial learning rate of 0.01, followed by cosine decay without restarts. To improve generalization, the fine-tuning process uses random resized cropping, horizontal flipping, random translation of up to 10% along both width and height, and Random Erasing with a probability of 0.25 over 2%–20% of the image area. Since wasp samples are less frequent than bee samples in nature at beehive entrance, class imbalance is addressed by combining cross-entropy with label smoothing of 0.1 and class-balanced weighting (Cui et al., 2019).

$$w_c = \frac{1-\beta}{1-\beta^{n_c}} \quad (1)$$

where β=*0.9998*, and the final loss is defined as,

$$\mathcal{L}_{CB}(z,y) = w_y \cdot \mathcal{L}_{CE}^{smooth}(z,y) \quad (2)$$

Model performance is monitored at the end of each epoch using both the standard and EMA-weighted versions, and fine-tuning is stopped when the validation loss does not improve for 10 consecutive epochs, with the checkpoint having the highest macro F1 score selected for testing and final deployment.

c) Stage 3

Following Stage 2, Stage 3 focuses on localizing wasps within the selected images that are likely to contain them. Given the limited availability of data, open-vocabulary detection models are considered for this stage, as they are trained on large-scale datasets compared to traditional CNN and Transformer models. It can support the detection of new object categories in the future without additional training. Therefore, such state-of-the-art models are analyzed for stage 3.

Based on analysis, DINO 1.5 Pro appears to be the most suitable model for this stage in terms of detection performance with mAP of 54.3 (Ren et al., 2024). However, its practical use is limited because the trained weights are not publicly available for download. The model's dependence on a commercial API makes offline deployment difficult and reduces its suitability for low-cost implementation. Among the models that are fully accessible, DINO Swin L achieves the closest performance to DINO 1.5 Pro with mAP of 52.5 (Liu et al., 2024b). It delivers the highest zero-shot accuracy among the models available for offline use and outperforms YOLO-World V2 X by approximately 5.4 mAP points (ultralytics, 2024). However, DINO Swin L is still a large transformer-based model, which may limit its applicability in edge devices. In contrast, YOLO-World V2 X is mainly based on the YOLO CNN architecture, which is generally more lightweight and computationally efficient. Therefore, although its detection accuracy is lower, it may provide a more practical balance between performance and deployment cost. Moreover, Vdoviak et al. (2025) show that YOLO-World V2 maintains low inference time and fast execution speed typical of YOLO-based models. This makes it a suitable candidate for the current task, with the added benefit of open-vocabulary detection. However, the results also suggest that the model would likely require fine-tuning to achieve better performance on a more specific target group, such as bees and wasps.

To adapt YOLO-World V2 for Stage 3, the model is adapted for wasp localization using prompt tuning in order to preserve its open-vocabulary capability for unseen classes. The backbone structure is kept unchanged, and the model is then fine-tuned for 30 epochs using Adam with momentum 0.9 and an initial learning rate of 0.01, followed by cosine decay without restarts. To improve generalization, the fine-tuning process uses horizontal and vertical translation of up to 10%, scaling of up to 0.5, and horizontal flipping. Unlike Vdoviak et al. (2025) multi-class setup, the current system focuses only on wasp detection. Therefore, only wasp instances are annotated during finetuning, while other objects such as bees, drones, and pollen-carrying bees are left unlabelled. In addition, negative images without wasps are included so that the model learns to better distinguish wasps from bees and background. Under this setup, the total loss function is defined as,

$$\text{TotalLoss} = \lambda_{box} BoxLoss + \lambda_{cls} ClsLoss + \lambda_{dfl} dflLoss \quad (3)$$

where $\lambda_{box} = 7.5$, $\lambda_{cls} = 0.5$, $\lambda_{dfl} = 1.5$.

Later while fine-tuning, Model performance is monitored at the end of each epoch using validation loss and AP50, and the checkpoint with the highest AP50 is selected for testing and final deployment.

d) Hardware

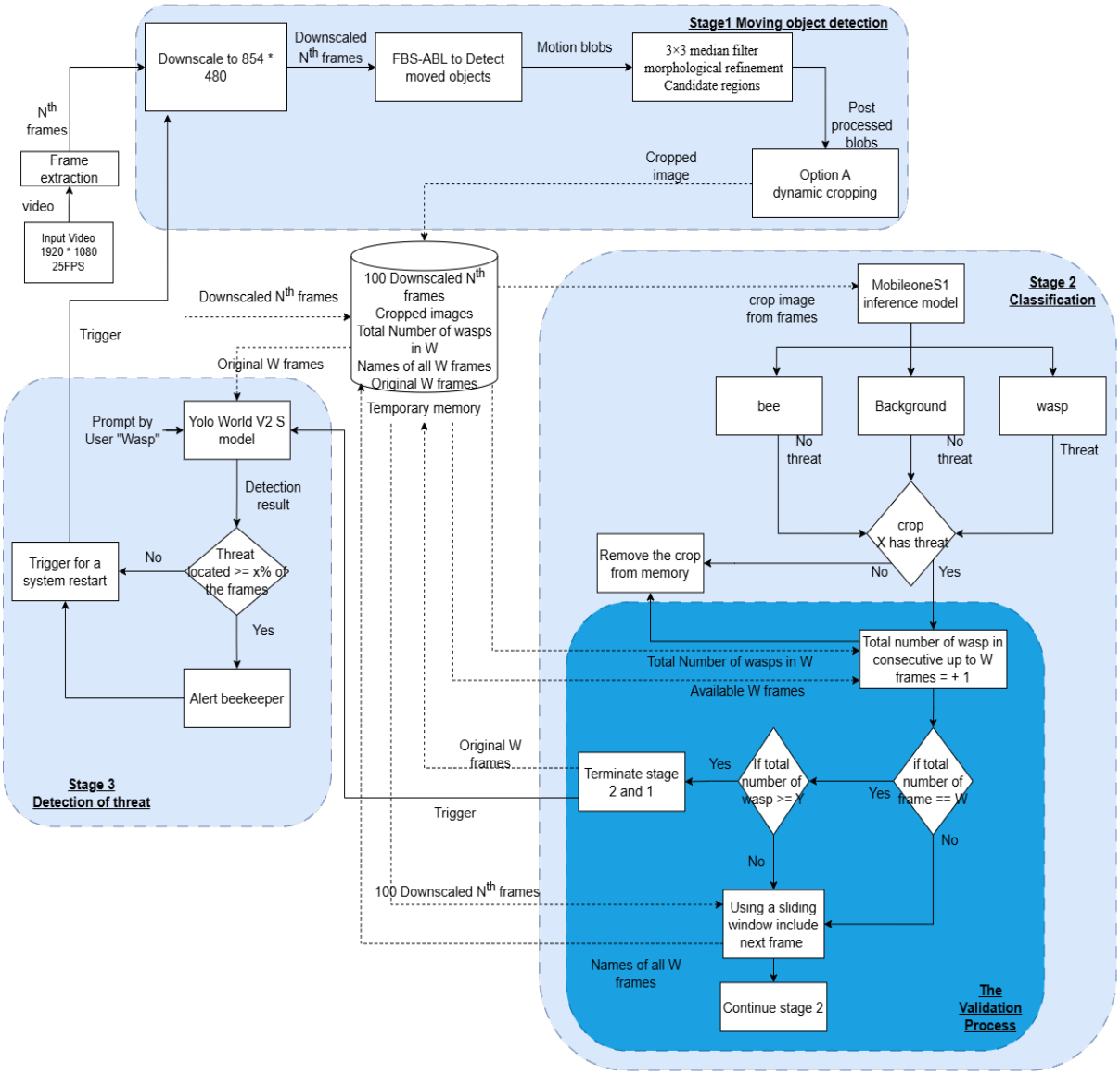
All model development, fine-tuning, and initial evaluation were carried out on a workstation with Windows 10, Visual Studio Code, an Intel Core i3-10100 CPU at 3.60 GHz, an NVIDIA GTX 1650 GPU, 24GB DDR4 RAM and Python as the implementation language. For edge deployment, the NVIDIA Jetson Nano was selected as the target device. It includes a quad-core ARM Cortex-A57 CPU, a 128-core Maxwell GPU, and 4 GB LPDDR4 shared memory. This device was chosen as edge device because it provides a low-cost platform for vision-based AI tasks while supporting both CPU-based and GPU-accelerated processing, which suits the proposed multi-stage pipeline.

e) Dataset

After customizing the models, the dataset was required to satisfy three main conditions. First, it had to contain images of both wasps and bees. Second, it had to be taken using different background settings to increase generalization. Finaly, it had to include consecutive frames with only a small time interval, since Stage 1 relied on FBS-ABL, whose performance is strongly

influenced by the temporal gap between frames. For this reason, Sledevič & Vdoviak (2025) were selected as the dataset for fine-tuning and testing. It was distributed under the CC BY 4.0 license and contained 11,008 images with YOLO-format annotations, including 116,853 worker bees, 14,062 pollen instances, 1,405 wasps, and 1,320 drones. However, since the dataset was not originally created for the specific task addressed in this study, it was manually filtered before use, as a considerable portion of the data contained larger time intervals between consecutive frames. As a result, a sub-dataset satisfying these requirements was generated and published at Manivannan (2026).

Figure 1
Architecture of the system (Kirishanth, 2026)



Results and Discussion

a) System architecture

Following the selection and customization of the models and the preparation of the dataset, the three stages are integrated into a one-tier architecture that can be executed on NVIDIA Jetson Nano. This enables the system to operate independently without relying on remote hardware for additional computational resources. The architecture consists of two main components: a low-power monitor and a high-power verifier. The low-power monitor, which includes Stages 1 and 2, operates continuously to detect possible wasp presence. When Stage 2 identifies a possible wasp, the high-power verifier is triggered to localize the threat within the image. To allocate sufficient computational resources for this process, the low-power monitor will be temporarily suspended while the high-power verifier performs localization. Furthermore, the complete architecture of the proposed system is presented in Figure 1 and is described as follows.

As illustrated in Figure 1, the input video is recorded at 1920×1080 pixels to preserve detailed visual

information at the hive entrance. Then every N^{th} frame is downscaled to 854×480 pixels for further processing in order to lower computational cost while preserving the original 16:9 aspect ratio. In Stage 1, FBS-ABL processes consecutive frames to identify motion regions at the hive entrance. After post-processing of these motion regions, candidate blobs are converted into cropped regions that are stored together with the corresponding recent frames in temporary memory. To limit memory usage, only the most recent 100 frames are stored. These cropped regions are then passed to Stage 2, where MobileOne-S1 classifies them as a bee, background, or a wasp.

Stage 2 acts as a lightweight verification layer before the more computationally expensive localization Stage 3 is activated. Analysis of the dataset showed that when a wasp appears, it is usually visible across multiple consecutive frames rather than in a single isolated frame. For this reason, the system does not rely on a single wasp prediction. Instead, when wasp predictions are detected, they are evaluated over a sliding window of 20 frames. If the total number of wasp predictions within the window reaches the threshold of 8, Stages 1 and 2 are suspended and Stage 3 is triggered. Otherwise, the window continues to advance until either the threshold is reached or no wasp predictions remain within the current 20-frame window. In that case, the validation process is cleared and returns to an idle state until the next wasp prediction is observed. This validation step helps reduce unnecessary activation of Stage 3 by requiring repeated evidence of wasp presence within a limited sequence of frames, thereby lowering the likelihood of false triggers. Moreover, since Stages 1 and 2 are temporarily suspended while Stage 3 is running, the system may, in rare cases, miss true wasp appearances during this interval. Then, to prevent unnecessary memory growth during this stage, the cropped regions are permanently removed from memory after classification, while only the running wasp count and the frame identifiers for the current window are retained. Once triggered, Stage 3 retrieves the corresponding full 20 frames from temporary memory and applies YOLO-World V2 S to localize wasps. If detections are confirmed in at least 60% of the selected frames, the system generates an alert for the beekeeper by uploading the images to the cloud and informing through email using RCLONE and MSMTP General Commands Manual. After that, the monitoring cycle is restarted and clears the temporary memory. This staged design reduces the amount of data processed by the most computationally demanding model, since only a small subset of frames reaches the final detection stage. As a result, the architecture supports efficient operation on low-cost Jetson Nano while maintaining the ability to detect and localize wasp threats in real time.

b) Results in Workstation

For Stage 1, the experiments focused on how the temporal gap between frames and the background update settings influence the performance of FBS-ABL. First, the number of frames used to initialize the background model was increased from 1 to 50 while keeping the background update interval fixed. This analysis was performed on two collections with different temporal gaps between consecutive frames in order to observe how frame interval influences motion extraction. The results showed that shorter frame intervals produced more stable behavior and higher precision, whereas larger frame intervals resulted in slightly higher recall but lower precision and greater fluctuation due to the increased temporal variation between consecutive background frames. In the low-interval collection, precision became largely stable after around 27 frames, while recall decrease as additional frames were included to initialize the background model. Therefore, 27 frames were selected for background model initialization, as this provided a suitable balance between the precision and recall. And since lower precision would increase the number of background crops passed to Stage 2, low-interval frame data were considered more suitable for the proposed system. In the second experiment, the interval for updating the background model was increased while the initial background model size was fixed at 27 frames. The results showed that a longer update interval caused only a small reduction in precision, while recall remained almost unchanged. However, a shorter update interval required more computational power due to more frequent background model updates. Therefore, an update interval of 30 frames was selected as a balance between real-time processing speed and accuracy.

For Stage 2, MobileOne-S1 was fine-tuned using 2,481 bee crops, 693 background crops, and 848 wasp crops represents the outputs of stage 1. The dataset was divided into fine-tuning and validation sets using an 80:20 ratio, while Collections 3 and 19 were reserved for testing in order to better reflect deployment conditions. During fine-tuning, both the standard and EMA-weighted models showed stable learning behavior, with the validation macro F1 score improving rapidly in the early epochs and then gradually stabilizing. A temporary drop in performance was observed around epoch 40, which aligned with the progressive learning step that increased the input resolution from 32 × 32 pixels to 48 × 48 pixels. Although this transition briefly affected performance, the model recovered and continued to improve. Since the EMA-weighted model showed more stable behavior toward the later epochs, the checkpoint with the best EMA macro F1 score was selected as the final Stage 2 model. On the test set, the selected model achieved a loss of 0.24 and a macro F1 score of 0.8941. The per-class F1 scores were 0.9422 for background, 0.9692 for bee, and 0.7708 for wasp.

The lower wasp score can be attributed partly to the smaller number of wasp samples available during fine-tuning, which restricts the diversity of features the model can learn for that class. Furthermore, wasps

share several visual similarities with bees, which may have increased the difficulty of reliable separation. Although the test macro F1 score of 0.8941 was lower than the best validation macro F1 score of approximately 0.95, the gap remained moderate and suggested only limited overfitting, which could likely be reduced by adding more diverse wasp data. In particular, the fine-tuning and validation losses decreased together and remained close, indicating stable convergence without clear signs of strong overfitting or underfitting, although the lower test performance on the wasp class suggested limited difficulty in generalization to unseen data.

For Stage 3, YOLO-World V2 S was fine-tuned for single-class wasp detection using 639 annotated frames containing wasps and 135 negative frames without wasps. The negative frames were included to improve separation between wasps, bees, and background under the single-class detection setup. The dataset was divided into fine-tuning and validation sets using 80:20 ratio, while Collections 3 and 19 were reserved for testing in order to better reflect deployment conditions.

During fine-tuning, the model showed rapid early improvement, with mAP50 increasing sharply in the first few epochs as the model learned the most obvious visual patterns of the target class. The curve then gradually stabilized, indicating that the model had learned most of the useful features available in the fine-tuning data. Minor fluctuations between epochs were likely caused by data augmentation and the relatively small dataset size. Similar to Stage 2, the fine-tuning and validation losses decreased together and remained close, indicating stable convergence without clear signs of strong overfitting or underfitting. However, unlike Stage 2, the validation and test performances in Stage 3 remained highly consistent. On the validation set, the model reached an mAP50 of 0.956, and the precision–recall curve remained close to the upper boundary across most confidence thresholds, indicating high precision over a wide range of recall values. On the test set of 193 images, the model achieved an mAP50 of 0.9566.

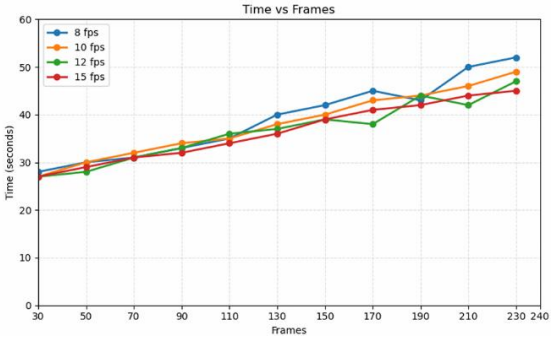
c) Results in NVIDIA Jetson Nano

After the individual stages were evaluated on the workstation, the complete pipeline was deployed on the NVIDIA Jetson Nano to assess its suitability for low-cost edge execution. On Jetson Nano, Stage 1 achieved 21.767 FPS, compared with 84.187 FPS on the workstation. Although this reduction was expected because of the Jetson Nano's lower processing capability and limited power budget of maximum 15W, the measured speed remained sufficient for the intended low-interval input setting. For Stage 2, the re-parameterized MobileOne-S1 deploy model achieved 108.5 FPS in FP32, while conversion to a TensorRT FP16 module increased the speed to 168.84 FPS with essentially unchanged accuracy and macro F1 score. For this reason, the FP16 version was selected for deployment. In Stage 3, YOLO-World V2 S was exported to ONNX on the workstation and compiled into a TensorRT engine on the Jetson Nano to avoid software compatibility issues in the device runtime environment. The YOLO-World V2 S detector achieved 4.07 FPS on the Jetson Nano, compared with 52.84 FPS on the workstation. Although this stage was substantially slower, it was considered acceptable because Stage 3 is activated only when Stage 2 indicates possible wasp presence, and during its execution the state 1 and 2 are suspended so that the detector can use the full device resources.

The fully integrated system was then evaluated using input streams configured to mimic a 10 FPS deployment setting. The results showed a fixed one-time startup delay of approximately 27s. This delay was mainly caused by initialization overhead on the Jetson Nano, including the 27 frames required by Stage 1 to initialize the background model and the one-time JIT compilation cost introduced by the Numba-accelerated functions. Although a warm-up phase was introduced in Stage 2 to reduce GPU startup overhead, the initial delay could not be removed entirely since Stage 2 depends on the outputs of Stage 1. After initialization, the total runtime increased approximately linearly with the number of frames across tested input rates between 8 and 15 FPS as in Figure 2, indicating stable and predictable per-frame processing cost. This behavior suggests that the deployed system can support near live surveillance within the tested range, despite the constant initialization delay.

Figure 2

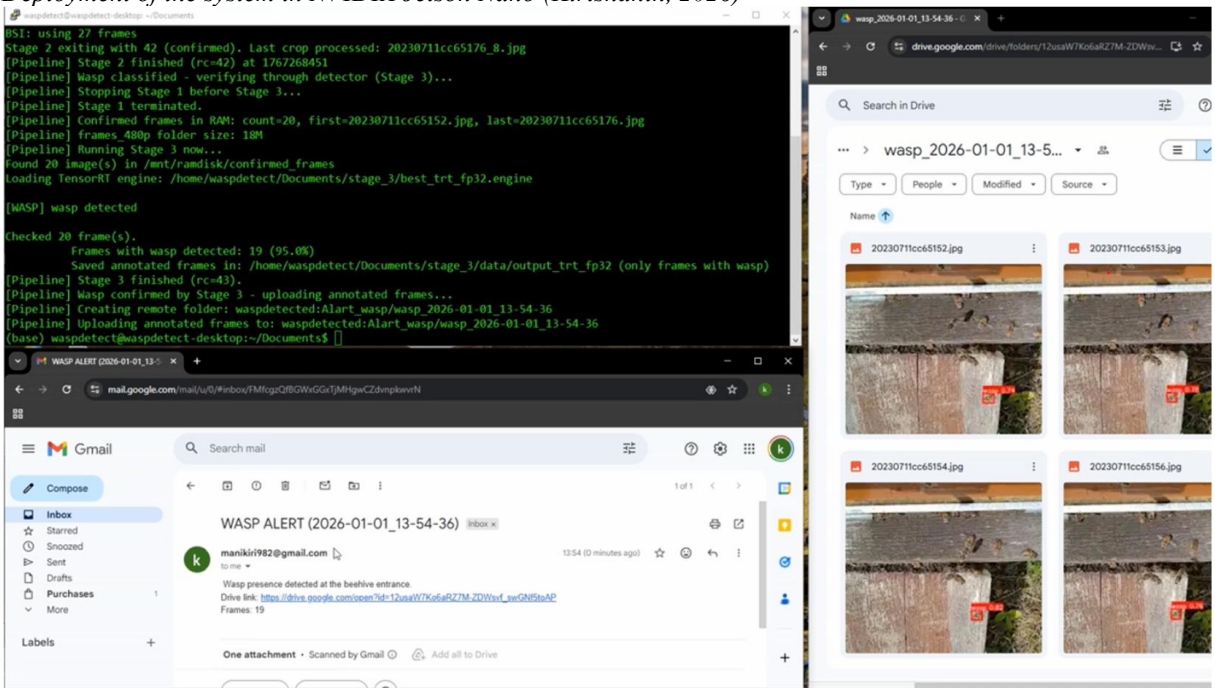
Runtime in Jetson Nano at Deployment for 8,10,12 and 15 FPS input frame rate (Kirishanth, 2026)



Following the successful evaluation of the system, Figure 3 presents an example of the final alert output. In this case, after the trigger condition was satisfied in Stage 2, Stage 3 was activated and confirmed wasp presence in 19 of the 20 selected frames, which exceeded the 60% decision threshold. The system then produced the final alert by uploading them to cloud storage, and sending an email notification to the beekeeper, which demonstrates the successful end-to-end operation of the deployed system on the Jetson Nano.

Figure 3

Deployment of the system in NVIDIA Jetson Nano (Kirishanth, 2026)



Conclusions

1. The wasp detection problem was successfully divided into three stages: motion-based candidate extraction, lightweight classification, and final verification with localization, allowing the system to function with limited computational resources.
2. FBS-ABL, MobileOne-S1, and YOLO-World V2-S were identified as the most suitable models for Stages 1, 2, and 3, based on the requirements of each stage.
3. The proposed one-tier, three-stage architecture enabled continuous low-cost monitoring through Stages 1 and 2, while Stage 3 was activated only after preliminary verification to reduce unnecessary computational load and false alarms.
4. The complete system was successfully deployed on the Jetson Nano and achieved near real-time wasp surveillance, with an initialization delay of approximately 27s across input rates of 8, 10, 12, and 15 FPS.
5. Future improvements should focus on reducing the initialization delay, expanding the dataset with more diverse wasp samples, evaluating the system under a wider range of real-world operating conditions and similar problems.

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ARTIFICIAL INTELLIGENCE AND THE WORK ENVIRONMENT: CHALLENGES AND SOLUTIONS FOR HUMAN CAPITAL DEVELOPMENT

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Abstract
Artificial intelligence (AI) is increasingly embedded in organizational processes, reshaping work structures, task composition, and competence requirements. While existing literature has extensively examined AI's macro-level labour market implications, less attention has been devoted to the organizational mechanisms through which AI influences human capital development in territorially differentiated contexts, particularly in smaller economies and rural and lower-density environments. Specifically, limited research has examined how AI-driven human capital transformation unfolds in small and territorially differentiated economies, where digital infrastructure and institutional support systems vary significantly. This exploratory study examines how AI integration is perceived to affect work processes and skill demands among employees in Latvian organizations and outlines structural conditions that may enable or constrain sustainable human capital transformation in territorially differentiated, rural, and lower-density contexts. The research combines theoretical analysis with empirical survey data collected from 61 employees across Latvian organizations. Within the surveyed sample, responses tend to associate AI adoption primarily with task restructuring and rising competence requirements rather than with direct workforce reduction. The observed response patterns are consistent with the view that human capital development outcomes may depend on organizational capability structures, training institutionalization, and change management practices. The results are interpreted within a territorially differentiated analytical framework, proposed conceptually rather than tested empirically, which raises the question whether in rural and lower-density contexts AI integration may remain primarily efficiency-oriented unless supported by systemic learning mechanisms. The study contributes to the understanding of AI as a capability-dependent transformation process and highlights the necessity of embedding territorial and regional development perspectives within analyses of AI-driven workforce transformation.
Keywords: artificial intelligence, human capital, territorial differentiation, rural and regional development, organizational transformation.

Introduction

Artificial intelligence (AI) has evolved from a specialized technological application into a broader transformation force within contemporary organizations (Brynjolfsson & McAfee, 2014; Agrawal et al., 2019). Unlike earlier digital technologies that primarily enhanced information processing efficiency, AI systems increasingly perform cognitive, predictive, and decision-support functions (Davenport & Ronanki, 2018). As a result, AI integration alters not only productivity levels but also the qualitative structure of work, redistributing tasks between human and algorithmic agents. Artificial intelligence can be conceptualized as a general-purpose technology (GPT), characterized by broad applicability, continuous improvement, and complementarities with organizational and institutional structures. General-purpose technologies generate systemic transformation effects that extend beyond direct productivity gains, reshaping complementary assets, skill structures, and innovation trajectories (Bresnahan & Trajtenberg, 1995). Recent macroeconomic research further suggests that the productivity effects of such technologies may follow a delayed 'J-curve' pattern, as organizational restructuring and intangible investments are required before performance gains materialize (Brynjolfsson et al., 2021). In this sense, AI-driven transformation cannot be reduced to automation effects alone; it represents a structural reconfiguration of production and coordination systems.

The academic debate has largely focused on automation risks and macroeconomic labor displacement (Autor, 2015; Acemoglu & Restrepo, 2019). However, the transformation of human capital at the organizational level remains less systematically examined, particularly in smaller and regionally differentiated economies. The assumption that AI adoption produces homogeneous effects across contexts neglects the structural role of organizational capacity, institutional environment, and territorial characteristics. From a digital transformation perspective, technological adoption constitutes a multi-layered organizational change process affecting strategy, structure, routines, and value creation mechanisms (Vial, 2019). AI integration therefore interacts with existing organizational capabilities and institutional contexts, producing heterogeneous outcomes across firms and regions.

From a human capital theory perspective (Becker, 1964), skills constitute a productive asset whose value depends on alignment with technological and organizational demands. Under AI-driven transformation, human capital cannot be understood as a static stock of qualifications. Instead, it represents a dynamic capability requiring continuous adaptation, reskilling, and learning integration.

This issue is particularly salient in territorially differentiated environments, where infrastructural density, access to digital expertise, and institutional support systems may vary, potentially producing uneven AI adoption trajectories across regions, including rural and lower-density contexts (Rodríguez-Pose, 2013). For this reason, the present study situates AI-related human capital transformation within a rural and regional development perspective. The aim of this

study is to explore how artificial intelligence integration is perceived to affect work processes and competence requirements in Latvian organizations and to identify organizational mechanisms that may enable sustainable human capital development under conditions of technological change.

The research question is:

What challenges do employees report when using artificial intelligence in their daily work, and which organizational mechanisms are perceived to facilitate sustainable human capital development in territorially differentiated contexts?

The survey instrument did not include regional identifiers; direct rural-urban comparison is therefore outside the scope of this exploratory stage. Accordingly, the territorial dimension is used here as an interpretive framework for situating the findings within broader rural and lower-density development contexts.

By situating AI within an organizational and regional development framework, the study contributes to a more context-sensitive understanding of technology-driven workforce transformation. Given the relatively limited organization-level empirical evidence on AI-driven human capital transformation in small and territorially differentiated economies, this study adopts an exploratory research design. The objective is to identify tentative patterns and generate hypotheses for subsequent confirmatory research, interpreted within a capability-based framework attentive to territorially differentiated and rural and lower-density contexts.

AI-Driven Organizational Transformation and Human Capital Reconfiguration

Artificial intelligence (AI) represents not merely a technological advancement but a structural transformation of organizational systems. Unlike earlier waves of digitalization that primarily enhanced information processing efficiency, AI increasingly performs predictive, analytical, and decision-support functions traditionally associated with human cognitive labor (Brynjolfsson & McAfee, 2014; Davenport & Ronanki, 2018). As a result, AI integration reshapes not only productivity levels but the qualitative architecture of work itself, redistributing tasks between human and algorithmic agents and altering competence requirements across organizational levels.

From a labor economics perspective, task-based models of technological change suggest that technologies affect discrete task components rather than eliminating occupations in their entirety (Autor, 2015; Acemoglu & Restrepo, 2019). AI systems particularly automate routine, codifiable, and data-intensive activities, thereby increasing the relative importance of non-routine analytical, interpretative, and integrative tasks (Agrawal et al., 2019). This redistribution aligns with augmentation-oriented interpretations, which emphasize that AI creates organizational value when complementing human judgment rather than substituting it (Brynjolfsson, 2022). In this context, the central issue is not job replacement but task reconfiguration and competence intensification. Recent management research conceptualizes this dynamic as the automation-augmentation paradox, whereby AI simultaneously substitutes specific tasks while amplifying the strategic importance of human judgment and integrative capabilities (Raisch & Krakowski, 2021). Rather than a binary automation outcome, organizations experience hybrid configurations in which algorithmic systems execute analytical components while humans retain interpretative, ethical, and contextual decision authority.

However, AI-driven transformation extends beyond task restructuring. Empirical research indicates that algorithmic systems embedded in workflow coordination and performance monitoring may alter autonomy structures and decision-making authority within organizations (Kellogg et al., 2020). While AI can enhance decision accuracy and efficiency, excessive reliance on algorithmic outputs may reduce discretionary space and reshape professional identity. The expansion of algorithmic management further illustrates this transformation. Empirical studies indicate that data-driven coordination systems alter control mechanisms, transparency, and performance evaluation structures within organizations (Lee et al., 2015). Algorithmic monitoring can increase efficiency and standardization, yet it may also intensify perceived surveillance and reduce discretionary autonomy (Newlands, 2021). These governance shifts influence not only productivity but also employee motivation and organizational trust. Studies further associate AI integration with increased performance expectations and technostress, particularly when reskilling mechanisms are insufficient (Tarafdar et al., 2007; Ayyagari et al., 2011). These findings suggest that AI adoption introduces both productivity gains and psychological pressures, making organizational mediation mechanisms critical.

The socio-technical systems perspective provides a conceptual lens for understanding this mediation. Technological effectiveness depends on alignment between technical infrastructure and social organization (Trist & Bamforth, 1951; Cherns, 1976). AI implementation therefore requires coordinated adjustments in work design, governance structures, and learning systems. Where technological deployment outpaces organizational adaptation, misalignment may generate skill mismatches, uncertainty, and resistance. Conversely, transparent governance frameworks and institutionalized training support can convert AI adoption into a catalyst for sustainable capability development. Human-AI collaboration literature further suggests that effective integration depends on designing complementary interaction architectures rather than pursuing maximal automation. Jarrahi (2018) argues that AI systems enhance decision-making quality when embedded within socio-technical arrangements that preserve

human interpretative authority. Accordingly, governance frameworks that clarify accountability, transparency, and learning feedback loops are critical for sustainable organizational adaptation.

These dynamics fundamentally challenge classical interpretations of human capital. Traditionally conceptualized as a relatively stable accumulation of knowledge and skills generating economic returns (Becker, 1964), human capital under AI-driven transformation becomes temporally compressed and continuously reconfigured. As routine cognitive functions are increasingly automated, the relative value of creativity, contextual reasoning, critical thinking, and cross-functional coordination intensifies (Autor, 2015; Brynjolfsson, 2022). Human capital thus shifts from a static stock of qualifications toward a dynamic organizational capability.

From a capability-based perspective (Teece, 1997), sustainable adaptation to AI integration depends on an organization's capacity to sense technological shifts, seize opportunities through structured competence development, and transform internal processes accordingly. Human capital development under AI is therefore not an automatic consequence of technological adoption; it emerges through deliberate institutionalization of learning architectures, knowledge transfer mechanisms, and change management practices. Knowledge transfer literature emphasizes that absorptive capacity conditions the effectiveness of technological integration (Cohen & Levinthal, 1990). Empirical and conceptual research in the Latvian context similarly identifies structural knowledge transfer gaps as barriers to organizational capability upgrading, particularly in regionally embedded enterprises (Ozoliņa-Ugore et al., 2025). In AI-intensive environments, such constraints may slow adaptation and intensify divergence between digitally mature and lagging organizations.

Importantly, AI-driven organizational transformation unfolds within territorially differentiated environments. Technological adoption capacity is mediated by infrastructural density, institutional support systems, and access to specialized knowledge networks. Regional development research indicates that innovation and digital maturity levels are unevenly distributed across spatial contexts (OECD, 2019). In Latvia, national strategic documents emphasize artificial intelligence adoption and digital competence upgrading as critical pillars of long-term competitiveness (Ministry of Environmental Protection and Regional Development, 2020). However, the translation of strategic priorities into organizational capability development depends on firm-level absorptive capacity and regional institutional ecosystems, suggesting potential implementation asymmetries across territories. Nevertheless, European Commission DESI reports indicate persistent disparities in digital maturity across regions (European Commission, 2023). Such structural asymmetries are particularly salient in rural and lower-density contexts, where enterprises may face constraints in accessing advanced digital expertise and continuous professional development ecosystems.

Empirical evidence from the Latvian FinTech sector indicates that AI-based tools influence not only operational efficiency but also trust formation and behavioural adaptation among users (Meldere & Andersone, 2025). These findings align with international research emphasizing that AI transformation extends beyond internal productivity effects toward broader relational and institutional dimensions (Pentjuša & Gaile-Sarkane, 2025). These findings are consistent with broader organizational behaviour research demonstrating that autonomy enhances intrinsic motivation and engagement under technologically mediated work conditions (Hackman & Oldham, 1976; Pentjuša & Gaile-Sarkane, 2025). In AI-supported environments, autonomy may function as a buffering mechanism against potential perceptions of algorithmic control. These findings are consistent with the argument that AI transformation is relational and systemic rather than purely technical.

Taken together, AI-driven organizational transformation operates across multiple interrelated levels. At the micro level, AI restructures task composition and intensifies competence requirements. At the organizational level, outcomes depend on governance alignment, structured learning systems, and knowledge transfer capacity. At the territorial level, infrastructural and institutional conditions mediate the depth and trajectory of capability reconfiguration. Human capital development under AI should therefore be understood as a dynamic, territorially embedded process emerging from the interaction between technological systems, organizational adaptation mechanisms, and spatial development conditions.

Ontological aspects of human capital in the context of AI

The expansion of artificial intelligence challenges classical ontologies of human capital by destabilizing the assumption that formal education and accumulated qualifications constitute relatively stable productivity assets (Becker, 1964).

In AI-integrated work environments, human capital increasingly encompasses adaptive learning capacity, digital literacy, critical interpretation of algorithmic outputs, and cross-functional coordination skills. As routine cognitive activities become automated, the relative value of non-codifiable competencies, such as creativity, contextual reasoning, and social intelligence, intensifies (Autor, 2015; Brynjolfsson, 2022). This shift aligns with skill-biased technological change theory, which predicts rising demand for higher-order cognitive capabilities alongside declining reliance on routine functions.

Importantly, the transformation of human capital is not solely cognitive but also organizational and psychological. Empirical research links AI integration to heightened performance expectations, technostress,

and perceived job insecurity, particularly when reskilling support is insufficient (Tarafdar et al., 2007; Ayyagari et al., 2011). Technostress research provides additional explanatory depth to this phenomenon. Empirical studies identify techno-overload, techno-invasion, and techno-complexity as structural stressors associated with advanced information systems (Tarafdar et al., 2007). Subsequent research suggests that rapid technological change may increase role ambiguity and cognitive strain, particularly when organizational support mechanisms are weak (Ayyagari et al., 2011). Within AI-intensive environments, these stressors may be amplified by perceived algorithmic opacity and performance monitoring intensity.

These findings suggest that human capital development cannot be reduced to skill acquisition alone; it must include structured change management processes that support sense-making and participation (Lewin, 1947; Kotter, 1996).

Beyond structural adaptation, the ontological status of human capital itself undergoes transformation. In AI-integrated environments, employees are no longer valued primarily for the possession of stable, task-specific qualifications, but for their capacity to interpret, contextualize, and critically engage with algorithmic systems. This shift represents an epistemic reorientation in which knowledge is increasingly co-produced through human-machine interaction rather than individually accumulated. Professional identity consequently evolves from task executor to system interpreter and adaptive coordinator. Human capital thus becomes relational and processual, constituted through continuous interaction with technological infrastructures rather than defined solely by pre-existing competencies. This reconceptualization aligns with organizational learning theory, which views knowledge as socially constructed and continuously reconfigured through interaction (Argyris & Schön, 1978). In technologically dynamic contexts, double-loop learning mechanisms become particularly important, enabling organizations not only to refine routines but to question underlying assumptions regarding task allocation and decision authority. The knowledge-based view of the firm further supports this interpretation, emphasizing that competitive advantage derives from the integration and transformation of distributed knowledge assets (Nonaka & Takeuchi, 1995). Under AI integration, human capital thus becomes embedded within collective learning processes rather than residing solely at the individual level.

Accordingly, human capital in AI-driven environments should be conceptualized as a dynamic, relational capability rather than a static accumulation of qualifications. Organizations that institutionalize continuous learning, transparent technological governance, and participatory adaptation mechanisms appear better positioned to transform AI integration into sustainable workforce development rather than episodic efficiency gains.

Knowledge transfer limitations further illustrate that human capital is not merely accumulated but socially mediated. Gaps between knowledge creation and effective organizational absorption can constrain adaptive capacity, particularly in technologically dynamic environments (Ozoliņa-Ugore et al., 2025). In AI-integrated contexts, insufficient absorptive structures may delay identity transformation and competence consolidation.

Building on the preceding discussion, the empirical component focuses on three interrelated dimensions identified in the literature: the perceived intensity of AI integration in daily work, the reconfiguration of task composition and competence demands, and the organizational mechanisms that mediate human capital outcomes. These dimensions frame both the questionnaire design and the structure of the analysis presented below. They are also relevant to rural and regional development debates, since the capacity to support skill adaptation may vary across territorially differentiated and rural and lower-density contexts.

Materials and Methods

The study is designed as an exploratory empirical investigation aimed at examining how artificial intelligence integration reshapes work processes and competence requirements within Latvian organizations. Given the relatively limited organization-level evidence on AI-driven human capital transformation in small and regionally differentiated economies, the research does not seek to test predefined causal hypotheses. Rather, it aims to identify structural patterns in employees' experiences and interpret these patterns through the theoretical lens of task reconfiguration and capability adaptation.

Empirical data were collected through an anonymous online questionnaire distributed via professional networks and organizational contacts across Latvia. Participation was voluntary. The final dataset consists of 61 respondents employed in organizations of varying size and sectoral orientation. The sample is sectorally diverse. The largest proportion of respondents represented the IT and technology sector (24.6%), followed by education (18.0%), finance and insurance (9.8%), public services (8.2%), with remaining sectors represented in smaller proportions.

In terms of demographic structure, 83.6% of respondents were female and 14.8% male. The dominant age group was 35-44 years (47.5%), followed by 45-54 years (32.8%), indicating that the sample primarily reflects mid-career professionals with substantial organizational experience. Although the sampling approach was non-probabilistic and based on accessibility, it enabled access to employees actively engaged in digitally supported work environments. Given the exploratory design of the study and its focus on identifying structural tendencies rather than statistically generalizable causal relationships, the sample size of 61 respondents is

methodologically aligned with the research objective. In this sense, the sample is analytically appropriate for examining AI-related workplace dynamics, even if it does not allow for statistical generalization to the entire Latvian labor market.

The questionnaire was constructed to capture three interconnected dimensions of AI integration: (1) the presence and intensity of AI usage in daily work; (2) perceived changes in task structure and work efficiency; and (3) shifts in competence requirements and organizational support mechanisms. AI impact was assessed using a ten-point evaluation scale, allowing respondents to indicate perceived intensity of influence on their daily tasks. Additional items examined whether AI use was associated with increased efficiency, altered decision-making processes, new skill acquisition demands, or reduced reliance on manual procedures. Open-ended questions invited respondents to describe organizational challenges and to propose measures that could facilitate more effective AI integration.

The analytical strategy combined descriptive statistical analysis with structured interpretation of thematic tendencies emerging from open-ended responses. Given the exploratory nature of the study and the moderate sample size, emphasis was placed on identifying distributional patterns, variance tendencies, and recurring interpretative themes rather than on inferential statistical modeling. The analysis therefore seeks to illuminate mechanisms of perceived task restructuring and competence intensification rather than to establish statistically predictive relationships. Given the exploratory design and the moderate sample size, inferential statistical modelling was not pursued. Instead, the analysis focuses on frequency distributions, response dispersion, and thematic patterns from open-ended answers. This choice aligns with the study's aim of generating hypotheses for subsequent confirmatory research rather than testing causal relationships. Accordingly, the reported findings should be read as indicative tendencies within the sample, not as generalizable estimates.

The survey did not include regional identifiers or formal rural-urban stratification variables. This is an explicit scope decision: the present study serves as a conceptual and exploratory first stage, designed to identify patterns relevant to broader rural and regional development debates, while spatially stratified empirical testing is reserved for a follow-up study. However, respondents were recruited through professional and organizational networks spanning multiple Latvian sectors. Territorial differentiation was not empirically measured through regional identifiers in the survey instrument. Consequently, territorial effects are interpreted analytically rather than statistically tested. Future research should explicitly include regional identifiers to enable empirical comparison of spatially differentiated AI integration patterns. Latvia's regional structure, characterized by uneven infrastructural density and digital maturity levels, provides a contextual framework within which heterogeneity in AI integration depth can be understood. The study thus incorporates territorial considerations analytically rather than through formal comparative segmentation.

Several limitations should be acknowledged. The sample size restricts representativeness, and the convenience-based recruitment strategy may favor respondents already exposed to digital technologies. The gender distribution of the sample is skewed toward female respondents (83.6%), which may reflect sectoral composition and should be considered when interpreting generalizability. Furthermore, the reliance on self-reported perceptions captures subjective evaluations rather than objective productivity indicators or independently measured skill acquisition outcomes. The empirical findings should therefore be interpreted as indicative patterns within a digitally engaged segment of Latvian employees rather than as generalizable estimates for the national workforce. Social desirability effects and self-selection into the survey may further shape reported perceptions of AI. Nevertheless, the study offers analytically relevant insight into organizational AI integration patterns in a small and regionally differentiated economy, contributing exploratory evidence to an area where systematic empirical research remains limited.

Results and Discussion

Within the surveyed sample, artificial intelligence appears to be embedded in daily work practices: 82.0% of respondents reported AI use in their workplace; 16.4% indicated no use, and 1.6% reported uncertainty. However, the data simultaneously indicate heterogeneity in perception and integration depth. A small proportion of respondents indicated uncertainty regarding whether AI is used in their workplace, suggesting that algorithmic systems are often embedded in digital tools without being explicitly recognized as 'artificial intelligence'. This finding reflects the normalization of AI functionalities within routine organizational infrastructures.

In total, 55.7% of respondents rated the impact as high on the 7-10 range, whereas 18.0% rated it as low on the 1-3 range, indicating substantial variation in integration intensity across organizations. Rather than demonstrating uniform transformation, the results suggest the existence of differentiated integration profiles. In some organizations, AI constitutes a structurally transformative element of work architecture; in others, its influence remains limited or functionally supportive. This pattern aligns with task-based theories of technological change, which emphasize that technologies restructure task composition incrementally rather than producing homogeneous or immediate occupational disruption (Autor, 2015; Acemoglu & Restrepo, 2019).

In line with this, 82.0% agreed that AI can improve employee efficiency, while 14.8% were unsure and

3.3% perceived a rather negative effect. This dual effect, combining efficiency enhancement with skill intensification, supports augmentation-oriented interpretations of AI adoption (Brynjolfsson, 2022). Within the sample, responses tend to portray AI as a complement to human labour rather than as a direct substitute. This tendency is consistent with augmentation-oriented interpretations in the literature, although confirmation would require broader, sectorally stratified, and spatially differentiated evidence. The relatively limited emphasis on workforce reduction or decreased human resource necessity is also consistent with this interpretation.

At the same time, the reported necessity to acquire new skills highlights the dynamic reconfiguration of human capital under AI integration. Employees experience rising expectations regarding digital literacy, analytical capability, and adaptive competence. These findings are consistent with skill-biased technological change perspectives, which predict increased demand for higher-order cognitive capabilities in technologically intensive environments (Autor, 2015). The responses are consistent with the proposition that human capital transformation is structurally embedded within AI adoption processes, although the exploratory design does not allow this claim to be tested causally.

Interestingly, negative responses related to decreased motivation or deteriorating work experience were marginal. While international research frequently emphasizes technostress and psychological strain associated with algorithmic monitoring (Tarafdar et al., 2007; Ayyagari et al., 2011), the present sample predominantly associates AI with functional improvements rather than emotional decline. This does not negate the existence of technostress but suggests that in the examined organizations, AI is currently perceived more as a productivity-enhancing tool than as a surveillance mechanism. It may also indicate that AI integration in this context has not yet reached levels of algorithmic control intensity observed in other sectors internationally.

Open-ended responses provide further insight into mediating organizational mechanisms. The most frequently mentioned support measures include: (1) clearer principles for AI usage, (2) practical and accessible training opportunities, and (3) transparent internal communication regarding implementation objectives. These responses reveal that the primary challenge is not technological complexity per se, but organizational alignment. This finding strongly resonates with socio-technical systems theory, which emphasizes that technological effectiveness depends on alignment between technical systems and social structures (Trist & Bamforth, 1951; Cherns, 1976). Where governance frameworks and communication channels are insufficiently structured, AI integration may remain partial or generate uncertainty.

From a capability-based perspective (Teece, 1997), these responses are consistent with the view that the depth of AI-driven transformation may depend on the institutionalization of learning mechanisms and structured change management practices. The survey responses are consistent with the view that organizations providing systematic training and clarifying AI governance may be better positioned to convert technological adoption into sustainable human capital upgrading. Conversely, where AI introduction lacks formalized support systems, employees may experience rising skill pressure without adequate institutional scaffolding.

The dispersion of impact evaluations further indicates that AI-driven transformation is neither linear nor uniform. At the national level, respondents most often evaluated Latvia's labor-market adaptation to AI as moderate at 49.2%, followed by positive evaluations at 21.3%, negative evaluations at 13.1%, and uncertainty at 16.4%. Some respondents report substantial improvements in work quality and task efficiency, while others perceive only marginal change. This heterogeneity may reflect differences in organizational maturity, digital infrastructure, leadership engagement, and absorptive capacity. In line with knowledge transfer research in the Latvian context (Ozoliņa-Ugore et al., 2025), the effectiveness of technological integration appears closely linked to the strength of internal knowledge diffusion mechanisms.

Although the study did not explicitly stratify respondents by territorial location, the observed variability in AI integration depth has implications for regionally differentiated environments. This limitation suggests that future research should incorporate territorial segmentation to empirically test whether regional digital maturity levels correlate with differences in perceived AI impact and competence upgrading intensity. A plausible hypothesis, to be examined in subsequent regionally and spatially segmented research, is that in rural and lower-density organizational contexts limited access to specialized AI expertise, advanced digital infrastructure, and continuous professional development ecosystems may constrain the depth of transformation, leaving AI adoption predominantly operational rather than strategic. The present data do not allow this hypothesis to be tested directly. This interpretation aligns with broader regional development research demonstrating that digital maturity and innovation capacity are unevenly distributed spatially (OECD, 2019; European Commission, 2023).

Contemporary regional economics further indicates that technological upgrading is closely linked to smart specialization strategies and regional innovation ecosystems (McCann & Ortega-Argilés, 2015). Regions characterized by dense institutional collaboration and diversified knowledge bases are better positioned to internalize digital transformation benefits. Conversely, structurally weaker regions may experience cumulative disadvantage, reinforcing existing economic disparities (Iammarino et al., 2019). These dynamics underscore the importance of embedding AI policy within broader regional

development frameworks.

Taken together, the survey responses point toward a pattern in which artificial intelligence in the participating organizations is perceived primarily as task restructuring and competence intensification rather than as labour substitution. Interpreted through a rural and territorial development lens, these patterns raise the question of whether similar processes unfold unevenly across territorially differentiated and rural and lower-density contexts. Human capital development under AI is contingent upon structured organizational mediation mechanisms, particularly training institutionalization and governance transparency. The observed response patterns are consistent with the theoretical proposition advanced in this study that AI-driven workplace transformation may be understood as a multi-level process in which task reconfiguration, organizational capability, and territorial context interact to shape human capital development. In the present study, however, the territorial dimension remains interpretive rather than empirically tested.

Conclusions

This study examined artificial intelligence as a structurally transformative force within organizational work environments and analyzed its implications for human capital development in a territorially differentiated context. By integrating theoretical perspectives on task-based technological change, augmentation versus automation, socio-technical systems theory, and dynamic capability development with empirical evidence from Latvian organizations, the study advances a multi-level understanding of AI-driven transformation. The conclusions are structured in two parts: first, the empirical contribution of the study, and second, its theoretical implications for understanding AI integration in organizational contexts.

Empirical contribution

1. Within the surveyed sample, responses point toward a pattern in which artificial intelligence is perceived to operate through task reconfiguration rather than direct labour substitution. Within the sample, AI adoption is perceived to be associated with increased work efficiency and intensified competence requirements, suggesting that technological integration may reshape task composition and elevate demand for analytical, interpretative, and adaptive capabilities. In this respect, the observed responses are consistent with augmentation-oriented interpretations of AI, where technology complements rather than replaces human labor.

2. At the organizational level, the survey responses suggest that human capital development is not an automatic consequence of technological adoption. The depth and sustainability of transformation depend on structured learning mechanisms, transparent governance frameworks, and effective internal communication. The survey responses are consistent with the view that organizations institutionalizing training and clarifying AI implementation principles may be better positioned to convert technological integration into long-term capability upgrading. Causal confirmation lies beyond the scope of this exploratory study. Conversely, where organizational mediation mechanisms remain weak, AI may generate skill pressure without corresponding competence consolidation.

3. AI visibility and employee understanding are uneven across workplaces. A small number of respondents reported uncertainty about whether AI is used in their workplace, suggesting that AI functionalities may be embedded in everyday tools and processes without being explicitly labelled or recognized as AI. This indicates that employee sense-making and awareness are important preconditions for sustainable capability development: without a clear understanding of where and how AI shapes work tasks, organizations may realize efficiency gains while leaving competence formation fragmented. Accordingly, transparent internal communication, practical guidance, and clear principles for AI use function not merely as supportive practices but as structural mechanisms that help employees translate AI-enabled task changes into coherent skill development trajectories.

4. The study advances a conceptual proposition that AI-driven transformation is territorially mediated and therefore relevant to rural and regional development research. This proposition is not tested empirically in the present sample, since the survey instrument did not include regional identifiers. The observed heterogeneity in AI integration depth is consistent with, but not diagnostic of, territorial differentiation. Regionally stratified confirmatory research is required to examine whether in rural and lower-density contexts AI adoption remains predominantly operational unless supported by systemic learning infrastructures.

Theoretical implications

5. The study proposes that artificial intelligence may be conceptualized not merely as an isolated technological innovation, but as a capability-dependent organizational process embedded within territorially differentiated development contexts. Sustainable human capital development under AI requires systematic alignment between task restructuring, organizational capability development, and regional innovation ecosystems. Future research should incorporate explicit territorial segmentation and longitudinal designs to further examine how AI reshapes human capital trajectories across diverse structural environments.

6. The present study constitutes the first, exploratory and conceptual stage of a broader research programme. A planned follow-up study will employ a larger, probabilistically sampled, and regionally stratified dataset, including explicit rural-urban identifiers and inferential statistical analysis, to empirically test the territorial and capability-based propositions developed

here and to assess their relevance for rural and regional development policy.

Taken together, the findings point to AI-related workplace transformation in Latvian organizations as an organizationally mediated process rather than a purely technological shift.

Given the exploratory design of the study, future research using longitudinal and territorially segmented data is needed to assess the durability and broader generalizability of these patterns.

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AI-BASED IMAGE CLASSIFICATION FOR HEN EGG FERTILITY DETECTION

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Abstract
Automating early detection of fertilized hen eggs improves hatchery efficiency by reducing labour and misclassification. This study develops and evaluates an AI-based image classification pipeline that distinguishes fertile from non-fertile eggs using candled images. A balanced dataset of 740 labelled images (370 fertile, 370 non-fertile) was collected under a controlled LED candling setup at day seven of incubation, with fixed camera and backlight geometry to reduce acquisition variability. Images were pre-processed (resized, normalised, optional grayscale) and augmented (rotation, flipping, brightness/contrast, zoom, noise). We implemented and compared three models: a convolutional neural network (CNN) trained with cross-entropy loss and Adam optimizer, a Random Forest classifier using handcrafted features, and a Support Vector Machine with RBF kernel. Models were tuned on an 80/10/10 train/validation/test split with stratified class proportions, complemented by k-fold cross-validation for robustness, and evaluated using accuracy, precision, recall, and F1-score alongside confusion matrices. Paired statistical tests indicated significant differences between the CNN and both classical baselines on the main metrics. The proposed CNN combined with image enhancement achieved the best overall performance (test accuracy approximately 85%), demonstrating improved reliability over manual candling and classical baselines. We also provide deployment artefacts including an inference API, Docker packaging, and CI/CD considerations for real-world integration. Generalisation may be limited by dataset size and single-site acquisition; future work will explore temporal imaging across incubation days, transfer learning, and domain adaptation for diverse shell types and hatchery environments.
Keywords: egg fertility, convolutional neural network, image processing, data augmentation, hatchery automation.

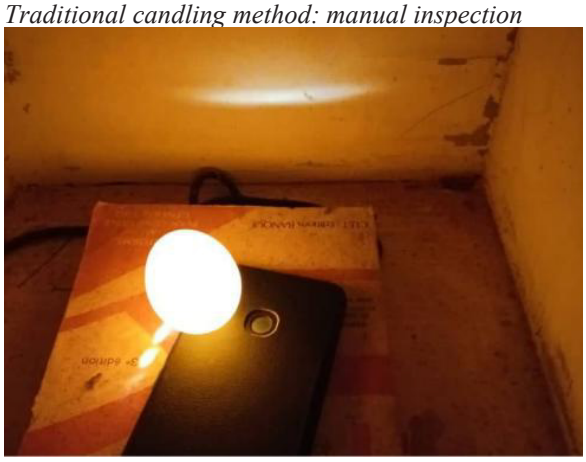
Introduction

Automated assessment of hen egg fertility is increasingly relevant to hatchery efficiency and incubator utilisation. Fertility is conventionally determined by candling (Figure 1), in which light transmitted through the shell reveals embryonic development; the method remains labour-intensive, operator-dependent, and sensitive to lighting and shell opacity (Hall et al., 2023a; Ramiro et al., 2018). Misclassification rates for manual candling have been reported at up to approximately 20%, with consequences for wasted capacity and loss of viable embryos. Image-based systems that apply computer vision and machine learning therefore continue to attract interest as scalable alternatives (Kamilaris & Prenafeta-Boldú, 2018; Liakos et al., 2018), and convolutional neural networks (CNNs) in particular have achieved promising separation of fertile and non-fertile candled eggs (LeCun et al., 2015).

A substantial body of work has addressed egg fertility classification from candled and incubator imagery. Studies have employed custom CNN architectures, object-detection frameworks such as YOLO and Mask R-CNN, and transfer learning with ImageNet backbones including VGG16, ResNet50, InceptionNet, and MobileNet (Pooja et al., 2025). Transfer-learning pipelines have reported test accuracies exceeding 98% for several pretrained networks (Saifullah, 2023), whereas detection–segmentation approaches based on Mask R-CNN with ResNet50 enable localisation of embryonic structures (Çevik et al., 2022). Despite this progress, published studies often differ in dataset scale, imaging protocol, incubation day, and—critically—in whether deep models are compared with classical machine-learning baselines on identical, stratified partitions of the same labelled corpus.

Accordingly, the objectives of this study are threefold: first, to construct a balanced dataset of candled images acquired at Day 7 of incubation from eggs collected and incubated under a documented protocol in Cameroon; second, to implement and evaluate a VGG16-based transfer-learning classifier comprising a frozen ImageNet feature extractor and a trainable binary classification head; and third, to benchmark its performance against Random Forest and Support Vector Machine (SVM) models. Additionally, to deliver a reproducible training and inference workflow, including containerised deployment, suitable for hatchery use.

Figure 1
Traditional candling method: manual inspection



Materials and Methods

Dataset and acquisition

The eggs were collected from farmers in two cities of Cameroon, Yaoundé and Bafoussam, who produce on average 160 eggs per week. The eggs were harvested under controlled temperature and humidity conditions, at least two days after laying. Each egg was checked to ensure that there were no cracks or stains before being

immediately placed in an incubator set at 37.5 °C and 50% humidity. The incubators, with a capacity of 90 eggs each, totaled three units: two in Yaoundé and one in Bafoussam.

A balanced corpus of 740 candled images was subsequently collected: 370 labelled fertile and 370 labelled non-fertile. Images were captured at Day 7 of incubation (standard candling window) with a fixed camera above a wooden platform with a circular cut-out, coated matte black, and a bright LED backlight in a darkened room (Figure 3); camera settings (low ISO, fast shutter, narrow aperture) were held constant. Each image was labelled as fertile or non-fertile by experienced technicians; ambiguous cases were resolved by consensus. Images were collected with permission from the collaborating hatchery; no personal data are included. The dataset was split into 80% training (592 images), 10% validation (74), and 10% test (74), stratified by class (Figure 2).

Figure 2
Dataset flow: train, validation, and test split

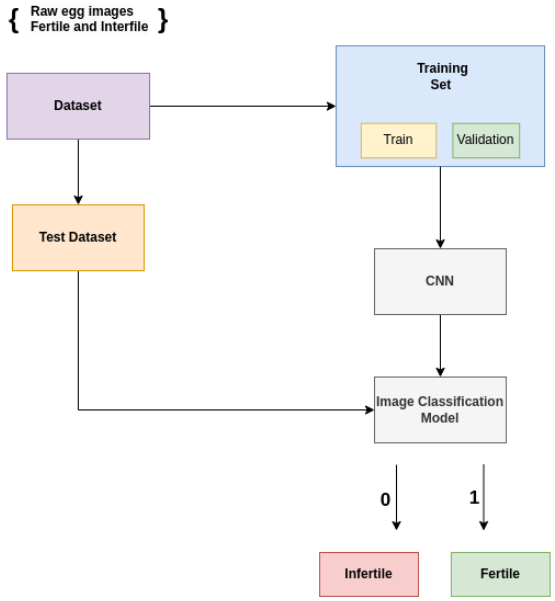
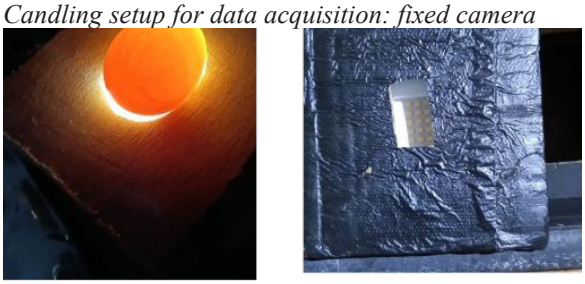


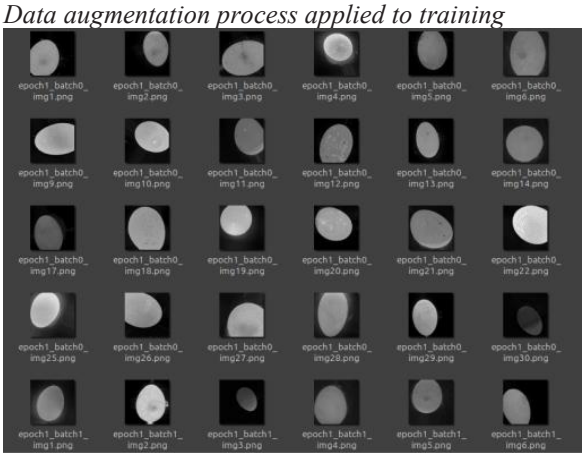
Figure 3
Candling setup for data acquisition: fixed camera



Preprocessing and augmentation

Images were resized to 512×512 pixels and pixel values normalised to [0,1] to meet consistent input requirements for the models (Liakos et al., 2018); optional CLAHE and gamma corrections were evaluated to improve contrast under varying lighting. Data augmentation is widely used to improve generalisation and robustness in image classification, especially when dataset size is limited (Alomar et al., 2023; Mumuni A. & Mumuni F., 2022). Augmentations (Figure 4) included rotations (±30◦), horizontal and vertical flips, brightness/contrast jitter, small zoom/crops, and additive Gaussian noise, applied on-the-fly during training to simulate lighting and orientation variability (Mumuni A. & Mumuni F., 2022).

Figure 4
Data augmentation process applied to training



Models and models training

Three supervised classifiers were implemented and evaluated on the same stratified train/validation/test partitions (80% training, 10% validation, 10% test). The primary model was a deep convolutional network based on the VGG16 architecture (Figure 5), formulated as binary classification of whole candled images rather than object detection. This design follows transfer-learning studies in egg fertility imaging (Saifullah, 2023; Pooja et al., 2025) and provides a direct comparison with classical machine-learning baselines trained on the same labels.

Each candled image was represented as a 512×512 grayscale array with pixel intensities linearly scaled to [0, 1]. Inputs were expanded to three channels and forwarded through a VGG16 backbone pretrained on ImageNet, from which the original classification layers were removed and the convolutional weights were kept fixed during training. Spatial responses were summarised by global average pooling and mapped to a fully connected layer of 128 units with rectified linear unit activation, followed by dropout (probability 0.5) and a sigmoid output denoting the estimated probability of fertility. Parameters were estimated by minimising binary cross-entropy with the Adam optimizer (mini-batch size 32). Training was limited to 20 epochs with on-the-fly augmentation as described above; training was halted early when validation loss ceased to improve, and the learning rate was reduced on plateau. Supplementary k-fold cross-validation was used to assess stability. Unless stated otherwise, metrics in Tables 1–5 refer to this VGG16 classifier.

For comparison, a Random Forest ensemble (Figure 6) and a Support Vector Machine (SVM) with radial basis

function kernel (Figure 7) were trained on flattened grayscale pixel vectors extracted from the same images, with feature standardisation applied before SVM fitting. These models serve as transparent benchmarks when GPU resources are limited or training sets are small (Çevik et al., 2022; Kamilaris & Prenafeta-Boldú, 2018).

Figure 5
Simple CNN design used for egg fertility classification

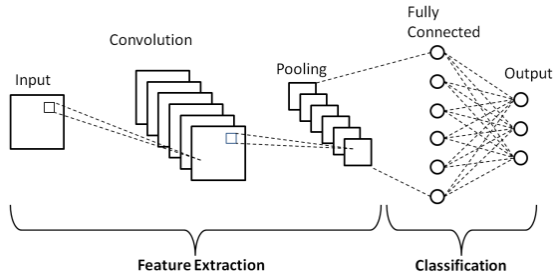


Figure 6
Random Forest architecture (ensemble of decision trees)

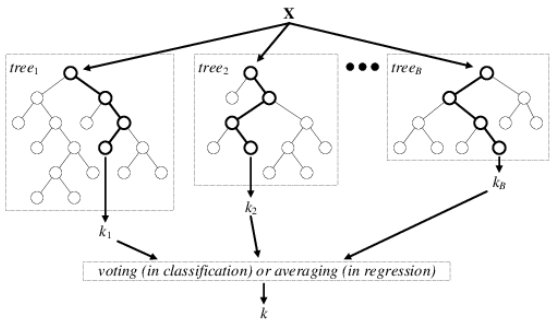
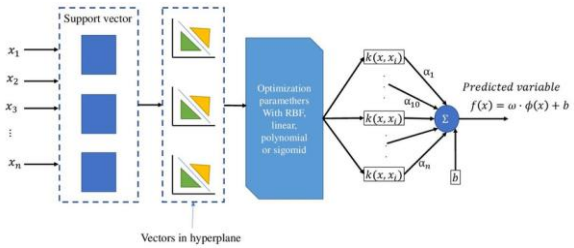


Figure 7
SVM framework with RBF kernel for non-linear classification



Models Evaluation

Model performance was assessed on the held-out test set and, for robustness, via k-fold cross-validation. Primary metrics were accuracy, precision, recall, and F1-score, which are standard for binary classification and allow trade-offs between false positives and false negatives to be quantified (Liakos et al., 2018). Confusion matrices were computed for class-wise analysis, following common practice in agricultural and egg-imaging studies (Ahmed et al., 2025). Pairwise statistical comparison between models used paired t-tests on the per-fold metric values at 95% confidence to test whether differences in accuracy, precision, recall, and F1(4) were significant.

The evaluation metrics are defined as follows (positive class = fertile; TP=true positives, TN=true negatives, FP=false positives, FN=false negatives):

$$Accuracy = \frac{TP+TN}{TP+TN+FP+FN} \quad (1)$$

$$Precision = \frac{TP}{TP+FP} \quad (2)$$

$$Recall = \frac{TP}{TP+FN} \quad (3)$$

$$F1 = \frac{2\times Precision\times Recall}{Precision+Recall} \quad (4)$$

Computational environment

Model training and evaluation for this study were performed on a Linux operating system running Linux Mint 22 (Wilma), kernel version 6.8.0-51-generic, with an x86_64 architecture, on a Dell Inc. Precision 5480 workstation. The processor was an Intel64 Family 6 Model 186 Stepping 2, GenuineIntel (13th Gen Intel(R) Core(TM) i7-13800H, up to 5.2 GHz). The workstation was also equipped with an NVIDIA RTX 2000 Ada Generation Laptop GPU and Intel Iris Xe integrated graphics. Python 3.12.3, compiled with GCC 13.2.0 64-bit (AMD64), was used for all computational tasks within the project virtual environment fertile-env. The environment included a comprehensive range of packages such as TensorFlow 2.18.0, Keras 3.7.0, NumPy 2.0.2, pandas 2.2.3, matplotlib 3.9.2, seaborn 0.13.2, scikit-learn 1.5.2, SciPy 1.14.1, OpenCV 4.10.0.84, Pillow 11.0.0, and h5py 3.12.1, among others. The system featured 14 physical CPU cores (20 logical cores) and 32.0 GB of RAM.

Results and Discussion

Overview of experimental results

Table 1 summarises model performance on the held-out test set: mean accuracy (1), precision (2), recall (3), and F1-score (4) with standard deviation across folds for the CNN, Random Forest, and SVM. The CNN achieves the highest metrics (accuracy 0.85, F1 0.85), followed by Random Forest (0.76, 0.77) and SVM (0.73, 0.75); recall is relatively high for all models, indicating fewer missed fertile eggs. Table 2 reports the pairwise statistical comparison (t-test): the CNN shows statistically significant gains over both Random Forest and SVM (all four metrics, $p < 0.05$), while differences between Random Forest and SVM are smaller and not significant.

Our results align with recent literature in the field; for instance, Çevik et al., 2022 reported strong performance of deep learning for egg fertility detection, consistent with our CNN results. Ensemble

CNNs can achieve high accuracy on small image datasets (Phung & Rhee, 2019), which aligns with our setup (740 images, 80/10/10 split). For Random Forest, sample selection strongly affects image-classification performance (Millard & Richardson, 2015); our RF baseline (76% accuracy) is in line with typical RF image results when limited training data are used. Trebar & Steele (2008) found SVMs effective but sensitive to feature design in classification tasks; our SVM (73% accuracy) reflects the challenge of hand-crafted features compared with the CNN. Chaganti et al. (2020). compared SVM and CNN for image classification and reported higher accuracy with CNNs, matching our ordering (CNN > RF > SVM). Overall, the reported accuracies (CNN ~85%, RF ~76%, SVM ~73%) are comparable to those in similar egg-fertility or small-scale image-classification studies.

Table 1

Performance comparison on the test set

Model	Accuracy	Precision	Recall	F1-Score
CNN	0.8503±0.07	0.8204±0.07	0.8804±0.07	0.8500±0.07
Random Forest	0.7622±0.06	0.7326±0.06	0.8125±0.06	0.7720±0.06
SVM	0.7262±0.07	0.6804±0.08	0.8245±0.07	0.7480±0.07

Notes: Mean ± s.d. across folds.

Table 2

Statistical comparison of performance metrics (t-test)

Comparison	*Accuracy*	*Precision*	*Recall*	*F1-Score*
CNN vs Random Forest	+9% *	+9% *	+7% *	+8% *
CNN vs SVM	+13% *	+14% *	+6% *	+11% *
Random Forest vs SVM	+4% ns	+5% ns	−1% ns	+3% s

Significance: * $p < 0.05$; ns = not significant; s = small effect.

Confusion matrices

Confusion matrices were computed on the held-out test set to inspect class-wise predictions (fertile vs non-fertile). Reporting confusion matrices is standard in egg-fertility and agricultural image-classification studies. Tables 3–5 show the corresponding counts (TP, TN, FP, FN) for the CNN, Random Forest, and SVM on one representative test split ($n = 74$, 37 per class); Table 1 instead reports mean metrics across k folds. The CNN (Table 3) achieves the highest diagonal counts (33 true positives, 30 true negatives) and the fewest false negatives (4), which is desirable when minimising missed fertile eggs. Random Forest (Table 4) and SVM (Table 5) show more false positives (11 and 14 respectively) and slightly more false negatives (7 and 6), consistent with their lower precision and recall in Table 1.

Key findings

The CNN produced the strongest overall performance and generalisation (Table 1), benefiting from end-to-end feature learning and augmentation, consistent with prior work on deep learning for egg fertility classification (Çevik et al., 2022) and with the general advantage of CNNs over hand-crafted features in image tasks (Chaganti et al., 2020; LeCun et al., 2015). Random Forest was faster to train and useful when compute is limited, in line with its role as an efficient baseline in image classification; SVM required careful feature scaling and kernel tuning to reach comparable recall (Trebar & Steele, 2008). The statistically significant gains of the CNN over both baselines (Table 2) support its selection for deployment.

Figure 8

Model performance summary: CNN, Random Forest and SVM maximum metrics

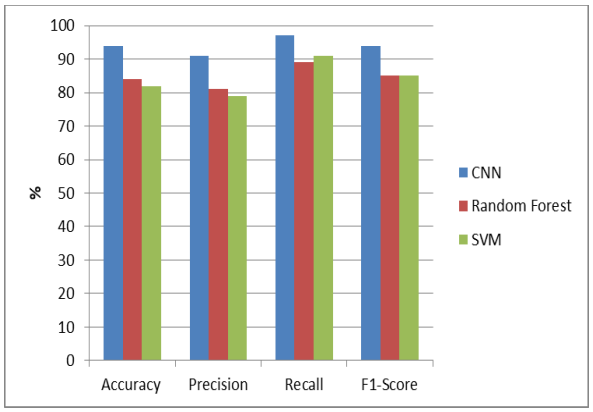


Table 3

Confusion matrix: CNN (test set)

	Predicted	
Actual	Fertile	Non-fertile
Fertile	33 (TP)	4 (FN)
Non-fertile	7 (FP)	30 (TN)

Table 4

Confusion matrix: Random Forest (test set)

	Predicted	
Actual	Fertile	Non-fertile
Fertile	30 (TP)	7 (FN)
Non-fertile	11 (FP)	26 (TN)

Table 5

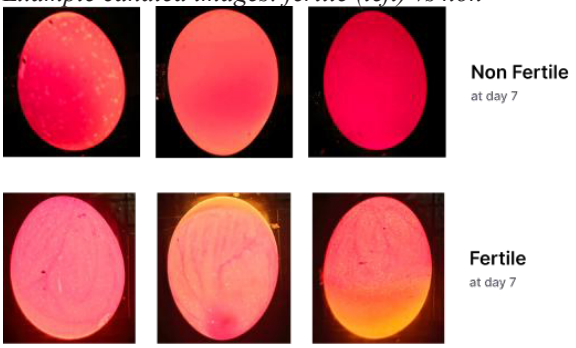
Confusion matrix: SVM (test set)

	Predicted	
Actual	Fertile	Non-fertile
Fertile	31 (TP)	6 (FN)
Non-fertile	14 (FP)	23 (TN)

Error analysis

Errors were dominated by false negatives where embryo features were faint or occluded by thick shells. The confusion matrices (Tables 3–5) show that all three models tended to miss fertile eggs (false negatives) more often when the embryo was poorly visible or the shell was thick; the CNN reduced this effect (fewest FN). Figure 9 shows representative fertile and non-fertile examples.

Figure 9
Example candled images: fertile (left) vs non



Ablation studies and practical notes

Ablations. To assess the contribution of individual components, we ran the CNN with selected changes. Removing data augmentation increased validation loss variance across epochs and reduced test F1(4) by several points, confirming that augmentation improves generalisation on the limited dataset (Mumuni A. & Mumuni F., 2022). CLAHE and gamma correction were evaluated as optional preprocessing steps; they gave a small improvement on low-contrast images where the embryo was hard to distinguish, but were not essential under our controlled lighting. Training and inference with grayscale inputs (single channel) achieved performance comparable to RGB with lower memory and compute, consistent with the importance of intensity and texture over colour for candling-based fertility cues.

Practical deployment. The classification threshold (sigmoid output) can be tuned to the hatchery cost structure: lowering the threshold favours recall (fewer false negatives, fewer fertile eggs discarded) at the cost of more false positives, whereas raising it favours precision. The best performing CNN was packaged as a REST-style inference API (e.g. Flask) that accepts an image and returns a fertility prediction; the API and model dependencies were containerised with Docker for reproducible deployment across environments. CI/CD pipelines (e.g. Jenkins or GitLab CI) can automate build, test, and deployment so that model or code updates are rolled out consistently to hatchery systems.

Quantifying operational benefits. Automation of candling has the potential to improve classification consistency, labour productivity, and hatchery economics. Although end-to-end operational gains were not measured in the field, the present experiments yield indicators that can be used to evaluate these outcomes.

Classification accuracy. Performance was assessed on the held-out test set using accuracy, precision, recall, F1-score, and confusion matrices (Tables 1 and 3–5). The CNN achieved 85% overall accuracy and 88% recall for fertile eggs (four false negatives among 37 fertile cases; Table 3), with fewer missed fertile eggs than the Random Forest (seven false negatives) and SVM (six false negatives) baselines. Manual candling error rates of up to approximately 20% reported in the literature provide an external benchmark; nevertheless, a definitive comparison with expert technicians requires a paired validation study in which the same images are classified independently by experienced candlers and by the deployed model.

Labour and throughput. Labour demand can be compared using a time-and-motion study that records mean seconds per egg for manual inspection (handling, positioning, and visual decision) versus the workflow adopted here (standardised image acquisition at a fixed station followed by batch inference via the REST API). Scaling time per egg to a per-1,000-egg basis permits direct estimation of staffing requirements; standardised imaging and automated inference additionally reduce variability associated with operator skill and ambient lighting.

Economic impact. Hatchery costs can be related to model outputs by combining false-positive and false-negative rates from the confusion matrices with unit costs for discarding fertile eggs and incubating non-fertile eggs, and by selecting an appropriate classification threshold (see Practical deployment). This study reports the classification error rates required for such an analysis; farm-level wage and revenue data were not collected.

Limitations

The dataset size (740 images) and single-site collection limit generalisability; multi-site, multi-breed data and temporal imaging across incubation days are recommended for future work to capture variability in shells, breeds, and equipment. Claims regarding superior accuracy relative to manual candling and reductions in labour cost were not established through a paired human–machine trial or hatchery economic survey; frameworks for evaluating these outcomes are presented under Quantifying operational benefits. All images were acquired under controlled lighting and camera settings, so performance in more variable hatchery environments (different rigs, cameras, or operators) may be lower unless the model is retrained or adapted with additional data. Thick or opaque shells (Figure 10) can hinder candling visibility (Hall et al., 2023b), which also affects automated detection and remains challenging for both human operators and AI systems (Çevik et al., 2022). The current work focuses on binary fertility classification at Day 7 only; extending to earlier/later incubation stages or multi-class embryo development labels will require larger datasets and careful re-evaluation of model performance and thresholds.

Conclusions

This study fulfilled the three objectives set out in the Introduction:

1. Dataset. A balanced corpus of 740 candled egg images was built with a documented egg-collection and incubation protocol and a fixed LED candling setup at Day 7.

Figure 10
Eggs with different shell types; thickness and opacity affect candling visibility



2. Model comparison. The objective of evaluating machine learning models for egg fertility detection was accomplished: the CNN achieved approximately 85% accuracy on the held-out test set, significantly outperforming Random Forest (76%) and SVM (73%) with statistically significant differences (Table 2), and was therefore selected for deployment as a prototype.
3. Reproducible pipeline and deployment. Training and evaluation code, preprocessing and augmentation settings, saved model weights, a REST-style inference API, and Docker packaging were delivered as deployment-ready artefacts for hatchery workflows.
4. Despite the modest dataset size, the results support the feasibility of AI-based fertility classification under controlled candling conditions. Data augmentation and preprocessing helped mitigate lighting and image-quality variability.
5. The results suggest that AI-based egg fertility detection has significant potential for commercial hatcheries (Çevik et al., 2022): automating candling can improve accuracy, reduce labour costs, and integrate with existing hatchery management systems—claims that are discussed in terms of measurable indicators under Quantifying operational benefits and that require confirmation in paired human–machine and hatchery cost studies.
6. Limitations include the modest dataset size (740 images) and sensitivity to eggshell thickness and lighting. Future work will expand datasets (including multiple species and incubation stages), consider transfer learning and multi-class classification by embryo stage, and integrate with automated sorting and predictive analytics for hatch-rate optimisation.

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AI-ENABLED RECOMMENDER SYSTEMS IN TOURISM:A SYSTEMATIC REVIEW OF HYBRID METHODS, SOCIAL MEDIA DATA AND USER SATISFACTION

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Abstract
As digital tourism platforms grow in size, they are increasingly adopting artificial intelligence and recommender systems to assist users in dealing with the vast amount of information about destinations, accommodations, events and reviews. Tourism recommendation is a challenging domain because a tourist's choices are influenced by their preference history, social network, seasonality, mobility, location, trust, and perceived usefulness of recommended services. This paper aims to systematically review the latest literature on AI-based recommender systems in the tourism sector, focusing on hybrid approaches, social media data and user satisfaction. The review is conducted in accordance with the literature-review design, which is based on transparent search, eligibility and thematic-synthesis principles. In total, the search process identified 92 records; after duplicate removal and screening, 31 full texts were assessed, and 19 publications were retained for thematic synthesis. Searches were conducted on peer-reviewed research related to tourism, travel, hospitality, smart tourism and point-of-interest recommendation. The review reveals that hybrid approaches are extensively discussed, as they can integrate collaborative filtering, content-based filtering, knowledge-based reasoning, contextual variables and AI-based representation learning. The literature reviewed, however, also reveals some common pitfalls, such as limited data, platform bias, privacy issues, and lack of real-world validation and satisfaction. The paper concludes by suggesting that future research on tourism recommender systems should link algorithmic accuracy to user-centred outcomes, transparent evaluation, responsible use of social data and value for destination management.
Keywords: AI-enabled recommender systems, tourism, hybrid recommendation, social media data, user satisfaction.

Introduction

Tourism is an information-rich industry, where tourists evaluate a multitude of different places, modes of transport, hotels and accommodation, restaurants, events and activities before booking or visiting. Hence, recommender systems are applicable in that they help to filter out the vast number of alternatives, based on the user's preferences and the characteristics of the items (Chaudhari & Thakkar, 2019). In digital tourism, AI-powered recommendations become particularly significant as platforms need to decipher behavioural patterns, location cues, review text, and context to offer personalised suggestions and recommendations (Bulchand-Gidumal, 2022).

A typical tourism recommender system will attempt to predict a tourist a value, for example, a location, service or tourism experience, at a specific time. This prediction can be made using collaborative filtering, which is based on the behaviour of similar users, or content-based filtering, which compares items with known user preferences with the attributes of attractions, hotels, activities or destinations (Roy & Dutta, 2022). They are effective but can only be used individually, as tourist behaviour can be influenced by time, season, travel purpose, group composition, location and immediate travel constraints (Rehman Khan et al., 2021).

Hybrid approaches are one of the most prominent research trends in recommender-systems research, as they are able to leverage the merits of various approaches. A hybrid tourism system can be a combination of collaborative filtering and content-based information, contextual variables, knowledge-based constraints, graph models or social-media signals (Fararni et al., 2021). This combination is useful because the decision to visit a destination is rarely based on a single factor. For example, a tourist may prefer museums, but weather, opening hours, distance, cost, and social reviews can cause them to change their mind (Massimo & Ricci, 2022).

The data from social media has also influenced the design of tourism recommendations. Information on perceived service quality and destination experience is conveyed through reviews, ratings, images, tags, check-ins and geotagged posts (Chang et al., 2019). User-generated content can provide a better and faster indication of the current trends and visitors' sentiments than formal tourism databases, and thus can be utilised for recommendation in dynamic destination environments (Missaoui et al., 2019). But this evidence is not neutral, as social media platforms may have noisy, biased, duplicated or strategically manipulated content (Li et al., 2021).

User satisfaction is a key result of tourism recommender systems, as a technically correct recommendation does not necessarily imply a satisfying travel suggestion. A recommendation can be high in an offline dataset, but if it is not convenient, poorly explained, unsafe, culturally inappropriate, or not in line with the purpose of the trip, it will not work (Ricci et al., 2022). Therefore, satisfaction is a user-centred construct in the present paper that is related to usefulness, trust, transparency, timeliness, diversity and decision support (Fan et al., 2022).

This paper aims to systematically review the literature in the field of AI-based recommender systems in the tourism industry with particular emphasis on hybrid approaches, social media data and user satisfaction. The review is based on three questions. Firstly, which hybrid and AI-based approaches are mentioned in

tourism recommender-system research? Secondly, how is social media or user-generated content utilised in tourism recommendation? Third, what are the concepts of user satisfaction, trust and evaluation found in the studies reviewed?

Materials and Methods

This paper was intended to be a systematic literature review. A systematic review is suitable because the aim is to locate, structure and analyse the current research and not to create a new prototype software or to simulate performance results. The PRISMA style of reporting requires the authors to describe the process of record identification, screening and inclusion, which enhances transparency and reproducibility (Page et al., 2021).

Peer-reviewed academic literature was reviewed for the topics of AI-powered recommender systems in tourism, travel, hospitality, smart tourism and point-of-interest recommendation. In order to plan the database searching, it was decided to use Scopus, Web of Science, IEEE Xplore, ACM Digital Library, ScienceDirect, SpringerLink and Google Scholar as they include both computing and tourism research. The search strings included the combination of the terms 'tourism recommender system', 'travel recommendation', 'AI recommendation', 'hybrid recommender', 'context-aware recommendation', 'social media data', 'user-generated content', 'tourist satisfaction' and 'point-of-interest recommendation'.

The inclusion criteria were that the publications had to be written in English, peer-reviewed, and directly related to tourism or travel recommendations. Studies also had to include at least one of the following dimensions: hybrid recommendation, data from social media, user-generated content, contextual adaptation, AI-based modelling, trust, satisfaction or user evaluation. Following Aggarwal's (2016) general recommender-system framework, broader recommender-system studies were only included if they offered concepts that are crucial to understanding tourism applications, such as hybridisation or evaluation practice.

Editorials, theses, non-academic reports, non-English publications (unless reliable translation was available), and papers that referred to tourism only indirectly were excluded. Studies were also excluded if they made unsupported claims with no method, data, review protocol or evaluation logic. This was a significant choice, as there are instances in recommender-system literature that combine conceptual frameworks, prototype descriptions and empirical claims without making the evidence and the proposal distinct.

The screening process comprised title and abstract screening, and full-text eligibility assessment. The title and abstract stage determined if the study was related to tourism recommendation or if it included the topics of AI, hybrid methods, social data or satisfaction. The full-text stage assessed the methodological detail provided in the paper to support extraction and synthesis. Before thematic analysis, duplicate records and inaccessible full texts were eliminated.

The screening log was introduced to enhance transparency of the screening process. A total of 92 records were initially found in the database and Google Scholar. Of the 74 titles and abstracts screened, 18 were duplicates and removed. Forty-three records were removed at the title and abstract stage due to not being focused on tourism recommendation, not using AI/hybrid/social-media methods, or not being relevant to user evaluation. Thirty-one full texts were then evaluated, and 19 publications were included in the final thematic synthesis based on the inclusion and exclusion criteria.

The quality assessment was used in a practical manner as it involved studies from both the computing and tourism outlets. Studies that explicitly stated the source of their data, the task of the recommendation, the algorithmic method used, the evaluation method and the limitations of the study were considered stronger. When a study made general statements of accuracy or satisfaction, but did not provide details of how this was measured, the study was treated with caution. This is in line with the general rule that systematic reviews should be transparent about the evidence-selection process, and not assume that all publications are equally reliable (Page et al., 2021).

Data extraction was done in both technical and tourism categories. Technical categories were algorithm type, hybridisation strategy, use of context, use of social media data, evaluation metric and type of dataset. Recommended item, destination setting, user need, satisfaction measure, trust-related feature and practical implication were the categories related to tourism. This is because the evaluation of a tourism recommender system should not only be considered as an algorithm but also as a service-support tool.

The information in the datasets was also coded as the reviewed studies used different forms of evidence. Public or platform-visible sources comprised ratings, reviews and TripAdvisor/social-media content, as shown in the social media analytics and mobile tourism recommendation studies (Chang et al., 2019; Missaoui et al., 2019). Other studies used destination metadata, point-of-interest categories, location traces, routes, or user-item interactions or platform-specific logs that are frequently private or not easily replicable (Massimo & Ricci, 2022; Hamid et al., 2021). In contrast, review-based studies aggregated existing datasets, algorithms and evaluation metrics instead of creating new user logs (Chaudhari & Thakkar, 2019; Roy & Dutta, 2022).

The synthesis was thematic and not statistical. A meta-analysis was not possible due to the significant differences in the datasets, destinations, algorithms, evaluation metrics and research design of the studies reviewed. Thematic synthesis enabled the evidence to be clustered into the following emergent areas: hybrid methods, social media and user-generated content, context awareness, user satisfaction, trust, evaluation

practice and responsible AI. This way, it also did not create false comparisons of numbers across studies that were not directly comparable.

Literature review

Recommender systems can be defined as information-filtering systems that are able to predict users' preferences based on their past interactions with the system, the description of the items or some contextual information (Aggarwal, 2016). In the context of tourism, this broad definition gets complicated as the recommended item could be a destination, an itinerary, a hotel, a restaurant, an event, an attraction or a point of interest (Chaudhari & Thakkar, 2019). Tourism products are also experiential and perishable; thus, the similarity of the products is not the only factor that influences a good recommendation, but also the traveller's situation and expectations (Kontogianni & Alepis, 2020).

Table 1

Inclusion and exclusion criteria for selecting studies (Author-developed criteria based on systematic-review reporting principles)

Criterion	Inclusion criteria	Exclusion criteria
Study type	Peer-reviewed journal articles and conference papers	Editorials, theses, white papers, blogs and non-academic reports
Language	Publications written in English	Non-English publications without reliable translation
Publication period	Main focus on 2019-2026, with foundational sources retained when needed	Outdated papers with no conceptual or methodological relevance
Domain	Tourism, travel, hospitality, smart tourism, destination or point-of-interest recommendation	General recommender-system papers with no tourism application or implication
Core topic	AI-enabled recommendation, hybrid methods, context awareness, social media data, user satisfaction or trust	Papers unrelated to recommendation methods, tourism data or user evaluation
Quality requirement	Clear method, dataset, review logic or evaluation approach	Unsupported claims, unclear method or inaccessible full text

One of the most popular recommendation methods is collaborative filtering, which can be used to find similarities among users or items and make predictions based on these similarities. It can be helpful when there is enough user-rating or interaction data, but can suffer from cold-start issues when there is little data for new users, new destinations or new services (Roy & Dutta, 2022). This can be mitigated by content-based filtering, which considers item attributes such as location, category, facilities, price range, or textual description (Massimo & Ricci, 2022).

Context-aware recommendation is especially relevant in the tourism sector as tourists make their decisions in a varying context. Context can be time of day, season, weather, distance, transport available, crowding, travel companion, budget and purpose of travel (Rehman Khan et al., 2021). The context-aware tourism system can then adjust the recommendations if the user changes location, the weather conditions change, or if a planned activity is no longer suitable (Hamid et al., 2021).

With the advent of AI and machine learning, tourism recommendation has gone beyond traditional similarity matching. Complex relationships between users, locations, reviews, images and sequences of behaviours can be processed using deep learning and representation learning (Deldjoo et al., 2020). Because tourism decisions are often made in the context of networks of places and experiences, graph-based recommendation can capture the relationship between tourists, destinations, activities and social connections. Social media and user-generated content are now a key source of tourism analytics. Ratings, comments, photos, geotags and check-ins on review platforms and social networking websites can offer information about real visitors' experiences (Chang et al., 2019). These data sources can enhance the recommendation as they contain opinions and contextual indications which are not necessarily present in formal destination descriptions (Missaoui et al., 2019). Meanwhile, online reviews can be biased towards extreme experiences or popular destinations, and towards active users, leading to fairness and representativeness concerns (Li et al., 2021).

Thus, Responsible AI is part of the conceptual background for tourism recommendation. For this review, responsible AI is defined as privacy protection, consent, bias reduction, explainability, fairness, and avoiding harmful destination-management effects. These concerns are important as recommender systems can rely on personal profiles, location traces and signals from social media, and popularity-biased recommendations can over-expose already popular destinations and restrict visibility for smaller or less digitally visible ones (Fan et al., 2022; Li et al., 2021; Rehman Khan et al., 2021).

Evaluation is also a methodological challenge, as shown in the literature. Many recommender-system research studies use offline metrics like precision, recall, RMSE and ranking accuracy (Silveira et al., 2019). While these measures are helpful to compare algorithms, they do not fully reflect whether travellers trust, understand or enjoy the recommendation (Ricci et al., 2022). Thus, the user-centred evaluation should

be included in tourism recommendation, particularly when it aims to enhance user satisfaction and decision quality (Fan et al., 2022).

A significant stream of literature is related to multimedia/multimodal recommendation. The communication of tourism experiences is often done through pictures, videos, maps, and short textual reviews, and so the content of the media can better depict the atmosphere of a tourist destination than just the rating alone (Deldjoo et al., 2020). This is significant for AI-powered tourism recommendations as visual and textual cues could be used to differentiate locations with the same formal classification that offer different experiences for visitors (Li et al., 2021).

In the field of smart tourism, research is also focused on the relationship between recommendations and the broader digital destination infrastructure. Smart tourism systems are a set of systems that include sensors, mobile apps, platform data and internet-based services to assist in pre- and in-trip decision-making (Kontogianni & Alepis, 2020). Recommendation systems in this context are not standalone algorithms, but part of a service ecosystem, such as maps, booking engines, review sites, and destination-management organisations (Hamid et al., 2021).

The literature on sustainable e-tourism also indicates that the consequences of recommendations should be assessed in terms of social and destination-level consequences. Contextual Suggestion systems can guide the travellers towards more appropriate and less congested alternatives by considering location, time, and user needs as inputs to the decision-making process (Rehman Khan et al., 2021). This is significant as recommender systems can either alleviate the pressure on popular attractions or exacerbate it if they only encourage popularity and click behaviour.

Results and Discussion

Hybrid approaches for tourism recommender systems

The literature reviewed shows that hybrid recommendation is one of the most important directions in tourism. The hybrid systems are appealing since the decision-making process of tourists involves preference history, destination attributes, situational constraints and social influence (Fararni et al., 2021). One approach is usually not enough, as collaborative filtering can fail to recommend new attractions and content-based filtering can fail to capture trends from similar travellers (Roy & Dutta, 2022).

There are several ways in which hybridisation can take place. There are also hybrid collaborative/content-based systems that aim to balance user similarity with the description of the content (Çano & Morisio, 2019). Other systems add contextual information like location, season or weather to adjust the recommendations during the trip (Rehman Khan et al., 2021). When recommendations need to take into account constraints like budget, accessibility, opening time or family suitability, knowledge-based rules can also be added (Ricci et al., 2022).

Hybrid AI systems are gaining attention because they seamlessly combine structured and unstructured tourism data. Structured data consists of ratings, prices, attraction categories, locations, opening hours, booking records and user-item interaction matrices. Written reviews, social-media posts, images and videos and free-text destination descriptions are all examples of unstructured data. Sentiment or topic features can be extracted from textual reviews, and images and multimedia descriptions can produce more comprehensive representations of destinations (Deldjoo et al., 2020; Chang et al., 2019). Graph-based approaches can also be used to model relations between users, places, categories and social links, which can be useful when tourist behaviour forms networks of movements and experiences (Gao et al., 2022).

Although these are the advantages of hybrid methods, they also come with design challenges. While many data sources can be combined to enhance representation, this can also make the system harder to explain and reproduce (Fan et al., 2022). Tourism studies should, therefore, document the components that are mixed, the reasons for choosing the hybrid approach, and the assessment of each component's contribution. In the absence of this transparency, hybrid recommendations can be a general term and not a well-tested approach to methodology.

Social media data and user-generated content

The data from social media has a unique value for tourism recommendations as it reflects visitors' perceptions and popularity of the destination in near-real environments. Reviews and ratings are explicit feedback on attractions, hotels, restaurants and activities (Chang et al., 2019). Visitors' location can be displayed through check-ins, geotags and posts, as well as the time they visit and their description of the visit (Missaoui et al., 2019).

User-generated content can add value to destination profiles, beyond official descriptions. A formal database might classify a site as a museum, and reviews might indicate that the visitors connect it to family learning, long lines, high admission fees or cultural value (Li et al., 2021). This distinction is important because travellers will often choose based on perceived experience and not just on category alone. Sentiment analysis and topic modelling can thus be used to find out what users actually talk about when it comes to the qualities of a recommender system (Chang et al., 2019).

Recommendation is also trend-sensitive, based on social data. The demand for tourism can shift rapidly due to festivals, weather, online exposure, seasonal events or viral content. A recommender system based on recent social signals is likely to react faster than a system based on historical ratings (Missaoui et al., 2019). But trend sensitivity should be applied wisely since popularity does not necessarily equate to suitability for all travellers. Excessive reliance on

social popularity can lead to a lack of destination diversity, placing additional pressure on already over-visited locations.

Ethical and methodological issues are also present. The information in social media can contain personal data, location data, and culturally sensitive data, posing privacy concerns (Fan et al., 2022). Online reviews can be fake, promotional, incomplete or biased to those who had a good or bad experience (Li et al., 2021). Therefore, research with social media data should include a description of data cleaning, bias control, privacy protection, and limitations of the platforms.

Awareness of context, personalisation, real-time adaptation

One of the characteristics that distinguishes tourism recommendation from many other domains is context awareness. A film or music recommendation might hold relevance for weeks, whereas a tourism recommendation might not be relevant within hours, due to changing weather, distance, crowding or opening time (Rehman Khan et al., 2021). Thus, location-aware and time-aware systems play a crucial role as travellers may require suggestions while they are already on the move in a destination (Hamid et al., 2021).

Another essential personalisation factor to consider in tourism is the purpose of the trip. A business traveller, family tourist, backpacker and cultural tourist will appreciate different aspects of a destination. User preferences should thus be captured in more specific ways, e.g. relaxing in nature, walking, visiting authentic countryside places, visiting family businesses, enjoying local cuisine, exploring culture and traditions. The average rating system may indicate popular places but not take into account whether it matches the traveller's needs and preferences (Massimo & Ricci, 2022). These situational rules can be added to preference prediction by contextual and knowledge-based elements (Ricci et al., 2022).

Real-time adaptation is useful but should not be overemphasised. According to the literature on smart tourism, the use of current data is recommended to increase the relevance; however, a review paper should not make any claims to real-time performance if the system has not been deployed and tested under real conditions (Kontogianni & Alepis, 2020). A more defensible statement is that the literature suggests that real-time adaptation is a viable design path, but further and more rigorous testing is required.

Explainability is also an issue with the context and personalisation. When a system suggests an indoor attraction due to rain, or because the user has expressed a preference for cultural attractions, the suggestion is more readily accepted if the reason for the suggestion is apparent. Explanations can contribute to user satisfaction as they help to decrease uncertainty and indicate that the system is reacting to the travel situation (Fan et al., 2022).

User satisfaction, trust and practice of evaluation

One of the outcomes is user satisfaction, which is not always reported in the literature. For instance, Silveira et al. (2019) demonstrate that the evaluation of recommender systems is frequently based on offline accuracy measures like precision, recall, RMSE and ranking performance. In addition to these technical aspects, Ricci et al. (2022) suggest that user-centred evaluation should be performed, and Fan et al. (2022) link trust, transparency, privacy and fairness to the perceived quality of recommendations. Thus, offline accuracy can be useful for technical comparison, but is not an exhaustive measure of tourist acceptance, trust or enjoyment of the recommendation.

Trust plays a particularly critical role in tourism as it is related to the cost, time, safety and emotional expectations of the decision. Reviews and ratings can boost trust by demonstrating that other visitors have had a good experience with the service or destination recommended (Chang et al., 2019). Explanation features are also able to help build trust by providing the reasons why an item was recommended and what data were used (Fan et al., 2022).

Based on the literature reviewed, satisfaction is a multi-dimensional phenomenon. In the literature on the evaluation of recommender systems and trustworthy-recommendation research, relevance, novelty, diversity, convenience, transparency, privacy, response time and trust are repeatedly associated with the quality of recommendations and user acceptance. Even a technically correct recommendation can be unsuccessful if it draws tourists to overcrowded destinations or to services that are inappropriate to their needs. Future research should therefore be based on algorithmic measurements as well as user studies and real tourism effects.

Also, destination-management effects should be taken into account in the evaluation. Recommendation systems can be problematic if they keep recommending the same popular destinations, thereby increasing their visibility while decreasing visibility of smaller local businesses. The sustainable tourism recommendation should thus take into account diversity, fairness and spatial distribution and not only the short-term click or booking likelihood (Rehman Khan et al., 2021). This is especially relevant in the context of rural and regional tourism, where recommendation systems can shape the distribution of visitors and the potential economic prospects.

Challenges and gaps for research

Real-world validation is an area of literature that is lacking. Many tourism recommender-system papers have been introduced that present architectures or frameworks, and few papers have tested systems with real tourists in real destination environments (Hamid et al., 2021; Rehman Khan et al., 2021; Silveira et al., 2019). This minimises the opportunity to connect algorithmic results to real satisfaction, trust and re-use. Field studies need to be reinforced, because the

behaviour of tourists is also affected by the limitations of the devices, the internet connection, the stress of travelling, the cultural expectations and the changing environmental conditions.

Other missing elements are transparency of the datasets used in tourism recommender-system studies. The literature reviewed is public and/or platform-visible review/social-media data, including TripAdvisor reviews, and location traces and destination-specific POI datasets that are not always reproducible (Chang et al., 2019; Missaoui et al., 2019; Massimo & Ricci, 2022). Public datasets can be used for comparison but may not reflect current platform behaviour or multilingual content or local destination diversity. Future research should give adequate detail of data sources, data pre-processing, access status, privacy protection and limitations.

Moreover, responsible AI is still poorly developed in many of the studies on tourism recommender systems (RS) which are based on profiles, location traces and social-media data. Recommendation systems can mimic popularity bias, exclude less popular destinations, or make recommendations based on sensitive behavioural signals. The use of location traces, social media posts or user profiles is a specific concern with regard to privacy (Fan et al., 2022). Thus, data governance, consent, bias mitigation and explainability should be considered as design issues in tourism research, and not as minor limitations.

Table 2

Main thematic findings from the systematic review (Author synthesis of reviewed literature)

Theme	Typical evidence in the literature	Implication for tourism recommenders
Hybrid methods	Combination of collaborative, content-based, knowledge-based, contextual and AI methods	Useful for complex tourism decisions where preferences, places and trip constraints interact
Social media data	Reviews, ratings, geotags, check-ins and user-generated content	Enriches destination profiles and supports trend-sensitive recommendations
Context awareness	Use of location, time, season, weather, mobility and trip purpose	Improves relevance when travel needs change during a trip
User satisfaction	Measured through usefulness, trust, intention to use and user feedback	Should be evaluated directly, not assumed from offline accuracy
Responsible AI	Privacy, bias, explainability, fairness and destination-management concerns	Prevents opaque or harmful recommendation practices

The last gap relates to the relationship between technical performance and tourism value. A recommender system can help to increase the accuracy of the ranking but not necessarily the quality of the travel experience. Future studies should focus on the following questions: Do recommendations save planning time? Do they facilitate informed decision-making? Do they enhance destination discovery, increase trust, decrease uncertainties, and distribute tourism benefits more fairly? Addressing these questions would render research on recommender systems more relevant for tourism managers, platform designers, and travellers.

Another drawback is that negative or mixed results are poorly reported. While there is a strong focus on the advantages of hybrid or AI-powered approaches, there is less attention on the situations where these techniques do not lead to better recommendation quality. This is important because more complex models can demand more data inputs, more calculations, and more personal data than simpler approaches (Fan et al., 2022). If results are limited or inconclusive, this will help researchers understand which tourism contexts require advanced AI and which can rely on simpler, more transparent recommendation logic.

Another real-life issue is infrastructure, cost and profit. A modern hybrid tourism recommender system must be interoperable with destination databases, mapping and booking APIs, cleaned review and social-media data, cloud or server capacity, model monitoring, privacy governance and staff to maintain the system. The profitability of such systems is likely to be achieved only if these costs are offset by measurable benefits like increased conversion, repeat use, better destination distribution, less planning effort, and greater user satisfaction (Hamid et al., 2021; Kontogianni & Alepis, 2020).

There is also a need for more interaction between computer scientists and scholars in the tourism field to benefit the literature. Technical studies can enhance modelling and evaluation parameters, and tourism studies can shed light on the motivation of visitors, carrying capacity of the destination, cultural interpretation and quality of service. Integrating these perspectives will enable future recommender systems to facilitate not only clicks or bookings, but also meaningful travel experiences and sustainable destination development (Rehman Khan et al., 2021).

Conclusions

1. AI-powered recommender systems are crucial in the tourism industry as they assist travellers in dealing with the overwhelming amount of information and discovering relevant destinations, services, and activities. The literature reviewed indicates that recommendations in tourism should take into consideration preference history, destination attributes, context, social influence and trust.

2. Hybrid methods are appropriate for tourism since they can incorporate collaborative filtering with content-based filtering, knowledge-based reasoning,

contextual information, and AI-based modelling. However, their value depends on the transparency of their design and evaluation, rather than simply claiming that multiple methods were used.

3. Social media data and user-generated content can enhance representation of destinations, awareness of trends and trust of users. These data sources should be treated with caution, as they could be noisy, subject to platform bias, privacy concerns, and/or unequal representation of destinations and/or travellers.

4. Technical accuracy is not the only indication of user satisfaction. The perceived usefulness, transparency, trust, diversity, convenience, timeliness and real user feedback are also important criteria to evaluate tourism recommender systems.

5. Clear review process, reproducible data, field-based evaluation, explainable recommendation design and privacy-aware data governance are the future research directions. This direction would enhance the technical aspects and the relevance to tourism of AI-based recommender systems.

6. Another finding of the systematic review is that future research should not only consider user-generated content as a mere technical input. Reviews, ratings and social posts are socially produced data, and their meaning is dependent on the design of the platform, user motivation, language, culture and the context of the destination. These data could be more rigorously analysed to provide more credible research into tourism recommendations and to minimise the potential for misleading or biased conclusions.

7. Future recommender systems should also consider particular preferences of the user and not just the general user rating behaviour or the general tourist type. What constitutes a useful recommendation can materially change depending on preferences such as relaxing in nature, walking, learning about local culture and traditions, visiting authentic rural places, supporting family businesses, and enjoying cuisine.

8. Lastly, the usefulness of AI-powered tourism recommender systems is contingent upon infrastructure, costs and profitability. Advanced AI is not necessarily justified and should be used only when the benefits of user satisfaction, destination-management value, and sustainable revenue outweigh the costs of data integration, maintenance, and privacy.

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FINANCIAL AND ECONOMIC IMPACT OF SOLE PROPRIETORS' ACTIVITIES ON THE DEVELOPMENT OF RURAL TERRITORIAL COMMUNITIES

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Abstract
The study examines the financial and economic impact of the activities of sole proprietors on the development of rural territorial communities in the context of the formation of local budget revenues. The research aims to assess the role of sole proprietors in strengthening the financial capacity of rural communities and stimulating local socio-economic development. The study is based on statistical, comparative and analytical methods. The empirical basis includes statistical data on the number of active sole proprietors, the structure of their economic activities and the volume of tax revenues to local budgets. The analysis focuses on rural territorial communities of Mykolaiv region, Ukraine. Surveys were conducted among the heads of 43 rural councils and 442 sole proprietors from 4 rural communities, representing approximately 30% of active entrepreneurs in the studied communities. The results show that sole proprietors play an important role in the formation of local budget revenues, job creation, the development of local markets for goods and services, and the provision of socially significant services to the population. However, several factors limit the full realisation of this potential. In particular, a mismatch between the place of tax registration and the actual place of business activity leads to disproportions in the distribution of tax revenues between communities. The study highlights the need to improve interaction between the entrepreneurial sector and local self-government authorities, strengthen information and advisory support for entrepreneurs, and expand their participation in public procurement and grant programmes in order to enhance the financial capacity and sustainable development of rural territorial communities.
Keywords: sole proprietors, taxation system, local budgets, rural territorial communities.

Introduction

Individual entrepreneurs represent an important component of the national economy, contributing to the satisfaction of social needs, the development of small businesses and the formation of budget revenues at different levels. In rural territorial communities, sole proprietors often constitute the foundation of local economic activity. Owing to relatively simple registration procedures and simplified regulatory requirements, this form of business organisation significantly stimulates entrepreneurial initiative, particularly in trade, transport and social services.

Entrepreneurship is widely recognised as a key driver of economic development, particularly in the context of rural areas, where it contributes to employment generation, income growth and the strengthening of local economies. In modern conditions, entrepreneurial activity is increasingly viewed as a crucial factor in ensuring sustainable development and economic resilience (Sadriddinovich, 2025; Pratama, 2023). At the same time, the role of taxation in shaping entrepreneurial activity has gained significant attention, as appropriate tax policy instruments can stimulate business development and reduce barriers to market entry (Boar & Knowles, 2024; Gordon & Sarada, 2018). In Ukraine, any citizen, who has reached the age of sixteen and has an officially registered place of residence, may register as an individual entrepreneur. In the context of decentralisation reforms and the expansion of fiscal autonomy of territorial communities, the role of local taxes and fees as a key source of local budget revenues has significantly increased. Among these sources, the single tax paid by entities operating under the simplified taxation system plays a particularly important role, especially for sole proprietors.

The simplified taxation system has become one of the main instruments supporting the development of small businesses while ensuring stable fiscal revenues for local budgets. At the same time, current socio-economic transformations, including the consequences of the full-scale war in Ukraine, demographic changes and structural shifts in the entrepreneurial environment, have intensified the need to reassess the role of individual entrepreneurs and the simplified taxation system in ensuring the financial sustainability of territorial communities.

This issue is particularly relevant for regions experiencing significant socio-economic challenges, such as Mykolaiv region, where the stability of the local economy largely depends on the development of small entrepreneurship and the stability of local budget revenues.

The aim of the study is to assess the financial and economic impact of the activities of sole proprietors on the development of rural territorial communities and to determine their role in strengthening the financial capacity and socio-economic resilience of local communities. To achieve this aim, the following research objectives were formulated: to analyse the role of sole proprietors and the simplified taxation system in the formation of local budget revenues; to assess the sectoral structure and dynamics of entrepreneurial activity in rural territorial communities of Mykolaiv region; to evaluate effects of sole proprietors' activities on local community development; to identify key challenges limiting the effective functioning of sole proprietors; to develop practical recommendations aimed at enhancing the financial capacity of rural territorial communities.

Materials and Methods

The research is based on a combination of general scientific, statistical and specialised economic

methods applied to assess the financial and economic impact of the activities of sole proprietors on the development of rural territorial communities.

The empirical basis of the study consists of statistical data on the number of active sole proprietors, the structure of their economic activities, and the volume of tax revenues received by local budgets. The analysis was conducted using data from official sources and open data related to the formation of the revenue side of local budgets of territorial communities (State Tax Service of Ukraine; Opendatabot; Clarity Project). The study focuses primarily on rural territorial communities of Mykolaiv region and on indicators characterising the contribution of sole proprietors to the formation of local budget revenues and the development of the entrepreneurial environment.

In the course of the research, methods of analysis and synthesis were applied to reveal the economic essence of entrepreneurial activity carried out by sole proprietors and to determine its role in the development of the local economy. The comparative method was used to examine the specific features of the simplified and general taxation systems and to assess their influence on the formation of tax revenues at the local level. Statistical and analytical methods were employed to analyse the number of sole proprietors, the structure of their activities, the dynamics of tax payments and selected indicators of entrepreneurial activity within the communities.

To assess the impact of sole proprietors' activities on the development of rural communities, the grouping method was applied. Using this approach, 43 territorial communities of Mykolaiv region were divided into three groups according to indicators such as the number of sole proprietors, the area of the community and the size of the population. One community from each group was selected for further detailed analysis, which made it possible to conduct an in-depth examination and calculate a system of indicators characterising entrepreneurial activity and the financial and economic impact of sole proprietors on local development.

To generalise the role of sole proprietors in community development, the approach of socio-economic profiling of entrepreneurial activity was applied. This approach made it possible to assess the contribution of sole proprietors to the formation of budget revenues, employment of the population, development of the local market for goods and services, participation in public procurement procedures and the implementation of socially significant functions within the community. The application of elements of the multiplicative effect assessment of small business activity enabled the identification not only of the direct fiscal impact of sole proprietors' activities but also of their indirect effects through job creation, support of local demand, participation in reconstruction processes and the provision of goods and services to the population. The methods of grouping and classification were also used to systematise the types of economic activities carried out by sole proprietors and to identify those sectors in which they provide socially important services to the population.

To identify the practical aspects of interaction between entrepreneurs and local self-government authorities, a sociological survey method was applied. In particular, a survey of the heads of 43 rural councils in Mykolaiv region was conducted in order to assess the effectiveness of sole proprietors' activities, their role in the socio-economic development of communities and the existing challenges in the field of local economic development.

In addition, within the framework of the public initiative 'FOP from Zero', a survey of sole proprietors was conducted in four rural councils of Voznesensk district of Mykolaiv region. The survey covered 442 respondents, representing approximately 30% of the active sole proprietors in the respective communities. The results of the survey were used to evaluate the level of awareness among entrepreneurs regarding local budgets, public procurement procedures, grant programmes, community initiatives and the issue of conducting business activities outside the community where the entrepreneur is officially registered.

The method of logical generalisation was applied to formulate conclusions regarding the socio-economic consequences of the activities of sole proprietors for the development of rural territorial communities. It was also used to substantiate practical recommendations aimed at strengthening the financial capacity of communities, stimulating entrepreneurial activity, expanding the participation of sole proprietors in public procurement and grant programmes, and improving interaction between the entrepreneurial sector and local self-government authorities.

Results and Discussion

The development of entrepreneurship, particularly in rural areas, depends on a combination of economic, institutional and regulatory factors. A number of studies emphasise the importance of creating favourable conditions for business activity, including access to financial resources, effective taxation systems and institutional support mechanisms (Irmeja & Leibus, 2025; Sproģe et al., 2024).

Individual entrepreneurs constitute one of the most widespread forms of business organisation in Ukraine. This form allows individuals to engage in entrepreneurial activities, create jobs and generate income with their intellectual and physical labour.

Both individual entrepreneurs and legal entities that meet specific criteria regarding income levels, the number of employees and the types of economic activity apply the simplified taxation system. Compared to the general taxation system, the simplified system provides reduced tax rates, simplified accounting procedures and less complicated reporting requirements. Consequently, it is particularly attractive for small and medium-sized businesses.

As of 2026, there are approximately 2.1 million sole

proprietors registered in Ukraine, which is six thousand more than at the end of 2025. Overall, during the four years of the full-scale war, the number of sole proprietors has increased by approximately 194 thousand. However, the growth rate has gradually slowed. The largest increase was observed in 2023, when the number of entrepreneurs grew by more than 5%. In 2024, the growth rate decreased to 3.5%, and in 2025 it dropped to only 0.39%.

The functioning of territorial communities largely depends on the stability of local budget revenues. In this context, the single tax paid by entrepreneurs operating under the simplified taxation system is one of the most significant sources of financial resources for local budgets.

In 2025, Ukrainian sole proprietors paid UAH 59.89 billion in single tax, which is 9% more than in 2024. Approximately 80% of this amount was paid by entrepreneurs of the third tax group, amounting to UAH 47.84 billion.

The situation in Mykolaiv region clearly illustrates the fiscal importance of this tax. During January-December 2025, local budgets of Mykolaiv region received UAH 1.9 billion in single tax revenues, which is 14.5% more than in 2024. The share of the single tax in total local budget revenues amounted to 16.3%.

Individual entrepreneurs operating under the simplified taxation system paid most of these funds. In particular, sole proprietors contributed approximately UAH 1.2 billion.

Thus, the single tax represents a stable financial source that enables territorial communities to finance social infrastructure, education, healthcare and other socially significant areas.

According to the Tax Code of Ukraine (Verkhovna Rada of Ukraine, 2010), the simplified taxation system in Ukraine is based on the division of taxpayers into several groups depending on income levels, types of activity and the number of employees.

Income limits for entrepreneurs are determined according to the minimum wage established on 1 January of the respective year and remain unchanged during the year: Group 1 - 167 minimum wages; Group 2 - 834 minimum wages; Group 3 - 1167 minimum wages.

Exceeding these limits may lead to the application of higher tax rates, mandatory transfer to another tax group or transition to the general taxation system.

For entrepreneurs belonging to the first and second groups, the single tax rate is fixed and does not depend on the actual income received. This allows entrepreneurs to easily predict their tax burden during the year.

According to the Tax Code of Ukraine, the maximum tax rates are determined as follows:

- Group 1 - up to 10% of the subsistence minimum;
- Group 2 - up to 20% of the minimum wage.

Local authorities determine the exact rates within these limits depending on the type of economic activity.

In 2026, the unified social contribution (USC) for entrepreneurs is set at 22% of the minimum wage. When entrepreneurs employ hired workers, they act as tax agents and must pay additional payroll taxes, including personal income tax (18%), the military levy (5%), and the unified social contribution (22%).

Table 1 presents a comparative overview of the main characteristics of the simplified taxation system for sole proprietors in Ukraine.

In addition, research highlights that public policy instruments, including taxation and state support measures, which determine incentives for business creation and expansion (Gordon & Sarada, 2018; Pratama, 2023), significantly influence the effectiveness of entrepreneurial activity.

The financial and economic impact of sole proprietors on the development of rural territorial communities is manifested through several key dimensions that determine the scale and structure of their contribution to local socio-economic development. Based on the results of the conducted research, the following main directions of influence can be distinguished: fiscal impact; impact on the quality of life and employment of the population; impact on the development of the local economy and entrepreneurial environment; impact on public procurement procedures; influence on social responsibility and civic engagement; and image-building and crisis-response functions.

The fiscal impact is primarily reflected in the contribution of sole proprietors to local budget revenues. The amounts of the single tax paid to local budgets represent an indicator of the economic capacity of a community and its support for small businesses. These financial resources are directed towards meeting the socio-economic needs of residents, including expenditures on education, healthcare, municipal infrastructure, public lighting, civil protection shelters and social programmes. In communities with relatively small population and territory, sole proprietors often form the foundation of stable budget revenues.

In this context, the role of self-employment and small-scale entrepreneurship becomes particularly important for rural development. In many countries, self-employed individuals constitute a significant share of the workforce and make an important contribution to the functioning of rural economies. For instance, within the European Union self-employment represents a considerable proportion of total employment, with a particularly strong presence in rural areas where economic opportunities are more limited and labour markets are less diversified (Irmeja & Leibus, 2025). Self-employed individuals often operate in sectors such as agriculture, tourism, crafts and local services, thereby contributing to the diversification of rural economies and the development of local markets.

Researchers emphasise that self-employment performs several important socio-economic functions in rural

areas. In addition to creating employment opportunities, self-employed individuals contribute to the provision of
essential services to rural residents and support the circulation of financial resources within local communities. Such activities strengthen local economic systems and reduce dependence on urban labour markets. Consequently, the development of self-employment is increasingly considered an important mechanism for supporting sustainable rural development and regional resilience.

Table 1
Key characteristics of the simplified taxation system for Groups 1–3 of sole proprietors as of 2026

Criterion	Group 1	Group 2	Group 3
Types of activities	Retail sale of goods at market stalls; household services to the population	Production and sale of goods; restaurant activities; services provided to the population and single-tax payers	All types of activities except those restricted by Article 291.5 of the Tax Code
Criterion	Group 1	Group 2	Group 3
Annual income limit	UAH 1,444,049 (167 minimum wages)	UAH 7,211,598 (834 minimum wages)	UAH 10,091,049 (1,167 minimum wages)
Number of employees	Not allowed	Up to 10 employees	No limit
Single tax rate	UAH 332.80 per month (up to 10% of subsistence minimum)	UAH 1,729.40 per month (up to 20% of minimum wage)	5% of income (without VAT) or 3% of income (with VAT)
Military levy	UAH 864.70 per month (10% of minimum wage)	UAH 864.70 per month (10% of minimum wage)	1% of income
Unified Social Contribution (USC)	UAH 1,902.34 per month	UAH 1,902.34 per month	UAH 1,902.34 per month
Reporting frequency	Annual declaration	Annual declaration	Quarterly declaration
Typical use	Small-scale businesses without employees and low income	Service sector, retail trade, restaurants	Businesses working with larger clients, international trade, higher turnover

Sole proprietors also play an important role in ensuring employment within territorial communities. According to available statistical data, the number of sole proprietors of Ukraine employing hired workers reached 259,976 in 2025, providing employment for more than 673 thousand employees. Although the number of workers employed by sole proprietors declined during the first years of the full-scale war, a gradual recovery has been observed in recent years, highlighting the stabilising role of small businesses in the labour market and their contribution to economic recovery.

The activities of sole proprietors stimulate the development of trade, services, processing industries, agribusiness and transport, ensuring that financial flows remain within the community. Through their activities, residents gain access to goods and services locally, which is particularly important for small rural communities where alternative economic infrastructure may be limited.

Another important aspect is the participation of entrepreneurs in public procurement procedures. The role of public procurement and interaction with local authorities is increasingly recognised as a significant factor influencing the effectiveness of entrepreneurial activity at the local level (Cheban et al., 2025). In rural communities of Ukraine, up to 18% of sole proprietors participate in public procurement, while in sectors such as food supply, repair services and transport their share in procurement contracts reached 38% in 2025. This contributes to faster provision of goods and services for community needs and ensures that public funds remain within the local economy.

In addition to their economic contribution, sole proprietors demonstrate high levels of adaptability to changes in the economic environment, taxation policies and social conditions. Many entrepreneurs actively introduce new service formats, digital solutions, delivery services and online platforms. Such activities perform an important image-building and crisis-response function for local communities.

Moreover, more than 50% of active sole proprietors support the Armed Forces of Ukraine, assist schools, hospitals and kindergartens, and participate in local community initiatives. Entrepreneurs frequently contribute to community improvement projects, the organisation of public events and social initiatives, thereby strengthening social cohesion and civic engagement.

Thus, sole proprietors should be regarded not only as taxpayers but also as active actors in the socio-economic development of territorial communities. They contribute to the formation of local budget revenues, create employment opportunities, ensure the availability of goods and services, participate in public procurement and contribute to improving the quality of

life of the population. In this sense, sole proprietors act as a multiplier of local development, combining fiscal, economic, social and infrastructural functions that collectively contribute to strengthening the financial capacity and sustainable development of territorial communities.

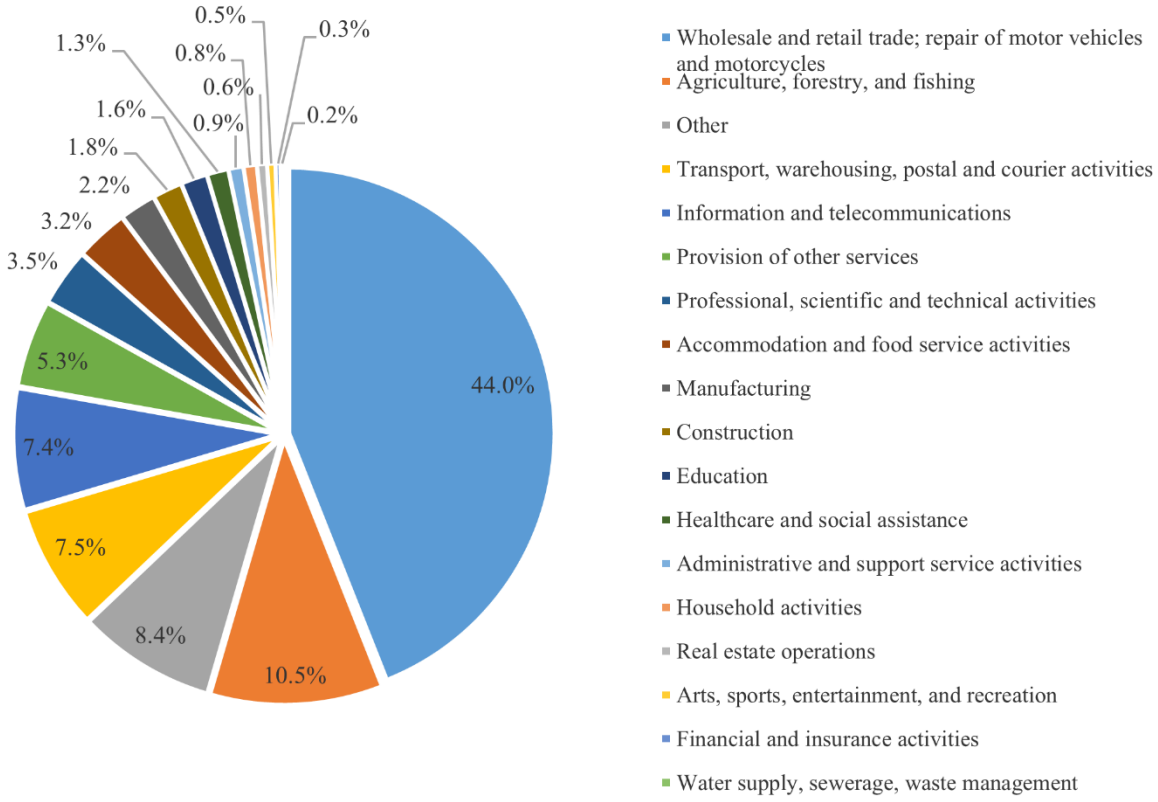
However, the extent to which this potential is realised in practice largely depends on regional conditions for conducting business activities, the specific characteristics of local economies and the effectiveness of cooperation between entrepreneurs and local self-government authorities. For this reason, rural communities of Mykolaiv region were selected for an in-depth analysis.

The selection of this region is explained by its strong agricultural orientation, the significant role of small entrepreneurship in providing goods and services to the population and the considerable impact of wartime and socio-economic challenges on local economic development. The research was also supported by the scientific and practical activities of Mykolaiv National Agrarian University, which actively cooperates with territorial communities in matters related to entrepreneurship development, strengthening the financial capacity of communities and implementing educational and advisory initiatives.

Analysis of the distribution of sole proprietors across sectors in rural territorial communities for the period 2024–2026 demonstrates a concentration of entrepreneurial activity in several key areas (Figure 1).

Figure 1

Distribution of Sole Proprietors in Rural Territorial Communities of Mykolaiv region, Ukraine by Economic Activity, 2024–2026



The largest share of entrepreneurs, approximately 44%, operate in wholesale and retail trade, as well as in the repair of motor vehicles and motorcycles. This is followed by agricultural, forestry, and fishing activities, which account for 10.5% of all sole proprietors, reflecting the traditional economic base of rural communities. Transport, warehousing, postal, and courier services comprise 7.5% of entrepreneurs, while information and telecommunications services account for 7.4%. Other services, including professional, scientific, and technical activities, collectively represent smaller proportions ranging from 0.3% to 5.3% of all rural sole proprietors.

The distribution indicates that rural entrepreneurship in Ukraine is heavily oriented towards trade, services, and agriculture, which are sectors that generate frequent cash flows and directly contribute to local economic activity. The predominance of trade- and service-oriented sole proprietors supports the formation of a stable tax base through single tax payments, thereby enhancing the fiscal capacity of local communities. Meanwhile, the presence of entrepreneurs in agriculture, transport, and other sectors diversifies the local economy and contributes to employment generation, including seasonal and part-time positions.

These findings are consistent with previous research highlighting that small businesses and individual entrepreneurs play a crucial role in sustaining local economies, providing employment opportunities, and forming an essential component of local budgets (Sadriddinovich, 2025). Moreover, the sectoral structure of rural entrepreneurship reflects the importance of aligning tax policies and simplified taxation incentives with the economic characteristics of each community. Such alignment is particularly relevant in regions facing high socio-economic vulnerability, where sole proprietors serve as a primary driver of local revenue generation and community resilience.

For the purpose of conducting a comparative analysis of the entrepreneurial activity of sole proprietors in rural territorial communities, the grouping method was applied. According to this approach, 43 communities of Mykolaiv region were divided into three groups based on the number of sole proprietors, territorial area and population size. One representative community was selected from each group, which made it possible to conduct an in-depth analysis and calculate a system of indicators characterising the level of entrepreneurial activity and the financial and economic impact of sole proprietors (Table 2).

Table 2

Characteristics of entrepreneurial activity and the financial and economic impact of sole proprietors in selected rural territorial communities of Mykolaiv region in 2025

Indicator	Veselynove community	Ochakiv community	Nechaiane community
Number of sole proprietors	705	458	116
Area of the community, km²	432.0	295.0	203.8
Level of entrepreneurial activity (number of sole proprietors per 1,000 inhabitants)	47	38	110
Territorial concentration of business (number of sole proprietors per 1 km²)	2	2	1
Coefficient of entrepreneurial renewal (ratio of newly registered sole proprietors to the total number)	0.133	0.183	0.189
Coefficient of entrepreneurial growth (ratio of the difference between newly registered and closed sole proprietors to their total number)	0.016	-0.024	0.009
Share of sole proprietors among participants in public procurement, %	5.9	7.3	3.2
Number of sole proprietors receiving grant support / volume of support, thousand UAH	2 / 620	3 / 840	0
Share of sole proprietors in the formation of local budget revenues, %	17.3	18.1	23.7

The results of the analysis indicate that sole proprietors play a significant role in strengthening the financial capacity of rural territorial communities, ensuring a substantial share of local budget revenues, which ranges from 17.3% to 23.7% in the analysed communities and may reach up to 30% in certain communities of Mykolaiv region.

The highest level of entrepreneurial activity, along with the greatest dependence of the local budget on the activities of sole proprietors, is observed in Nechaiane community, which demonstrates the crucial role of small business in ensuring its economic resilience. In Veselynove community, a relatively stable trend in entrepreneurial development is observed, whereas Ochakiv community shows a negative dynamic (negative growth coefficient), primarily due to the significant destruction experienced over the past four years of martial law.

The level of participation of sole proprietors in public procurement and their involvement in grant funding remains relatively low, which limits their potential contribution to local economic development.

Overall, the activities of sole proprietors constitute a key factor in community economic development, as they ensure not only tax revenues but also support recovery processes. The findings confirm that the financial and economic impact of sole proprietors is complex and manifests through a combination of fiscal, economic and social effects; however, the level of its realisation largely depends on local business conditions and the effectiveness of interaction between entrepreneurs and local self-government authorities.

The findings of this study are consistent with previous research emphasising the importance of institutional support, regulatory frameworks and public policy measures in fostering entrepreneurial activity and enhancing local economic development (Irmeja & Leibus, 2025; Sproģe et al., 2024).

In order to identify practical aspects of the impact of entrepreneurial activity on territorial development, the authors conducted a survey among 43 heads of rural councils in Mykolaiv region regarding the effectiveness of sole proprietors' activities and their role in community development.

The results showed that despite the significant contribution of sole proprietors to local development, several challenges limit the full realisation of their potential. The most significant issue identified by respondents was the mismatch between the place of tax registration and the actual place of business activity. As a result, part of the tax revenues is transferred to the budgets of other communities rather than to those where economic activity actually takes place. And vice versa. The community receives budget replenishment, but remains without necessary goods and services, which reduces the level of social security of the population. Another issue highlighted by respondents concerns the need to stimulate entrepreneurial activity and improve the development of entrepreneurial infrastructure. It was also noted that limited knowledge and experience prevent entrepreneurs from actively participating in public procurement procedures, while insufficient information and practical guidance restrict their ability to apply for grant funding.

In addition to the survey of local authorities, the authors participated in the public initiative 'FOP from Zero' and conducted a survey of entrepreneurs in four rural councils of Voznesensk district of Mykolaiv region.

The survey was carried out between February and May 2025 and covered 30% of active entrepreneurs, 442 sole proprietors participated in the survey.

The results revealed several important trends: 28% conduct their business activities in other communities; 51% do not possess sufficient information about the formation and use of local budget funds; 72% expressed interest in participating in grant programmes but lack experience and knowledge of application procedures; 57% are not aware of existing regional initiatives aimed at supporting entrepreneurs and territorial community development.

These findings indicate the existence of a significant information gap between the entrepreneurial sector and local self-government institutions, which limits the effective use of financial instruments for business development and reduces the potential contribution of entrepreneurs to the socio-economic development of territorial communities.

Taking into account the results of the authors' empirical research; the experience of Voznesensk City Council, which introduced advisory positions supporting small and medium-sized businesses; the results of surveys among rural council heads and entrepreneurs, a set of practical measures aimed at strengthening the financial and economic impact of sole proprietors on community development was developed.

The implementation of these measures will contribute to improving cooperation between entrepreneurs and local authorities, expanding opportunities for attracting financial resources for business development and strengthening the financial capacity of territorial communities.

Table 3

Policy measures for enhancing the financial and economic impact of sole proprietors on the development of rural territorial communities in Mykolaiv region, Ukraine

Policy area	Mechanisms of implementation	Expected outcomes
Enhancing financial awareness of sole proprietors	Organisation of training events, seminars and public presentations on local budget formation, participation in public procurement	Increased transparency of budget processes and improved trust
Developing information and advisory support systems	Establishment of business support advisory centres within local authorities; dissemination of information on development opportunities	Increased entrepreneurial activity and improved efficiency of business
Facilitating participation in grant programmes	Provision of training on grant application procedures; dissemination of information on national and international funding programmes	Increased access to external financial resources for business development
Formation of institutions for interaction with the authorities	Organisation of regular meetings, forums and consultation platforms for dialogue between business and local authorities	Strengthened partnerships and improved coordination of local economic development
Promoting civic and business engagement	Informing entrepreneurs about the activities of NGOs, business associations and entrepreneurship support initiatives	Increased involvement of entrepreneurs in community development processes
Stimulating place-based business registration	Creation of favourable business conditions, infrastructure development and incentives for conducting business within the community	Increased local tax revenues and strengthened economic capacity of the community
Policy area	Mechanisms of implementation	Expected outcomes
Improving local tax policy instruments	Introduction of preferential single tax rates for selected types of activities and informing on the benefits of local business registration	Legalisation of economic activity and expansion of employment
Digitalisation of interaction between entrepreneurs and local authorities	Development of digital platforms for communication, access to services, grant information and public procurement opportunities	Reduced administrative barriers, improved access to information and increased efficiency of interaction

These proposed measures are summarised in Table 3. The proposed recommendations were submitted to the heads of rural councils in Mykolaiv region for consideration and possible implementation. The recommendations were accompanied by links to practical resources, including examples of best practices from Voznesensk City Council, databases of grant programmes and contacts of academic staff and student initiatives of Mykolaiv National Agrarian University.

The practical contribution of the authors also includes participation in the creation of open information resources for entrepreneurs, the development of an electronic platform for interaction between entrepreneurs and local authorities and the organisation of consultations aimed at improving the financial literacy of entrepreneurs, particularly in relation to local budgets and public procurement procedures.

Conclusions

1. The study confirms that sole proprietors constitute a significant factor in the socio-economic development of rural territorial communities, ensuring a substantial share of local budget revenues and contributing to employment and the provision of essential services.
2. It has been established that the financial and economic impact of sole proprietors is multidimensional and manifests through fiscal, economic and social effects, including the formation of local budget revenues, development of local markets and strengthening of community resilience.
3. The results of the empirical analysis reveal considerable differentiation in the level of entrepreneurial activity across the analysed communities, which is determined by local economic conditions, demographic characteristics and external challenges.
4. The study identifies key constraints that limit the full realisation of the potential of sole proprietors, in particular the mismatch between the place of tax registration and the actual place of business activity, as well as the low level of participation in public procurement and grant programmes.
5. The proposed system of measures aimed at enhancing interaction between entrepreneurs and local self-government authorities, strengthening information and advisory support, and expanding access to financial resources can contribute to increasing the financial capacity and ensuring the sustainable development of rural territorial communities.

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ADAPTIVE GOVERNANCE MODELS FOR RURAL DEVELOPMENT IN SOUTHERN UKRAINE DURING POST-WAR RECOVERY

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Abstract
The article examines the formation of adaptive governance models for rural development in southern Ukraine in the context of post-crisis and post-war recovery. The study aims to identify the key socio-economic factors, institutional mechanisms and governance instruments influencing the adaptive capacity of territorial communities, and to develop an indicator framework for assessing the effectiveness of local development management. The methodological approach combines qualitative and quantitative methods, including benchmarking, stakeholder analysis, expert assessment and multi-criteria analysis. The empirical basis of the research comprises 4 territorial communities of southern Ukraine: Kutsurubska, Kostiantynivska, Voznesenska and Shevchenkivska – which differ in terms of economic structure, financial capacity and levels of entrepreneurial activity. The analysis reveals a significant differentiation in the socio-economic potential of these communities. Communities characterised by a more diversified economic structure and a higher density of entrepreneurship demonstrate greater financial capacity and a higher level of resilience to socio-economic challenges. The multi-criteria assessment identifies key constraints on territorial development, including infrastructure damage, limited accessibility of basic public services, strong dependence of local economies on the agricultural sector, population decline, and institutional coordination challenges among development actors. These factors significantly influence the ability of communities to respond to socio-economic changes. The study proposes a framework system of adaptive governance indicators integrating economic, infrastructural and institutional dimensions. The proposed indicator system may serve as an analytical tool for monitoring local development policies, evaluating management effectiveness and supporting evidence-based decision-making in the process of rural recovery and long-term territorial development.
Keywords: adaptive governance, rural development, territorial communities, local self-government, post-war recovery.

Introduction

Rural areas play a crucial role in economic stability, food security and social cohesion in Ukraine, but structural transformations, demographic shifts and institutional pressures significantly complicate their development.

The decentralisation reforms in Ukraine have significantly expanded the powers of territorial communities and transformed approaches to local development policy. Greater financial autonomy has created new opportunities for strategic planning and the implementation of territorial development programmes. Previous studies emphasise that rural development largely depends on the ability of local institutions to establish effective governance mechanisms and coordinate the use of resources (Davydenko et al., 2022). These transformations stimulate the search for governance models capable of combining long-term strategic planning with adaptation to rapidly changing socio-economic conditions.

Governance challenges intensify during post-war recovery due to infrastructure damage, disrupted logistics and limited financial resources, requiring local authorities to simultaneously restore services and support economic stability.

In international academic discourse, increasing attention is being paid to the concept of adaptive governance as the capacity of governance systems to respond to uncertainty, risks and dynamic socio-economic changes. Research demonstrates that such models combine strategic planning with the continuous adjustment of management decisions (Manevska-Tasevska et al., 2021), thereby strengthening institutional resilience and improving coordination across different levels of governance. The experience of European Union countries confirms the growing importance of multi-level governance and partnerships between the state, business and civil society (Pollermann et al., 2020).

Ukrainian scholars also emphasise the transformation of public governance systems in the context of contemporary challenges, particularly the adaptation of local self-government to the conditions of martial law and the dependence of post-war recovery effectiveness on the quality of public administration (Kruglashov & Shvydiuk, 2025; Fedyk S. & Fedyk O., 2024). At the same time, it is highlighted that the effectiveness of territorial development is determined by the ability of public authorities to implement integrated policies that combine economic, social and institutional dimensions (Borshchevskyi et al., 2024), as well as to modernise governance mechanisms and develop cooperation between authorities, businesses and local communities (Nazaruk & Rud, 2025).

The southern regions of Ukraine are characterised by specific socio-economic conditions, particularly agrarian specialisation and the dependence of economic activity on the state of engineering and transport infrastructure, which necessitates the development of effective governance models capable of aligning strategic development priorities with the use of community resources.

Despite the growing academic interest in rural development, the formation of adaptive governance models in the context of post-crisis and post-war recovery remains insufficiently explored, while existing approaches rarely combine the analysis of socio-economic characteristics of communities with the assessment of governance institutions and

indicator-based methods for evaluating their adaptability.

Therefore, this study aims to substantiate approaches to the formation of adaptive governance models for rural development in southern Ukraine during the post-crisis recovery period. The study focuses on the socio-economic characteristics of territorial communities, stakeholder interaction, key development challenges and the development of an indicator-based framework for assessing governance adaptability.

Materials and Methods

The methodological framework of the study is based on a combination of qualitative and quantitative approaches to the analysis of rural development, ensuring both the depth of institutional interpretation and the reliability of empirical results. The research design integrates comparative analysis, institutional mapping, expert assessment and multi-criteria analysis (MCDA), which together form a coherent methodological basis for obtaining and validating research findings.

The empirical basis of the study comprises four territorial communities in southern Ukraine – Kutsurubska, Kostiantynivska, Voznesenska and Shevchenkivska – selected as representative cases of agrarian-oriented territories affected to varying degrees by hostilities. The selection of communities was based on three criteria: rural socio-economic profile, exposure to war-related disruptions, and differences in financial capacity and entrepreneurial structure**.** The study employed a staged analytical procedure combining statistical, expert and institutional analysis. This approach ensures methodological validity and enables the identification of key development challenges and the evaluation of governance effectiveness.

In the first stage, socio-economic characteristics were assessed using an indicator-based approach, including budget revenues per capita, the structure of entrepreneurship and the density of economic activity. The data were collected from open analytical sources (Clarity Project, statistical materials and community budgets) and used for comparative analysis of economic capacity and the level of diversification of the studied territories.

In the second stage, stakeholder analysis was conducted to identify key actors involved in rural development governance and to evaluate their influence on decision-making processes. The empirical results of this stage were obtained through expert assessment. A total of 12 experts participated in the study, including representatives of local self-government bodies, regional development specialists and academic researchers in the field of public administration and rural development. The expert survey was conducted during September–November 2025 using a structured questionnaire. Five stakeholder groups were evaluated: local self-government bodies, agricultural enterprises, non-agricultural business entities, civil society organisations, and regional or donor institutions. Experts assessed their relative influence on managerial decision-making using a five-point scale, where 1 indicated very low influence and 5 indicated very high influence. The final scores were calculated as average values followed by normalisation to ensure comparability between groups**.** This procedure increased the objectivity and reproducibility of the obtained results.

In the third stage, the identification and evaluation of key development challenges were carried out using MCDA. Five groups of constraints were assessed: infrastructure damage, dependence on agricultural production, limited entrepreneurial diversification, demographic decline, and institutional coordination problems. Each factor was evaluated according to three criteria: scale of impact, duration of influence and managerial response capacity, using a five-point scale where higher values indicated stronger significance.

The selected criteria reflect key dimensions of territorial development constraints within the adaptive governance framework. The scale of impact captures the extent of influence on local development, the duration reflects the temporal persistence of challenges, and managerial response capacity indicates the ability of local authorities to address them.

The integral significance index was calculated as the arithmetic mean of the three criteria. Equal weights were assigned to each criterion, reflecting their assumed equal importance and ensuring methodological neutrality in the absence of a justified basis for prioritisation.

This approach enabled the ranking of territorial constraints and provided a transparent and reproducible basis for interpreting the results. This methodological approach ensures the consistency between the evaluation procedure and the subsequent interpretation of results presented in the study.

In the fourth stage, the level of adaptability of the territorial governance system was assessed using a system of adaptive management indicators. These included the availability of public services, infrastructure recovery capacity, economic sustainability and the level of coordination of managerial decisions. The evaluation combined quantitative data with the qualitative analysis of strategic documents and community development programmes, which enabled the identification of gaps between declared strategic objectives and their actual implementation.

The findings should be interpreted with certain limitations, including the relatively small number of case studies and the partial reliance on expert judgement. At the same time, the application of methodological triangulation enhances the reliability of the results and provides a comprehensive understanding of rural development governance in the context of post-war recovery.

Results and Discussion

Socio-economic characteristics determine the resource base and development capacity of territorial communities (Borshchevskyi et al., 2024). The analysis of these characteristics makes it possible to assess the resource base of local development and determine the level of economic diversification of territories.

The empirical analysis covers the Kutsurubska, Kostiantynivska, Voznesenska and Shevchenkivska territorial communities of southern Ukraine and allows a comparative assessment of their economic structure and development diversification. All four communities were significantly affected by hostilities in 2022, which caused infrastructure damage and disrupted economic ties. The Kutsurubska community remains the most vulnerable due to recurring infrastructure destruction, which complicates local economic recovery.

The economic structure of most studied communities is dominated by the agricultural sector, which increases their dependence on agricultural production and seasonal fluctuations. The Voznesenska community demonstrates a more diversified economy, with developed trade, transport and service sectors, which expand its tax base and financial capacity.

Key indicators of economic activity and financial capacity are presented in Table 1.

Table 1

Comparative Analysis of Socio-Economic Capacity of Selected Territorial Communities of Southern Ukraine (based on Clarity Project, 2026; Decentralization Portal, 2026)

Territorial community	Budget for 1 resident, UAH	Share of agricultural sector enterprises, %	Density of entrepreneurial activity (per 1000 inhabitants)	Main directions of economic activity
Kutsurubska	11,200	72	26	Agricultural production, agricultural services
Kostiantynivska	12,500	65	27	Agricultural production, processing activities
Voznesenska	16,800	38	34	Industry, transport, trade, services, agricultural production
Shevchenkivska	10,600	69	23	Agricultural production, trade, small business

A comparative analysis of the indicators presented in Table 1 demonstrates a significant differentiation in the socio-economic potential of territorial communities. The highest levels of budget revenues per capita and the density of entrepreneurial activity are observed in the Voznesenska community, reflecting a more diversified economic structure, whereas in the Kutsurubska, Kostiantynivska and Shevchenkivska communities, agrarian specialisation prevails, making them more dependent on the dynamics of agricultural production. At the same time, such communities play an important role in ensuring food security, while the combination of agricultural orientation and limited diversification necessitates the application of more flexible approaches to territorial development governance.

The results of the analysis indicate that differences in financial capacity, economic structure and levels of entrepreneurial activity create varying preconditions for the implementation of local development policy, while economic indicators only partially reflect the characteristics of the governance system. Contemporary studies emphasise the decisive role of effective interaction between public authorities, business and civil society in ensuring the effectiveness of territorial development policy (Borshchevskyi et al., 2024).

The system of territorial community development governance is formed through the interaction of key stakeholders, with local self-government bodies playing a leading role by ensuring strategic planning, management of budget resources and coordination of development programmes in cooperation with business, non-governmental organisations, regional authorities and international support programmes. Expanding stakeholder participation in decision-making processes enhances governance effectiveness and promotes a more coordinated use of resources (Davydenko et al., 2022), while the development of inclusive institutions facilitates broader engagement of local actors and prevents practices that may constrain the potential of rural areas (Zawojska & Siudek, 2025).

Agricultural enterprises play a key role in shaping local economic activity, employment and budget revenues. In addition to the economic function, agricultural enterprises often participate in the implementation of social and infrastructure projects, forming partnership models of interaction between business and local governments. Similar forms of cooperation are considered in scientific literature as an important element of modern systems of multi-level governance (Pollermann et al., 2020).

Public organisations and local initiative groups enhance inclusiveness in community development processes. Active interaction between local authorities and civil society contributes to the formation of more inclusive mechanisms for managerial decision-making (Storonyanska et al., 2022).

A supporting function in the community development

management system is also performed by regional authorities and international donor programmes, whose participation is related to the attraction of financial resources, the implementation of technical assistance programs, and the strengthening of the institutional capacity of communities (OECD, 2022).

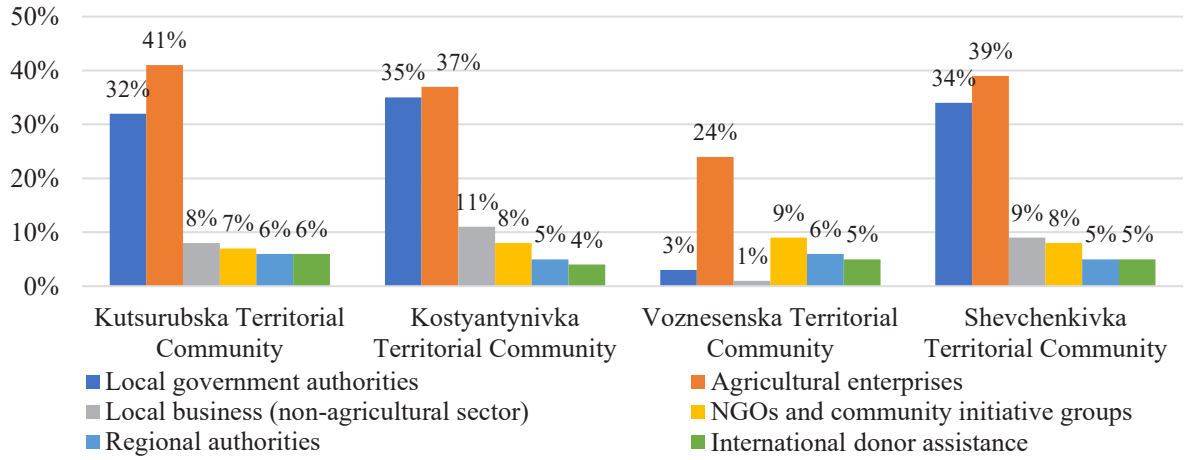
Using an expert assessment method, the relative importance of different groups of actors in the processes of managerial decision-making within territorial communities was determined. Experts assessed the level of influence of each stakeholder group on managerial decision-making at the local level. The obtained assessments were generalised through the calculation of average values and the subsequent normalisation of the results.

The results of the expert assessment made it possible to determine the institutional structure of management of the development of the studied territorial communities and to compare the ratio of influence of different groups of actors in the processes of managerial decision-making.

The comparative structure of the influence of key stakeholders in the community development management system is presented in Figure 1.

Figure 1

Stakeholder influence on local development decision-making in selected territorial communities of Southern Ukraine (based on expert assessment)



The results confirm the dominant role of local authorities and agricultural enterprises in decision-making processes. Such a distribution of influence is due to the significant role of agricultural production in the formation of economic activity of territories, ensuring employment of the population and the formation of the revenue side of local budgets. At the same time, in the Voznesenska Community, there is a more tangible influence of non-agricultural business entities, which reflects a more diversified structure of the local economy.

Other groups of stakeholders, including civil society organisations, regional authorities and international support programs, perform an auxiliary function in the management system of territorial development. Their participation contributes to attracting additional financial and institutional resources and strengthening the managerial capacity of communities. At the same time, the effectiveness of territorial development policy directly depends on the inclusiveness of governance models and the active involvement of local actors. This approach is fully consistent with the principles of the European initiative LEADER, which is based on the bottom-up approach and the activities of local action groups (LAGs). The experience of EU countries, in particular France, Germany and Italy, confirms the effectiveness of the LEADER program in ensuring territorial resilience (Pollermann et al., 2020), which correlates with our data on higher community adaptability under the condition of systemic coordination between local authorities and agribusiness.

However, in contrast to the stable environment of the European communities, Ukrainian realities form a specific challenge – the need to simultaneously combine security recovery measures and strategic development planning. A comparison with EU studies on financial mechanisms for rural development (Storonyanska et al., 2022) demonstrates that domestic adaptive models remain focused on operational crisis management. At the same time, European governance practices have already moved to the stages of long-term digital and environmental transformation.

The significant role of international donors in the community management system confirms the scientific theses on the priority of strengthening municipal governance as a foundation for the effective absorption of external aid (OECD, 2022). The evolution of governance models in Ukraine should involve a gradual transition from a ‘survival’ strategy towards the implementation of institutional tools similar to LEADER and broader integration into the European governance space (Nazaruk & Rud, 2025). The effectiveness of municipal governance in the

context of European integration largely depends on the implementation of the principles of good governance.

The analysis of stakeholder interactions in territorial development governance provides a basis for identifying the main development challenges. The effectiveness of local development policy depends on the ability of authorities to identify structural constraints in a timely manner and determine priority areas of intervention (Borshchevskyi et al., 2024; Nazaruk & Rud, 2025). In the context of post-crisis recovery, such analytical work becomes especially relevant, as communities simultaneously face economic, infrastructural and demographic challenges.

The analysis of the socio-economic characteristics of communities and the peculiarities of local development management made it possible to identify several key groups of factors influencing the development of territories. These include infrastructure constraints, economic factors, demographic trends, and governance barriers. Each of these groups forms specific challenges for territorial development and requires appropriate management decisions at the level of local self-government.

One of the most tangible challenges in the development of the studied communities remains the state of engineering and transport infrastructure. Damage to infrastructure and limited access to transport and public services significantly constrain economic activity and reduce investment attractiveness.

The structure of the local economy is also an important factor in development. The high share of the agricultural sector in the entrepreneurial environment of most of the studied communities forms their dependence on the dynamics of agricultural production. The seasonal nature of agricultural activity and fluctuations in agricultural markets create additional risks for the economic stability of territories (Nehrey et al., 2025). In such conditions, the development of small business, the service sector and the processing industry becomes an important factor in increasing the economic sustainability of communities.

Demographic processes also have a significant impact on the socio-economic development of territories. Population reduction, labour migration and population aging reduce the labour potential of communities and complicate the development of the local economy.

To systematise the identified development challenges of territorial communities, the study applies a multi-criteria analysis approach, which enables the assessment of the relative importance of various factors. Within the framework of the study, the assessment was carried out according to three criteria: the scale of the impact of the factor on the development of the territory, the duration of its action and the possibilities of managerial response. The results were aggregated into an integral index, enabling the prioritisation of development challenges.

The results of the multi-criteria assessment made it possible to establish the priority of the key challenges in the development of the studied communities (Table 2).

Table 2

Prioritization of Key Development Challenges in Selected Rural Communities of Southern Ukraine Based on Multi-Criteria Assessment (based on Borshchevskyi et al., 2024; Nazaruk & Rud, 2025; OECD, 2022)

Challenge Group	Specific development factor	Scale of impact (1–5)	Duration of exposure (1–5)	Managerial response capacity (1–5)	Integral significance index
Infrastructure	Damage to transport and engineering infrastructure	5	5	3	4.33
Economic	High sectoral dependence of the local economy on agricultural production	4	4	3	3.67
Entrepreneurial	Limited diversification of the structure of local entrepreneurship	4	4	4	4.00
Demographic	Population decline and increasing labour migration	3	5	2	3.33
Institutional	Limited management resources and coordination between stakeholders	3	3	3	3.00

Note: The integral significance index is calculated as the arithmetic mean of the three evaluation criteria.

Higher values of the integral significance index indicate more critical constraints that require immediate managerial attention, while lower values reflect challenges with either limited impact or greater controllability within the existing governance system.

The results of the assessment indicate that infrastructure constraints demonstrate the highest impact, followed by economic and entrepreneurial factors.

The second most significant group comprises economic

constraints, particularly the high dependence of local economies on the agricultural sector and the insufficient diversification of entrepreneurial activity. This structure is typical for most rural areas of southern Ukraine and leads to increased sensitivity of communities to fluctuations in agricultural markets. Scientific studies emphasize that the diversification of economic activity and the development of small businesses are important prerequisites for increasing the economic sustainability of rural areas (Nehrey et al., 2025).

Lower values of the integral index are characteristic of demographic and institutional factors. At the same time, their impact is long-term, since demographic processes determine the potential of labour resources, and institutional constraints affect the effectiveness of local development programs.

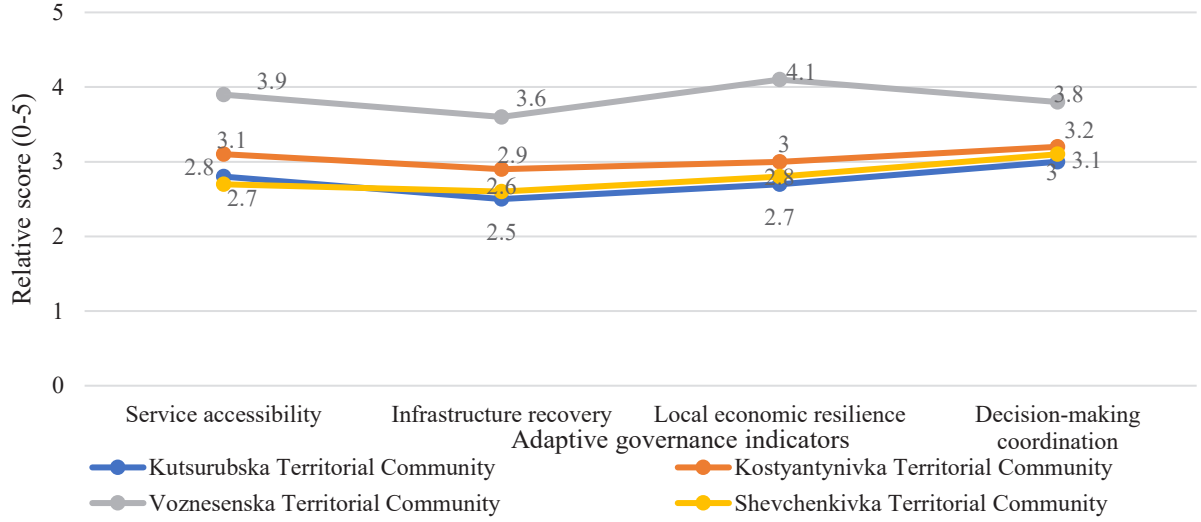
The results obtained indicate that the challenges of development of the studied communities are complex and are formed under the influence of interrelated economic, infrastructural and institutional factors. In such conditions, it is of particular importance to assess the effectiveness of mechanisms for managing the development of territories and to identify gaps between strategic development goals and the practice of their implementation.

For this purpose, the study conducted a comparative assessment of the key indicators of adaptive management in the development of territorial communities. These indicators include the availability of basic public services, the capacity for infrastructure recovery, the economic resilience of the local economy, and the level of coordination of managerial decisions among the main stakeholders in territorial development. The integral values of these indicators make it possible to assess the relative level of adaptability of the management system in the communities under study.

The results of the comparative assessment of the indicators of adaptive management in the development of territorial communities are presented in Figure 2.

Figure 2

Comparative Assessment of Adaptive Rural Governance Indicators in Selected Territorial Communities of Southern Ukraine (based on expert assessment and community development indicators)



The comparative assessment reveals substantial differences in institutional capacity across the studied communities. The highest integral values are observed in the Voznesenska Territorial Community, which can be attributed to a diversified economic structure, a high level of entrepreneurial activity, and a well-developed system of public services.

In the Kutsurubska, Kostiantynivska and Shevchenkivska communities, lower values are recorded for most indicators, reflecting their dependence on the agricultural sector and limited opportunities for economic diversification. This is particularly evident in the indicators of economic resilience and infrastructure recovery capacity, which determine the ability of communities to respond to contemporary challenges.

At the same time, the indicators of coordination of managerial decisions are relatively homogeneous across all communities, indicating the presence of basic institutional mechanisms of interaction between public authorities, business and civil society. Effective coordination, as highlighted in academic studies, is a key factor in enhancing the effectiveness of territorial development policy (Davydenko et al., 2022).

The findings confirm that the adaptability of territorial development management systems is shaped by a combination of economic, infrastructural and institutional factors. This necessitates the application of integrated approaches based on strategic planning, systematic monitoring, and the flexible adjustment of managerial decisions.

An important tool for improving governance efficiency

is the use of adaptive management indicators. In modern studies of territorial development, the indicator approach is considered as one of the key tools for increasing the transparency of management and the validity of managerial decision-making (Borshchevskyi et al., 2024; Nazaruk & Rud, 2025).

The proposed framework of adaptive management indicators integrates economic, infrastructural and institutional dimensions of territorial development and assesses the capacity of local governance systems to adapt to socio-economic change. Its key feature is the combination of quantitative development indicators with measures of management quality, allowing the assessment of both development outcomes and governance effectiveness.

The structure of the system of indicators for adaptive management of rural development is given in Table 3.

Table 3

Indicator Framework for Adaptive Governance of Rural Development in Territorial Communities (author's elaboration based on Borshchevskyi et al., 2024; Nazaruk & Rud, 2025; OECD, 2022)

Adaptive Governance Dimension	Key indicators	Quantitative and qualitative indicators	Data sources	Managerial importance
Accessibility of public services	Level of availability of basic public services	Number of healthcare and educational institutions per 10,000 population; number of administrative services provided through Administrative Service Centres (ASCs); proportion of the population with access to basic public services (%)	Community statistics; reports of local self-government bodies	Assessment of the level of provision of the population with basic services
Restoration and development of infrastructure	Capacity of the community to restore infrastructure	Share of restored infrastructure facilities (%); length of repaired roads (km); share of restored engineering networks (%); volume of investment in infrastructure restoration (UAH/year)	Local budgets; infrastructure recovery programs	Determining the capacity of communities to modernize infrastructure
Economic sustainability of the territory	Level of economic activity and diversification of the economy	Density of entrepreneurship (number of enterprises per 1000 inhabitants); share of non-agricultural business (%); budget revenues per capita (UAH); rate of change in the number of enterprises (%)	Clarity Project; open budget data; regional statistics	Assessment of economic stability and adaptability of the local economy
Institutional capacity of management	Quality of management processes	Number of partnership projects between local authorities and businesses (units); number of public consultations per year; level of transparency of budget information; share of implemented local development projects (%)	Reports of local self-government bodies; expert assessments	Assessment of the effectiveness of the local government system
Adaptability of management decisions	Management ability to respond to changes in the environment	Frequency of updating development strategies (years); share of the development budget in the structure of the local budget (%); the number of innovative management tools (programs, digital services, grant projects); number of implemented development projects per year	Strategic documents of communities; local development programs	Assessment of the level of adaptability of the territorial development policy

Note: Quantitative values of indicators can be calculated on the basis of statistical data of territorial communities, open budget sources and analytical databases of regional development.

The proposed framework is based on universal indicators of budgetary capacity and institutional interaction. These indicators are derived from the Clarity Project open data and statistical reports of territorial communities. This provides an opportunity to extrapolate the results of the study to other rural areas of Ukraine facing similar challenges of post-war recovery, depopulation and infrastructure constraints. The generalisation of the study results indicates that the effectiveness of rural development management is determined by the interaction of economic, infrastructural and institutional factors and depends on the ability of communities to combine strategic planning with adaptive responses to socio-economic changes. The proposed system of indicators of adaptive management can be used as an analytical tool for monitoring territorial development policy and supporting management decisions.

Conclusions

1. The effectiveness of rural development governance in southern Ukraine is determined by the interaction between the socio-economic capacity of communities and the institutional characteristics of local governance. A comparative analysis of communities in the south of Ukraine revealed significant differences in financial capacity, economic structure and level of entrepreneurial activity. Communities with a more diversified economic structure are characterized by higher budget revenues and a higher density of entrepreneurship, which increases their ability to respond to socio-economic challenges.

2. The analysis of the structure of interaction of stakeholders showed that local self-government bodies and enterprises of the agricultural sector play a key role in the formation of managerial decisions. At the same time, the participation of civil society organizations, regional authorities and international support programmes contributes to strengthening institutional interaction and attracting additional resources for community development.
3. Multi-criteria analysis made it possible to determine the main limitations of the development of the studied communities. The most significant among them are infrastructure problems, particularly damage to transport networks and limited availability of basic public services. Important factors are also economic constraints associated with the high dependence of the local economy on the agricultural sector and insufficient diversification of entrepreneurial activity.
4. The study confirms that rural governance effectiveness in southern Ukraine depends on the interaction between economic capacity, infrastructure resilience and institutional coordination. Communities with a more developed entrepreneurial environment and a higher level of institutional interaction demonstrate greater resilience to socio-economic changes.
5. The study proposes a framework system of indicators for adaptive management of rural development, which integrates economic, infrastructural and institutional indicators. The proposed approach forms a methodological basis for monitoring the effectiveness of local development policy, allows to identify key limitations of territorial development and increase the validity of managerial decisions. The use of such an indicator system can contribute to the formation of more flexible models of rural development management in the context of post-crisis recovery.

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CHANGES IN EXPORTS AND MARKET CONCENTRATION IN THE BEEF CATTLE INDUSTRY IN LATVIA

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Abstract
The European Union (EU) has high standards in livestock farming, yet its resilience is threatened by asymmetric competition, climate risks, and geopolitical risks. A challenge for Latvia's beef cattle industry is the export of live cattle, which reduces the industry's long-term added value. These changes in export dynamics and market concentration in Latvia's beef cattle sector are an important indicator for assessing the market structure and level of competition in the sector. Therefore, *the present research aims* to identify the main factors influencing the volumes and composition of beef cattle exports in Latvia during 2014-2024. The present study analysed data on the number of live beef cattle exported from Latvia by destination country, sex, age group, and breed. To identify the level of export concentration for beef cattle and its impact on the sustainability of the industry, the following two indices were calculated: composition of breeds (HHI) and the structural sustainability index (SI). The research results indicated that across all the dimensions analysed – cattle exports by destination country, sex, age group, and breed – a negative relationship was found between the export concentration (HHI) and the structural sustainability index (SI); however, the strength of the relationship varied significantly. The sustainable development of the beef cattle industry in Latvia was primarily linked to the diversification and structural balance of export markets, whereas the diversification of biological dimensions (beef cattle breed, sex, and age group) played a secondary but complementary role in the long-term sustainability of the industry.
Keywords: beef cattle, cattle exports, Herfindahl-Hirschman index, structural sustainability.

Introduction

The EU livestock sector has the highest standards in the world for animal welfare, environmental protection, and product safety. However, compliance entails additional costs that are not always compensated in an uneven market environment (European Commission, 2025). Sector resilience is supported by an integrated One Health approach addressing animal health, disease prevention, and preparedness to manage diseases, and antimicrobial resistance. Nevertheless, viability and strategic autonomy remain challenged by geopolitical instability, climate change, environmental degradation, and the structural transformation (European Commission, 2025; FAO, 2025; Jongeneel et al., 2021). Latvian beef sector is integrated into the EU's common market, where major producers include France, Germany, Italy, Spain, the Netherlands, Ireland, and Poland, each slaughtering over one million cattle annually. Across the EU an average of 22.8 million cattle were slaughtered annually during 2019-2023 (Cozzi et al., 2025). The CAP shows that in 2014-2024 strategic plan for Latvia (2023-2027) provides for a two-tier support mechanism for the beef cattle sector: coupled income support stabilizes farm revenues and profitability in the short term and mitigates potential production reductions, while investment support enhances long-term competitiveness, including emission reduction, animal welfare, and renewable energy use (Ministry of Agriculture, 2025). Despite these measures, the Latvian beef sector faces a structural challenge. While live beef cattle exports generate short-term income, they limit domestic value creation because processing and downstream activities occur abroad. Consequently, potential gains in employment, tax revenues, and economic growth are foregone. To date, no comprehensive analysis has been conducted on the composition of live beef cattle exports in Latvia, the factors affecting sector resilience or the risks associated with export concentration by breed, age, sex, and destination markets. Such analysis is essential to assess structural risks, identify export dynamics, and support policy initiatives designed to increase domestic value added. Therefore, *this study aimed* to identify the key factors influencing the volume and composition of beef cattle exports in Latvia during 2014-2024.

The following hypotheses were proposed: 1) $\mathbf{H_0}$: age, breed, sex of beef cattle, and export destination do not affect beef cattle exports from Latvia; 2) $\mathbf{H_1}$: export concentration by beef cattle breed, age, sex, and export destination increases risks to sector sustainability and economic resilience.

Materials and Methods

Data and information were obtained from the public information system of the Rural Support Service (RSS) and included: the total number of beef cattle, the number of exported live beef cattle by sex (female and male), age group (0-6 months; 6-12 months; 12-24 months; 24 and more months), and breed. A classification of cattle breeds was based on those available in the RSS information system database: Aberdeen-Angus (AB), Herefords (HE), Limousins (LI), Charolais (SA), Simmental (SI), and beef cattle crossbreeds (XG). For data analysis, beef cattle with a negligible volume of exports were included in a single group, *'Other breeds'*.

Export data for live beef cattle were structured by destination country code according to ISO 3166 standard: Armenia (AM), Belgium (BE), Bosnia and Herzegovina (BA), Bulgaria (BG), Croatia (HR), Estonia (EE), Germany (DE), Hungary (HU), Iraq

(IQ), Italy (IT), Kazakhstan (KZ), Lithuania (LT), Netherlands (NL), Poland (PL), Romania (RO), Slovakia (SK), Slovenia (SI), Turkey (TR), Turkmenistan (TM), and Uzbekistan (UZ). Export destination countries with a small number of cattle exported were included in a single category, *'Other countries'*.

Additional data from the RSS represented the total number of beef cattle registered in Latvia, their distribution by age group, and the number of suckler cows. To provide data analysis capabilities and a uniform structure, variables were coded numerically. Animal sex was coded as follows: 1 = female, 2 = male. Beef cattle breeds were coded from 1 to 7 according to the main beef cattle breeds produced in Latvia (1 – XG, 2 – SA, 3 – LI, 4 – HE, 5 – AB, 6 – SI, 7 – 'Other breeds'). The age groups of beef cattle were coded from 1 to 4, with 1 representing the youngest age group (0-6 months) and 4 representing those from 24 and older months. Export destination countries were coded from 1 to 21; the codes were assigned in alphabetical order. The research period was 2014-2024.

A Pearson chi-square (χ^2) test was performed to identify relationships between age groups, breeds, years, and export destination countries for exported beef cattle. Cramer's V was used to identify the strength of the relationship. The level of statistical significance was set at $\alpha = 0.05$.

Standardized indicators (Z-scores) were created for the analysis: the proportion of beef cattle (ZBeef_Share), the proportion of suckler cows (ZSuckle Cow_Share), and the proportion of beef cattle exported (ZExport_Share) in the total number of cattle. In addition, proportions of beef cattle (Beef_ratio_0-6, Beef_ ratio_6-12, Beef_ratio_12-24, Beef_ratio_24+) were calculated for each age group.

A Generalized Linear Model (GLM) was used to test the hypothesis. The appropriateness of a Poisson distribution was initially assessed; however, overdispersion was observed, and therefore, the analysis used a GLM with a negative binomial distribution. The GLM was applied to test the null hypothesis that sex, age group, breed, and export destination country did not affect the number of cattle exported. The level of statistical significance was set at $\alpha = 0.05$, and p-values < 0.05 were interpreted as indicating a statistically significant effect on live beef cattle exports.

To identify export concentration and sustainability for live beef cattle exports, an HHI was calculated for each year and for four dimensions: export destination countries, and the sex, age group, and breed of beef cattle (Nendissa et al., 2019; Schweizer et al., 2022). The structural sustainability was calculated according to the formula:

$$HHI = \sum_{i=1}^{n} di^2 \quad (1)$$

where *di* is the proportion of a certain group of beef cattle (export destination countries, the sex, age group, and breed of beef cattle) in total exports in a year. *HHI* values ranged from 0 to 1. A value close to zero indicated a wide diversity of beef cattle exports and a balanced market structure, while higher values indicated export concentration for some live beef cattle categories and, consequently, lower structural resilience.

A Gini-Simpson index (Helfenstein et al., 2022) was calculated to assess the structural sustainability of beef cattle exports. The HHI was converted to a sustainability index. The sustainability index was calculated according to the formula:

$$SI_1 = 1 - HHI_1 \quad (2)$$

where SI_1 is the structural sustainability index for the respective dimension (export destination countries, the sex, age group, and breed of beef cattle); HHI_1 is the Herfindahl–Hirschman index for the same dimension, with a higher value indicating more structural stability. The total structural sustainability index was calculated as a four-dimensional arithmetic mean:

$$SI_{Total} = \frac{SI_{Countries} + SI_{Breed} + SI_{Sex} + SI_{Age}}{4} \quad (3)$$

where SI_{Total} is the total sustainability index, $SI_{Countries}$ is the structural sustainability index representing destination countries for beef cattle exports, SI_{Breed} is the structural sustainability index for the structure of beef cattle, SI_{Sex} is the structural sustainability index for the sex structure of beef cattle; SI_{Age} is the structural sustainability index for the age structure of beef cattle. Such an approach enabled us to identify and assess the structural sustainability of beef cattle exports from Latvia across all four variables analysed. The statistical calculations were performed using IBM SPSS Statistics Version 29.0.2.0.

Results and Discussion

The beef cattle industry in Latvia

In Latvia, the composition of live beef cattle sector is changing. As noted by Kalle et al. (2025), the EU Livestock Welfare Plan includes restrictions on the duration of live-animal transport, which significantly affects the economic viability of export-oriented livestock sectors, particularly in countries where live-animal trade represents substantial share of farm incomes. The stricter requirements pose significant challenges to the sustainability of beef cattle farming. For example, Estonia exported approximately 60000 live beef cattle to third countries, including Turkey and Uzbekistan, in 2023. This indicates that the Baltic States are oriented towards beef cattle exports, not domestic processing.

The European Commission plans to review the legal framework for live animal exports, including a potential ban or stricter control measures. Particular attention will be given to the transport of newborn calves and pregnant cows. These amendments have not

yet been assessed under World Trade Organisation (WTO) law (FAO, 2025), as EU animal welfare rules mainly apply to the internal market, while exports to third countries remain subject to less stringent requirements (del Campo et al., 2025; Molitorisová & Burke, 2023). Although global beef demand is increasing, the competitiveness of EU beef production is declining. The EU's share in global beef exports is projected to decrease from 7% in 2020 to 6% in 2030 (Jongeneel et al., 2021). Therefore, analysing export destination countries and the biological characteristics (breed, sex, and age) is essential for identifying risk factors and improving beef cattle sector resilience.

Analysis of the cattle industry (Table 1) shows 2014 - 2024 that the average number of cattle was 393 thousand in 2014-2024 of which beef cattle accounted for 77.5 thousand (20%). Suckler cows averaged 52.9 thousand (13.6 %). The share of beef cattle increased from 11.2 to 28.84 % over the period.

Correlation analysis using the Pearson chi-squared (χ^2) test (Table 2) indicated a statistically significant relationship between the share of beef cattle, suckler cows exported live beef cattle in Latvia during 2014 - 2024.

Table 1

Average indicators of cattle distribution and structure in Latvia, 2014-2024

Descriptive Statistics					
Variables	N	Minimum	Maximum	Mean	Std. Deviation
Beef cattle	11	46954	97585	77546.18	18336.285
Beef share	11	11.20	28.84	20.0303	5.78266
Suckle cow share	11	8.17	18.94	13.6507	3.31699
Export share	11	16.15	30.87	25.7424	5.16721
Cattle	11	325568	419384	393154.64	26645.497
Suckler cows	11	34282	62976	52978.00	10130.450
Exported beef cattle	11	8682	30044	20662.27	7942.603
Valid N (listwise)	11	x	x	x	x

Note*: Beef cattle* and cattle the total number (heads); *Beef share*, *Suckler cow share,* and *Export share* proportion (%); *Suckler cows* and *exported live beef breed cattle* – total number (heads); *Valid N -(listwise)* excludes missing data). Period: 2014-2024, (n=11).

Source: *Author's calculations based on RSS data, 2025.*

A very strong positive correlation between beef cattle and suckler cows ($r = 0.995$; $p < 0.001$) indicates a close relationship between beef cattle share and suckler cow numbers, confirming the structural interdependence of the beef cattle sector. The expansion of suckler cows directly contributes to increased beef cattle production. A statistically significant positive correlation was also observed between the number of beef cattle and export volumes ($r = 0.785$; $p = 0.004$).

Table 2

Pearson correlation matrix of standardised structural indicators (Z-scores) for live beef cattle in Latvia, 2014–2024

Variables	Correlations	Zscore beef share	Zscore suckle cow share	Zscore export share
Zscore beef share	Pearson Correlation	1	0.995**	0.785**
	Sig. (2-tailed)	x	0.000	0.004
	N	11	11	11
Zscore suckle cow share	Pearson Correlation	0.995**	x	0.792**
	Sig. (2-tailed)	0.000	n/a	0.004
	N	11	11	11
Zscore export share	Pearson Correlation	0.785**	0.792**	x
	Sig. (2-tailed)	0.004	0.004	n/a
	N	11	11	11

Note: Z-beef share, Z=suckler cow, and Z-export denote standardised shares (%). Period: 2014-2024, (n=11). Calculation in IBM SPSS Statistics Version 29.0.2.0.

Source: *Authors' calculations based on RSS data,2025.*

The number of suckler cows and exported beef cattle showed a significant positive correlation ($r = 0.792$; $p = 0.004$), indicating that increases in beef cattle and suckler cow shares contribute to higher export volumes. Compared to Ireland, where around 90% of beef production is exported due to a limited and price-sensitive domestic export (Kelly et al., 2024), Latvia also exports a substantial share of live beef cattle. The results indicate a strong relationship between beef cattle production and export patterns in Latvia, highlighting the role of suckler cows key determinant of export capacity and sector competitiveness. In contrast, in Europe, suckler cows are primarily kept on pasture- based farms (Cozzi et al., 2025).

Beef cattle exports from Latvia

During 2014-2024, a total of 227285 live beef cattle were exported from Latvia (Table 3). Exports were dominated by male beef cattle (M=1.70; Mdn = 2.00),

accounting for 69.6 % (158153), while females represented 30.4 % (69132 animals). Annual exports (Figure 1) indicate an increase of 9.30-12.30% in beef cattle exports during 2018-2023, followed by a decrease of 1.20% in 2024 compared to 2023. A Pearson chi-square (χ^2) test confirmed a statistically significant relationship between the sex and the number of live beef cattle exported (χ^2 = 8141.693; df = 10; p < 0.001) in the period 2014-2024.

Table 3

Descriptive statistics of beef cattle exports from Latvia, 2014-2024

Statistics	Animal sex	Age group	Export countries	Export year
(N)Valid	227285	227285	227285	227285
Missing	0	0	0	0
Mean	1.70	2.16	13.85	2020.08
Median	2.00	2.00	15.00	2020.00
Mode	2	2	15	2023
Std. Deviation	0.460	0.733	4.071	2.857
Variance	0.212	0.537	16.577	8.160
Skewness	-0.851	0.545	-0.384	-0.424
Std. Error of Skewness	0.005	0.005	0.005	0.005
Kurtosis	-1.275	0.378	-0.269	-0.795
Std. Error of Kurtosis	0.010	0.010	0.010	0.010
Range	1	3	20	10
Minimum	1	1	1	2014
Maximum	2	4	21	2024

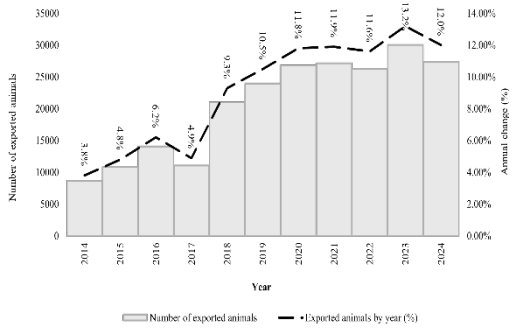
Note: *Calculation in IBM SPSS Statistics Version 29.0.2.0.*
Source: *Authors' calculations based on RSS data, 2025.*

During the analysis period, male cattle were exported more, and their share ranged from 59% (in 2022) to 82% (in 2023), while the share of female cattle was lower, ranging from 17.9% to 40.7%. In 2023 and 2024, the trend changed, and the exports of live male cattle increased, reaching more than 80% of the total exports. Export distribution by sex showed significant annual variation (χ^2test, p<0.001); high exports of reproductive-age cows reflect adjustments in production and marketing pathways. Female exports increased markedly during 2014-2022 (from 24.8 to 40.7%), which may pose risks to the sector's sustainability. High exports of reproductive age-females (heifers) can reduce herd reproductive capacity, limit genetic potential and weaken long-term competitiveness sexes females (heifers) can reduce herd reproductive capacity, limit genetic potential and weaken long-term competitiveness Charolais accounted for the largest share of exports compared to other breeds (Cozzi et al., 2025).

The sex distribution of live beef cattle exports varied statistically significantly from year to year, possibly due to market demand and price fluctuations. Cramér's V and Phi values (0.189; p < 0.001) indicated a weak to moderately strong relationship. The beef cattle exports were generally dominated by males; however, for the crossbreeds and Hereford, the proportions of both sexes were almost equal (Figure 2).

Figure 1

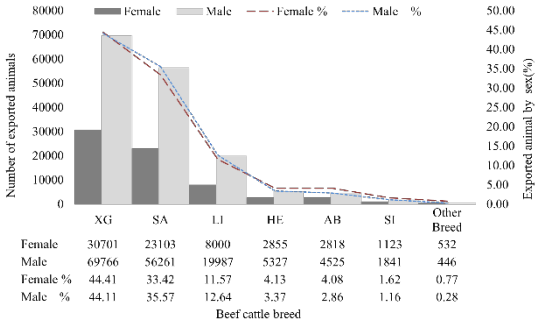
Live beef cattle exports (number and %) from Latvia, 2014-2024



Source*: Authors' calculations based on RSS data, 2025.*

Figure 2

Distribution of exported beef cattle by breed and sex in Latvia,2014-2024



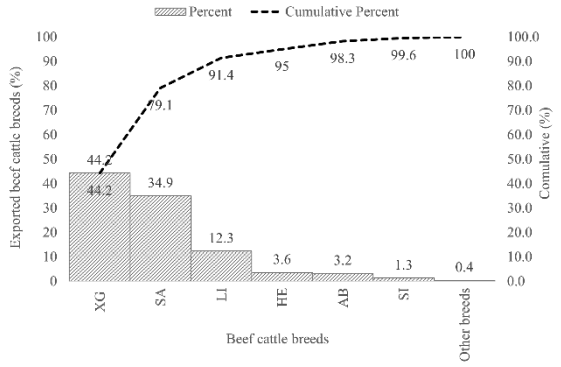
	XG	SA	LI	HE	AB	SI	Other Breed
Female	30701	23103	8000	2855	2818	1123	532
Male	69766	56261	19987	5327	4525	1841	446
Female %	44.41	33.42	11.57	4.13	4.08	1.62	0.77
Male %	44.11	35.57	12.64	3.37	2.86	1.16	0.28

Note: Breed proportion (%) by sex (breed count/total animals of the respective sex) x100. Example: XG females 44.4%.
Source: *Authors' calculations based on RSS data, 2025.*

As regards the composition of breeds, the majority of exported cattle represented beef cattle crossbreeds (XG), i.e., 100467 cattle or 44.2% of the total cattle exported (Figure 3).

Figure 3

Beef cattle exports by breed (% and cumulative %) in Latvia, 2014–2024

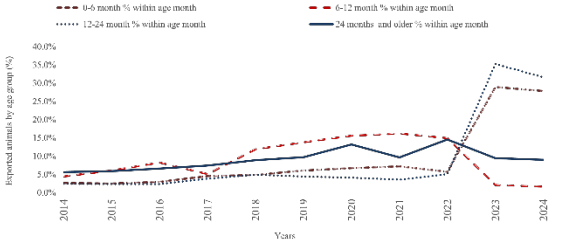


Source: *Authors' calculations based on RSS data, 2025.*

Charolais accounted for the compared to the diversification largest share of exports (34.92%; n=79364), followed by Limousin (12.31%; n=27987). Hereford (3.6%; n = 8182) and Aberdeen (3.23%; n=7343) had smaller shares, while the Simmental cattle breed accounted 1.30% (=2964), and "Other breeds" accounted for 0.43% (N=978). The cumulative percentages showed that live beef cattle exports were dominated by XG and Charolais, accounting for more than 79% of the total number of cattle exported, which may indicate selective export market demand in EU Member States or specific market requirements. Three breeds (XG, SA, and LI) accounted for 91% of the total live beef cattle exports, indicating a high level of market concentration with both risks and competitive advantages in the international market. The age groups structure of exports reflects market demand and production specialization in Latvia during 2014-2024. The export ratio to total beef cattle was highest for the 6-12 month age group (M = 20.67%; SD = 12.96), indicating strong demand in foreign markets. In contrast, the 0-6-month and 12-24-month age groups showed similar but lower ratios (6.36% and 6.73%, respectively). Both of these age groups showed a marked positive asymmetry (skewness close to 1.8), suggesting that exports were below average and increased substantially only in certain years. Exports of live beef cattle aged over 24 months were minimal (on average, 0.5 %), indicating low and stable demand for this age group. Overall, live beef cattle exports were concentrated mainly in younger beef cattle age groups cattle with a higher market demand. The Pearson chi-square test confirmed statistically significant differences in annual exports by beef cattle age groups ($\chi^2(30) = 95\ 558.64$; $p < 0.001$), reflecting shifts in market demand over time. In some years, certain age groups were predominant. The live beef cattle exports were predominated by those aged 6-12 months (59.5%; n = 135317), followed by those aged 12-24 months (20.34%; n= 46236), 0-6 months (14.8%; n= 33722), and 24 months and older (5.3%; n= 12010). Figure 4 shows, that until 2022, exports were predominated by beef cattle aged 6-12 months, accounting for 70-80% of the total exports.

Figure 4

Distribution of live beef cattle exports by age group (%) in Latvia, 2014–2024



Note: Percentages represent the share of beef cattle by age group in total annual exports (Crosstabs: Export_Year × Age_Group)

Source: *Authors' calculations based on RSS data, 2025.*

In 2023-2024, a significant structural shift was observed – the exports of live beef cattle aged 0-6 and 12-24 months increased rapidly, reaching 33% and 53% of the total live beef cattle exports, respectively, while share 6-12 months beef cattle declined. Exports of live beef cattle over 24 months remained below 10% throughout the analysis period, indicating a consistently minor role of this group in the export structure.

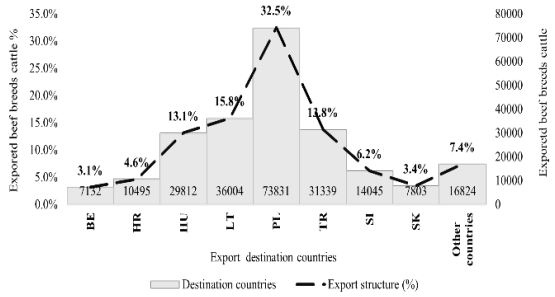
The distribution highlights structural changes in live beef cattle exports from Latvia during 2014-2024. Exports increased mainly in the young cattle segment and represented a few age groups, which increased the vulnerability of the industry to external market fluctuations. Cramer's V ($V = 0.374$; $p < 0.001$) and Phi ($\varphi = 0.648$; $p < 0.001$) indicated a moderately strong relationship between the export year and the age group. This confirms that changes in the age structure of cattle exported were significant, and reflect specialization in beef cattle exports, while also implying vulnerability to shifts in market demand. As indicated by Hocquette et al., 2018, the requirements of the European Green Deal and environmental sustainability objectives determine the need for the agricultural sector to adapt to economic and environmental challenges. The heterogeneity and the different adaptability of the agricultural sector in various regions are characteristic of Europe (Strid et al., 2025). The situation in the beef industry is similar in Estonia, where the limited interest of local consumers in the preparation of beef dishes limits the development of the domestic market. As a result, most of the cattle are exported, mainly to Poland and Lithuania (Kalle et al., 2025). The distribution of beef cattle exports by country in 2014-2024 (Figure 5) indicates a high level of export concentration, as the exports were dominated by several countries: Poland (32.5%), Lithuania (15.8%), Turkey (13.8%), and Hungary (13.1%).

Export activity has increased since 2020, indicating a rising demand and potential dependence on evolving market trends. The Farm to Fork Strategy under

European Green Deal further emphasises the transition towards fair, healthy, and environmentally sustainable food systems (Tinitana-Bayas et al., 2024). The Pearson chi-square test showed statistically significant differences in export distribution across countries and years ($\chi^2(200) = 106\ 940.51$; $p < 0.001$), indicating an uneven distribution. Effect size measures (Cramer's V = 0.271; Phi = 0.686; $p < 0.001$) suggest a moderately strong relationship between export volumes, countries, and years. Pearson and Spearman correlation coefficients showed a weak but statistically significant negative correlation, indicating a gradual diversification of export markets over the analysis period**.** Overall, the results revealed a stable but dynamically changing export pattern with an increasing diversity of markets. This means that the concentration of beef cattle exports to some countries has decreased, but not significantly, which indicates a gradual diversification of export markets and adaptation to changing demand and foreign trading conditions.

Figure 5

Distribution of live beef breed cattle exports by destination country (%) in Latvia, 2014-2024



Source: *Authors' calculations based on RSS data, 2025.*

Testing the export impact hypothesis for the beef cattle industry

To assess the effect of independent variables on the dependent variable (number of beef cattle exported), two hypotheses were put forward. H_0: the age, breed, sex of beef cattle, and export destination countries do not affect beef cattle exports from Latvia. A Poisson regression model was initially applied; however, the Goodness-of-Fit results (Pearson/df = 230.74) indicated significant overdispersion. Therefore, the generalized linear model (GLM) with a negative binomial and log link function was employed. This significantly improved model compliance scores (Pearson/df = 5.33; Deviance/df = 2.506), while the AIC decreased from 372703 to 34787 confirmed the model suitability. Type III analysis showed that all the factors included significantly affected live beef cattle exports. The highest statistical significance was found for the factor of beef cattle breeds (Wald $\chi^2(6) = 4393.35$), which indicated a marked export concentration in certain breeds. This suggested structural dependence on a limited genetic base, with potential risk for biodiversity and resilience to market or disease shocks. The effect of sex factor (Wald $\chi^2(1) = 418.59$) revealed that male beef cattle were exported significantly more than female cattle, thus indicating the specialization in meat production. The distribution of age groups (Wald $\chi^2(3) = 952.66$) confirmed that the exports mainly focused on the category of young beef cattle, reflecting strong market demand during the study period. While economically beneficial in the short term, this pattern may affect the herd structure and long-term sector sustainability. Export destination (Wald $\chi^2(20) = 2149.18$) showed a very high geographical concentration of exports to Poland, Lithuania, Turkey, and Hungary for majority of exports. This pattern poses structural risks, as it reflects limited market diversification and increased dependence on specific countries' economic and political conditions. The results of the Omnibus test confirmed that the independent variables generally had a significant impact on beef cattle exports (Likelihood Ratio $\chi^2 = 8491.35$; $df = 30$; $p < 0.001$). Therefore, the null hypothesis (H_0) was rejected, and the alternative hypothesis H_1 was adopted – export concentration for beef cattle by breed, age group, sex, and export destination increases risks to sector sustainability and economic resilience.

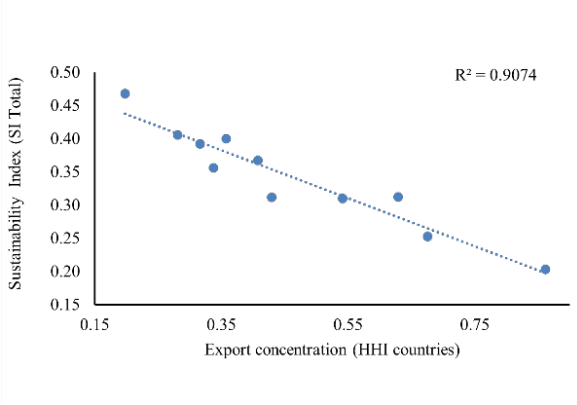
Testing the structural sustainability hypothesis for export concentration for beef cattle

To identify the concentration and sustainability of beef cattle exports, a Herfindahl-Hirschman Index (HHI) was calculated for each year and for four dimensions: export destination countries as well as the sex, age group, and breed of beef cattle (see Equation (1) and (2)). The composition and concentration of live beef cattle exports from Latvia showed that the level of export concentration across all the dimensions ranged from 0.20 to 0.92, indicating significant variability of cattle exports during the analysis period. The highest export concentration levels for beef cattle (HHI > 0.8) were observed for 2015, 2016, and 2024. Particularly high concentration was found in the sex and age group dimensions (HHI>0.4), while during 2018-2022 concentration values range from 0.6 to 0.8, reflecting a relatively one-sided market structure in this period. In contrast, lower export concentration values for beef cattle (HHI < 0.4) could be observed in 2019-2023, coinciding with a greater geographical and structural diversity of exports.

The values of the Sustainability Index (SI Total) for beef cattle exports showed an inverse pattern: as the HHI decreased, the SI increased, confirming an inverse linear relationship between export concentration and sustainability (see Equation 3). The Total Structural Sustainability Index (SI Total) ranged from 0.20 to 0.47, indicating a moderate but gradual increase in the structural sustainability of the industry over time. Overall, the results indicated that in Latvia during the period 2014-2024, beef cattle exports have become progressively less concentrated and more diverse, which has contributed to an improvement in the structural sustainability of the

sector. The finding supports the hypothesis that a reduction in export concentration for beef cattle was strongly associated with an increase in the structural sustainability. The distribution analysis (Figure 6) shows a strong negative linear relationship (R^2 = 0.907) between the
export concentration by export destination country (HHI countries) and the overall level of structural sustainability (SI Total). This suggested that diversification of export markets plays a significant role in enhancing the resilience and sustainability of the sector. The most pronounced fluctuations in export concentration for beef cattle exports were observed in 2014-2015, when HHI values exceeded 0.8, indicating high dependence on a limited number of markets. In the following years up to 2020, the HHI declined to approximately 0.20, reflecting a substantial expansion of export market and more balanced geographical distribution of beef cattle exports.

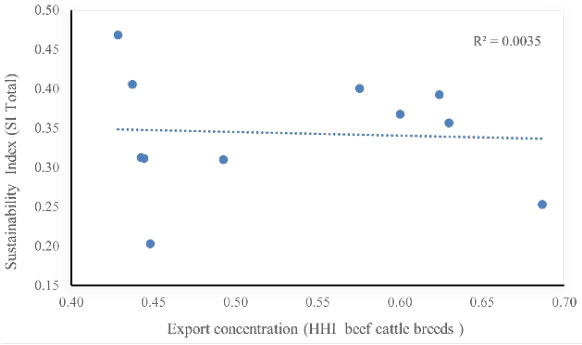
Figure 6
Export concentration by countries and sustainability index in the Latvian beef cattle industry, 2014-2024



Note: Each point denotes one year. The dashed line indicates a linear trend (R^2 = 0.9074).
Source: *Authors' calculations based on RSS data, 2025.*

This trend coincides with an increase in the Total Structural Sustainability Index, indicating a strong relationship between a decrease in the concentration of beef cattle exports to certain countries and an increase in the structural resilience and stability of the cattle industry. In contrast, Figure 7 reveals a very weak negative correlation between the beef cattle exports by breed (HHI Breed) and the Total Structural Sustainability Index (SI Total), suggesting that breed composition plays a less significant role in overall structural sustainability.
The results indicated that the export concentration of beef cattle by breed remained at a moderate level throughout the study period, fluctuating between 0.43 and 0.69. This implies that the diversification of the composition in beef cattle breed composition has progressed more slowly compared to the diversification of export market.

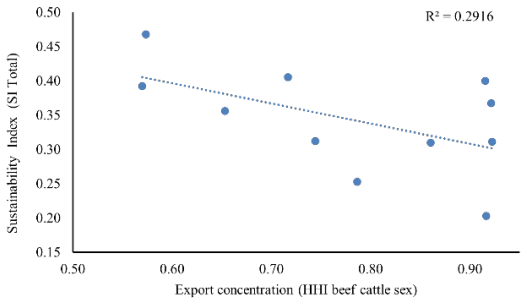
Figure 7
Export concentration by breed (HHI) and sustainability (SI) in the Latvian beef cattle industry, 2014–2024



Source: *Authors' calculations based on RSS data, 2025.*

Consequently, certain breeds continue to maintain a dominant position with the export structure, limiting the extent of structural diversification in this dimension. A relationship between the export concentration for beef cattle by sex (HHI Sex) and the total structural sustainability index (SI Total) is shown in Figure 8. The correlation analysis showed a weak negative linear relationship (R^2 = 0.292), indicating that the export concentration for beef cattle following changes in the distribution of cattle by sex only partially correlated with a change in the SI Total.

Figure 8
Export concentration by sex (HHI) and sustainability (SI) in the Latvian beef cattle industry, 2014–2024



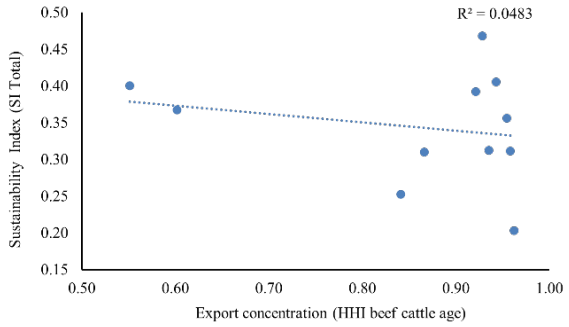
Source: *Authors' calculations based on RSS data, 2025.*

High export concentration for beef cattle by sex (>0.9) was found for 2014-2018, indicating high concentration for a certain cattle sex and age. Only in recent years (2023-2024), a decrease in export concentration for beef cattle by sex was found, which coincided with an increase in the total structural sustainability index. This suggests that as the structural sustainability of the cattle industry increases, the export concentration for beef cattle by sex decreases. In recent years, the HHI for beef cattle age groups has significantly decreased (up to 0.55-0.60), while the total structural sustainability index has increased slightly (to 0.37-0.40). This indicates an increase in the

diversity of age groups of beef cattle exported, which increased the adaptability and resilience of the cattle industry.

Figure 9

Export concentration by age (HHI) sustainability index (SI) in the Latvian beef cattle industry, 2014–2024



Source: *Authors' calculations based on RSS data, 2025.*

However, the distribution of beef cattle exports by age group remained relatively stable throughout the analysis period and therefore did not pose a significant risk to fluctuations in the structural balance. The results suggest that the proposed hypothesis put forward can be partially confirmed, as a negative correlation was found between the export concentration (HHI) for beef cattle and the structural sustainability index (SI) of the cattle industry across all four dimensions: export destination countries and the sex, age group, and breed of beef cattle. However, the strength of this relationship varied, depending on the dimension. The strongest negative relationship was observed for the concentration of beef cattle exports by destination country, whereas weaker corelation were found for breed, sex, and age group of beef cattle. In periods when export concentrations for beef cattle were high, the values of the structural sustainability index were lower, thus indicating lower structural resilience of the industry. This pattern was especially evident in the early period from 2014 to 2016, when the concentration of beef cattle exports by destination country, sex, and age group exceeded 0.9, while the structural sustainability index remained below 0.3. Following 2019, a gradual decline in export concentration was observed alongside a corresponding increase in the structural sustainability index, reflecting a diversification of the cattle industry and the trend of rebalancing. These developments can also be interpreted with a wider policy framework, particularly in light of the coupled income support provided for the beef cattle sector under the CAP Strategic Plan of Latvia for 2023-2027. This policy aims to maintain production potential and promote the long-term stability of the cattle industry (Ministry of Agriculture, 2025).

Overall, the research results revealed that the structural sustainability indicators of beef cattle exports were lower during periods when a small number of export destination countries, breeds, and age groups were involved, while a more diverse distribution of beef cattle exports correlated with higher structural resilience of the cattle industry. Accordingly, the sustainable development of the beef cattle industry is strongly linked to the diversification of beef cattle exports and market balance maintenance, thereby making it possible to mitigate external shocks and the long-term effects of fluctuations in demand.

Conclusions

1. The research results suggest that the proposed hypothesis was partially confirmed. Across all dimensions - export destination countries and the sex, age group, and breed of beef cattle a negative relationship was observed between export concentration (HHI) and the structural sustainability index for the cattle industry; however, the strength of this relationship varied significantly. The composition and concentration of live beef cattle exports from Latvia showed that export concentration across all dimensions ranged from 0.20 to 0.92. Lower export concentration values (HHI < 0.4) were observed in 2019–2023. The Total Structural Sustainability Index (SI Total) ranged from 0.20 to 0.47, indicating considerable variability in cattle exports during the analysis period.

2. The composition of beef cattle exports from Latvia was characterised by high export concentration across several dimensions, indicating structural vulnerability of the cattle industry. A significant negative relationship between export concentration and structural sustainability ($R^2 = 0.907$) was identified for some export destination countries, indicating dependence on limited market opportunities. Particularly high export concentration was observed in beef cattle breeds and export destination countries—Poland (32.5%), Lithuania (15.8%), Turkey (13.8%), and Hungary (13.1%). This indicates that geographical concentration is the main source of structural vulnerability in the cattle industry. This suggests that diversification of export markets plays a significant role in enhancing the resilience and sustainability of the sector.

3. The correlation analysis showed a weak negative linear relationship ($R^2 = 0.292$) between export concentration in the cattle sex dimension and the level of structural sustainability. High export concentration (>0.9) was observed during 2014–2018, indicating a strong dominance of a particular cattle sex. Only in recent years (2023–2024), a trend was observed a decrease in export concentration by sex . This indicates that a more balanced distribution of beef cattle exports among sex groups leads to higher structural resilience in the cattle industry. This suggests that as the structural sustainability of the cattle industry increases, export concentration by cattle sex decreases.

4. Regarding export concentration by breed and age group, the relationship with the structural sustainability index was weak. Export concentration by breed

remained relatively stable (HHI 0.43–0.69), while concentration by age group declined (HHI 0.55–0.60). This suggests that biological factors had a limited impact on the overall structural sustainability of the beef cattle industry compared to the geographical diversification of export markets.

5. The research results revealed that the sustainable development of the beef cattle industry was mainly linked to the diversification of export markets and structural balance maintenance.

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THE IMPACT OF THE RURAL DEVELOPMENT PROGRAMME SUPPORT ON AMMONIA EMISSIONS FROM AGRICULTURE

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Abstract
The Gothenburg Protocol (1999), under the Convention on Long-Range Transboundary Air Pollution of the United Nations Economic Commission for Europe (1979), targets ammonia (NH_3) emissions alongside other pollutants. Its 2012 revision established legally binding national emission reduction commitments (ceilings) for 2020 and beyond, placing a significant focus on agricultural sources for NH_3. It was only in 2022 that Latvia's NH_3 emissions finally met this established ceiling, and even then, by only a narrow margin. As agriculture generates about 85% of total NH_3 emissions, it is important to prevent the increase in NH_3 emissions from livestock and other sectors of agriculture. So far, no attempts have been made to estimate the net impact of policy measures on ammonia emissions. Research mainly focuses on mitigation measures, farm practices, manure application, emission factors, and modeling of agricultural ammonia emissions. This study aims at assessing the net direct impact of rural development support under two support categories on these emissions using the data at county level from Latvian Environmental, Geology and Meteorology agency along with the data on the Rural Development Program (RDP) public financing from Paying Agency of the Ministry of Agriculture. Calculations show that the RDP affects 40% of total agricultural emissions, and as the number of arable farms increases, emissions from this sector also increase. The results obtained show that the impact of agri-environmental support on ammonia emissions is only moderately positive, while the positive impact of other RDP support is significant. The results of the study should be used in the future structuring of support.
Keywords: ammonia emissions, Rural development program, impact evaluation, coarsened exact matching.

Introduction

Ammonia emissions are of considerable importance because they contribute to air pollution and are closely associated with agricultural activity. Worldwide livestock sector contributes up to 90% of total ammonia emissions from agriculture. In 2018, about half of Latvia's agricultural NH_3 emissions came from nitrogen fertilizer use and crop soils (≈49%), with the rest from manure management (~51%), reflecting nearly equal contributions (Lenart, 2021). Frolova et al. (2020) in their study found that manure-related sources (livestock housing, storage, and manure used as fertilizer) still dominated total agricultural NH_3 by contributing about 73% of total emissions. At the same time, they noted a rapid rise in emissions from synthetic fertilizers in recent years. Forecast share of 45% emissions from crop farming has been already exceeded in 2021. This trend might be exacerbated by increased Rural Development Program (RDP) support for manure storage facilities further contributing to the lower share of livestock farming in total NH_3 emissions form agriculture. The 2021 data shows that NH_3 emissions from the livestock sector are only 46%, meaning that emissions from the crop sector are growing at a faster pace (Latvian Environment, Geology and Meteorology Centre, 2025). Ge et al. (2020) in their paper describe a novel ammonia emission model. Their approach is based on quantifying agricultural emissions with improved spatial details and temporal dynamics. The model can differentiate between various agricultural sectors including crop and fertilizer types.

Most articles on the need to reduce NH3 focus on manure storage facilities, so in case the LV threshold is exceeded, it is necessary to focus on large users of mineral fertilizers - changing the support conditions accordingly. The various guidelines for the evaluation of RDP require the estimation of program contribution in reducing ammonia emissions from agriculture. Several EU Member States including Latvia have implemented specific measures to reduce ammonia emissions under the new Common Agricultural Policy (CAP) Specific Objective SO5 'Environmental care'. The judgement criteria for reaching this objective include the question: To what extent have CAP Strategic Plan interventions advanced air quality, including a reduction in chemical substances? The Specific Objective SO5 contains the Key objective: 'to foster sustainable development and efficient management of natural resources such as water, soil and air, including by reducing chemical dependency'. The corresponding context indicator recommended by Performance Monitoring and Evaluation Framework (PMEF,2025) is 'Ammonia emissions from agriculture'. Previous evaluation reports have addressed these questions superficially using indirect, naïve approaches. The assessment has been based upon the output indicators like share of farms with investments in farming practices that enable reduction of ammonia emissions. These indicators do not provide an opportunity to evaluate the net direct impact of RDP support on emissions. In 2016, ammonia emissions in Latvia exceeded the 2020 commitment level by a highest margin in Europe at 15%. It was only in 2022, after a prolonged period of non-compliance, that Latvian NH_3 emissions met the established ceiling, albeit by at a narrow margin. Agriculture contributes approximately 85% of total National ammonia emissions. Unlike the worldwide pattern with livestock sector contributing for up to 90% of total ammonia emissions from agriculture, crop farming in Latvia yields higher emissions than livestock farming. According to World Bank Group (2026), fertilizer consumption in kilograms per hectare

of arable land in Latvia in 2022 was in line with other Nordic and Eastern European countries such as Finland, Sweden, Estonia, Lithuania, Hungary, Romania. Norway is an exception with its developed fertilizer production sector. These levels are considerably lower when compared to Western Europe, Latin America or East Asia. The situation thus can be considered rather ambiguous and robust evaluation of the impact of the RDP support is crucial. There is limited research available on the assessment of the impact from policy interventions on ammonia emissions. Marconi, Raggi and Viaggi (2015) analyze factors explaining the reduction in the nitrate mineral fertilizer application rate in the municipalities of Italian province of Emilia-Romagna. Their results indicate that the observed decrease in the application rate of nitrate mineral fertilizers was positively influenced by both the uptake of specific Agri-environmental schemes (AES) and the location in Nitrate vulnerable zones (NVZ). The authors found that participation in AES is less important than the location in a NVZ. On the other hand, research abounds on two prominent issues: the need to limit ammonia emissions and recommended emission reduction measures. Wyer et al. (2022) point that 81% of global ammonia emissions are the result of agriculture, which in the European Union contributes to 50% of particulate matter air pollution. He attributes the particulate matter as a cause of chronic respiratory illnesses and premature mortality. Rather unreasonably, he considers regulating ammonia usage cost efficient.

Materials and Methods

The Latvian Environmental Geology and Meteorology center reports air polluting emissions once in four years (2025). The average annual emissions from reporting points are mapped onto a square grid with cell sides 0.1 degrees long. The study uses novel approach by averaging reported values from points over the counties where these points belong. The centers of the cells along the country border could fall within the territories of neighboring countries. In these cases, data are omitted from the data panels because attributing these cells to Latvian administrative units is ambiguous. Moreover, the unknown share of such emissions could come from the respective neighboring country (countries). Similarly, data are omitted if centers of the cells fall within Baltic Sea or Riga Gulf. After the attributing of reporting points to administrative units, unit averages of ammonia emissions are calculated. Units with non-zero values of reported emissions are retained for data panels used in further analysis.

The analysis is done at the administrative unit level with Coarsened Exact Matching (CEM) method. Coarsened Exact Matching (CEM) is a method proposed by Iacus, King and Porro (2012) for causal inference that temporarily coarsens variables into broader categories (bins) for matching units from the same bin in treatment and control groups. First, the variables for establishing bins are selected, and bin sizes are established. The proper number of variables and bin sizes should be selected empirically to satisfy two conditions simultaneously: the results of weighted CEM regression are statistically significant, and both multivariate and univariate imbalance do not increase. As proven by Veveris, Hazners and Benga (2025) the optimal selection is three variables divided into four bins. After coarsening the variables into bins, the data panel is divided into strata. Panel units with equal values for all k variables are included in the same stratum. Strata with missing units either for treated or untreated units are not selected for further processing. After the establishment of suitable strata, overall multivariate imbalance, univariate imbalance are calculated using coarsened data. Also, the difference in means for treated and untreated units within strata is calculated using original data. Usually, further calculations are justified if the multivariate imbalance, univariate imbalance and difference in means have not increased.

The overall imbalance using the coarsened data panel is calculated by Formula:

$$\mathcal{L}_1(f,g) = \frac{1}{2}\sum_{l_1 \ldots l_k} \left| f_{l_1 \ldots l_k} - g_{l_1 \ldots l_k} \right|, \quad (1)$$

where $\mathcal{L}_1$ - multivariate imbalance,

$f_{l_1 \ldots l_k}$ - k-dimensional relative frequencies for the treated units,

$g_{l_1 \ldots l_k}$ - k-dimensional relative frequencies for the control units.

The similarity or dissimilarity between the distributions of covariates in treatment and control groups is represented by overall imbalance. After that, a contingency table is created by putting all unique values for all covariates into the rows. Two columns for treatment and control groups are created. The columns contain the frequencies for the respective group. Then the absolute values of the differences between frequencies in treatment and control columns are added up and divided by two.

After the justification of further actions by imbalance and mean values criterions the weights for all valid stratums kept for matching are calculated. The treated units are assigned the weight of 1. In other words, treated units are unweighted. The weights for control units are calculated by Formula (3):

$$w_t = 1\,, \quad (2)$$

$$w_c = \frac{n_t}{n_c} \times \frac{N_c}{N_t} \quad (3)$$

where w_t - weights for the treated units,

w_c - untreated unit weights,

n_t - number of treated units within the stratum,

n_c - number of untreated units within the stratum,

N_t - number of treated units in the matched data sample,

N_c - number of untreated units in the matched data sample.

After the calculation of weights, the Weighted Ordinary Least Squares (Weighted OLS) regression is performed by regressing the outcome variable of interest, Y on treatment variable T:

$$B = (T^T WT)^{-1} T^T WY, \quad (4)$$

where B - matrix with two rows and one column containing intercept β_1 and regression slope β_2,
T - matrix with n rows and two columns whose first column is set to 1, the second column contains the binary treatment variable,
W - square matrix with n rows and columns whose diagonal contains the calculated weights and all other cells with zero values,
Y - vector with n rows representing the values of outcome variable,
n - number of units in the matched data sample.
The regression slope, β_2 represents the value of the ATT effect.
After the estimation of total aggregate impact at the country level is calculated:

$$TI = \frac{ATT * TF}{S_T - S_0}, \quad (5)$$

ATT - average treatment effect.
TF - total public financing,
S_T - average support for treated units,
S_0 - average support for untreated units.
Here, the denominator represents the treatment received by quasi-treated units.
The data on total RDP support from 2014 to 2020 in Agri-environmental and other measures are retrieved from Program Paying agency unpublished data files (Rural Support Service, 2025).

Results and Discussion

The creation of data panels for analysis at the highest level of aggregation of administrative units is based upon the experimental data by National Statistics (Centrālā statistikas pārvalde, 2025). Two data panels were created for estimating the net impact of RDP support on total Latvian ammonia emissions. Three pre-treatment variables for both data panels were selected based on their empirically proven suitability for CEM regressions in terms of overall multivariate imbalance, univariate imbalance and difference in means. Out of 592 Latvian administrative units, 474 units were selected based on available data for reported ammonia emissions and RDP support (MoA, 2022). Excluding area payments, the included RDPs measures comprised advisory services, farm management and support services; investments in tangible assets; the restoration of agricultural production potential damaged by natural disasters; and farm and business development. Furthermore, it encompassed basic services and village regeneration in rural areas, forest areas expansion, the establishment of producer groups and organizations, cooperation initiatives, and insurance premiums for Crops, animals and plants. Support for LEADER local development), the following pre-treatment variables were selected: Share of A-sector (Agriculture) in total output, share of S-sector (Other Services) in total output and Gross monthly salary. Panel units were divided into two equal groups divided by a median of received support. Units with lower support were considered quasi-untreated. Units with higher support were considered quasi-treated. A binary treatment variable was assigned accordingly. Three pre-treatment variables were divided into four equal groups, so that every unit becomes represented by its coarsened value ranging from 1 to 4. The original data panel of 474 units was divided into 64 strata. After excluding six unsuitable strata, the coarsened data panel contained 223 treated units and 207 untreated units. The calculated overall multivariate imbalance (Formula 2), univariate imbalance for coarsened data samples, as well as difference in means for original data samples for all variables are shown in Table 1.

Table 1
Multivariate distance, univariate distances and differences in means before and after the matching

Multivariate L1 distance	Before		After	
	0.1280		0.111	
Pre-treatment variables	Univariate imbalance			
	L1	mean	L1	mean
Share of A-sector in output	0.127	0.0331	0.120	0.021
Share of S-sector in output	0.139	0.003	0.099	0.003
Gross salary	0.063	44.95	0.061	36.54

After matching, the multivariate imbalance, univariate imbalances, and standardized mean differences for all pre-treatment variables decreased. Hence, the research can proceed for the intended estimation of causal inference using the coarsened data panel. The regression was performed using Formula 4. The regression results are shown in Table 2.
As the statistical significance has been reached, the coefficient for treatment variable with the value 0.0076 shows the average changes in ammonia emissions from a single county caused by the RDP support in measures other than area payments.
The second data panel was set up similarly, using area payments as treatment variable. This panel includes data from RDP measures such as: Agri-environment and climate, organic farming, compensation payment for NATURA 2000 forest areas, and payments for areas with natural or other specific constraints.

Table 2
The results of the weighted OLS regression

Variables	Coefficient	SE	t-stat	p-value
Intercept	0.0156	0.0007	20.848	0.000
Treatment	0.0076	0.0010	7.366	0.000
R2				0.107
Adjusted R2				0.105
F(1,452)				54.263

The following pre-treatment variables were selected: Share of M-sector (Professional Services) in total output, Total output and Gross Value Added. The original data panel of 474 units was divided into 41 strata. After dropping 3 unsuitable strata, the pruned data panel contained 219 treated units and 223 untreated units. The overall multivariate imbalance, univariate imbalance and difference in means are shown in Table 3.

Table 3
Multivariate distance, univariate distances and differences in means before and after the matching

Multivariate L1 distance	Before		After	
	0.083		0.079	
Pre-treatment variables	Univariate imbalance			
	L1	mean	L1	mean
Share of M-sector in output	0.072	0.010	0.061	0.009
Total output	0.080	609.01	0.077	487.11
Gross Value Added	0.076	349.25	0.072	337.57

The regression was performed using Formula 4. The regression results are shown in Table 4. The coefficient for treatment variable with the value 0.0020 shows the average changes in ammonia emissions from a single county caused by the RDP area payment support.

Table 4
The results of the weighted OLS regression

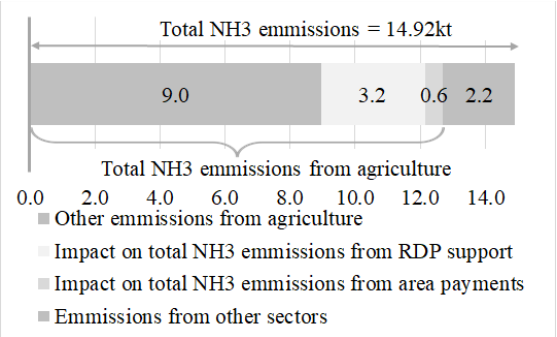
Variables	Coefficient	SE	t-stat	p-value
Intercept	0.0185	0.0008	24.620	0.000
Treatment	0.0020	0.0011	1.860	0.064
R2				0.007
Adjusted R2				0.005
F(1,463)				3.459

The aggregated impact at the country level is calculated for the results obtained for both data panels with formula 5. For data panels containing support in measures other than Agri-environmental measures, the average support received by a county stood at EUR 3,324.411 for quasi-treated units and EUR 648,586 for quasi-untreated units. The difference of EUR 2,675.825 between these two values represents the average treatment received. The total public financing paid in these measures was EUR 1.126 billion. The calculated ATT effect on ammonia emissions was 0.008 kt. The calculated aggregate effect at the country level was 3.19 kt. For data panels containing support in Agri-environmental measures, the average support received by a county stood at EUR 2,987.845 for quasi-treated units and EUR 697,253 for quasi-untreated units. The difference of these values at EUR 2,290.592 was considered the average treatment received. The implementation of these measures involved total public expenditure of EUR 649.2 million. The calculated ATT effect on ammonia emissions was 0.002 kt. The calculated aggregate effect at the country level was 0.56 kt. The net impact from both types of support on National ammonia emissions is shown in Figure 1.

Thus, the RDP support contributes to about one fourth of total National ammonia emissions and more than 40% of emissions from agriculture. Since RDP

measures that are not related to area payments have a greater impact on ammonia emissions, special attention should be paid to these measures.

Figure 1
Breakdown of total Latvian ammonia emissions by factor, 2022



In Latvia, farms are increasingly moving towards arable crop specialization, which has an increased impact on these emissions. Therefore, when supporting arable crop specialization farms, particular attention should be paid to reducing ammonia emissions. The main source of ammonia emissions from crop farming is the application of nitrogen-based fertilizers, specifically synthetic fertilizers and animal manure/slurry. While the broader agricultural sector's largest overall source of ammonia is livestock farming (stables, manure storage, and grazing), within crop production itself, fertilizer application takes center stage. These findings should be taken into account when the national annual target for ammonia emissions is not met.

Conclusions

1. The aggregation of environmental grid data from observation points should be applied at the detailed territorial level for further counterfactual analysis.
2. The impact of the policy interventions on air-polluting emissions can be estimated by applying matching methods to administrative unit data panels containing aggregated average emission values.
3. RDP support for measures other than AES contributes more than one fifth of total National ammonia emissions.
4. RDP support for AES also is positive. However, it contributes only for less than four percent of total National ammonia emissions.
5. A continuous increase in RDP support for investments may lead to further increase in ammonia emissions from agriculture.
6. Although the certain share of support under the RDP is targeted for reducing the air-polluting emissions by AES, the net impact from this type of support on the ammonia emissions is positive. Therefore, to sustain the acceptable level of ammonia emissions from agriculture in the future, the respective policy interventions should be revised.
7. Agricultural support programs should place greater emphasis on sector-specific targeting and eligibility conditions, given the increasing contribution of the arable farming sector to ammonia emissions.

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BIOFUEL EXPANSION AND AGRICULTURAL LAND USE: ASSESSING FOOD–FUEL COMPETITION IN POLAND

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Abstract
The development of biofuel production from agricultural raw materials has raised concerns about their competition with food production, especially given limited land resources and ambitious climate policy goals. The literature mostly analyses the economic efficiency, emissions, and technological aspects of biofuel production, with less attention paid to land-use competition, particularly in developed countries such as Poland. The aim of this study is to assess the extent to which biofuel production from agricultural feedstocks competes with food production for land resources in Poland and to examine its impact on feedstock availability for animal feed, export levels, and farm income. The analysis is based on data from Statistics Poland and the National Support Centre for Agriculture (KOWR), covering the period 2005–2024, and includes bioethanol, biodiesel, and agricultural biogas production in Poland. Area allocated to biofuel feedstock production increased fivefold, reaching approximately 1.1 million hectares (ca. 10% of arable land). Despite this growth, no clear evidence of direct competition with food production was found. This was primarily due to increases in agricultural productivity, which allowed both biofuel production and food output to expand simultaneously, with additionally rising agricultural exports. However, partial competition for higher-quality land was identified, particularly in rapeseed and maize cultivation. The findings suggest that, under conditions of productivity growth and surplus production capacity, biofuel development does not undermine food security. Nevertheless, policy design should account for localised land competition and potential environmental risks associated with intensified production systems.
Keywords: biofuels, food–fuel competition, bioenergy crops, food security, agricultural land use.

Introduction

Energy production from agricultural feedstocks is currently widespread. The dynamic development of this activity has been driven by the need to reduce the consumption of fossil fuels and greenhouse gas (GHG) emissions. A wide range of feedstocks can be used for biofuel production; however, the most valuable are those that can be utilised in modern applications, such as liquid transport fuels. This direction of use enables substituting for fossil fuels consumed by internal combustion engines. In such cases, biofuels must be characterised by high energy density and ease of storage.

One of the key challenges in developing biofuel production from agricultural raw materials is competition with food and feed production. Another important issue concerns whether the emissions associated with inputs used in the biofuel production process remain lower than the emission reductions achieved through substituting fossil fuels. Otherwise, the intended environmental objective will not be achieved. Competition between the production of feedstocks for food and energy in agriculture may involve various dimensions, including land use. This study assesses how competition for land between food and biofuel production in Poland has evolved and the level it reached during 2005–2024. As noted by WBA (2025), Poland and Germany account for half of the European Union's biodiesel production.

The 'food versus fuel' dilemma in land-use refers to the direct competition for limited arable land between crops intended for human and animal consumption and those cultivated for energy (Goh et al., 2019; Rathmann et al., 2010; Żołądkiewicz, 2016). This issue has gained global significance due to rising oil prices, the need to reduce greenhouse gas (GHG) emissions, and the pursuit of energy security (Rathmann et al., 2010).

Direct and Indirect Competition

Biofuel production from agricultural feedstocks encompasses multiple dimensions, with competition being the most fundamental. This competition can be conceptualized as both direct and indirect. Direct competition arises from the fact that first-generation biofuels are produced from edible agricultural raw materials, such as maize, sugarcane, wheat, and vegetable oils (rapeseed, palm, and soybean oil) (Żołądkiewicz, 2016).

Another important dimension of competition concerns market mechanisms. Farmers may shift toward energy crops due to their higher profitability, which leads to the gradual substitution of traditional food crops (e.g., a shift from wheat to maize in the United States or from soybeans to sugarcane in Brazil). Such changes are often driven by subsidies – either for feedstock production or for biofuel production itself (Kulawik, 2008; Rathmann et al., 2010; Zięty et al., 2022) – as well as by blending mandates requiring the incorporation of biofuels into liquid fuels. These dynamics have not only local but also international implications, affecting production in exporting countries due to price differentials (WBA, 2025).

This form of competition contributes to what is referred to as *land competition*, i.e., a scarcity of land available for food production, which may lead to increases in global food and agricultural commodity prices. The use of food crops for energy purposes is also considered ethically contentious due to *competition for food* (Eygu, 2026). However, the empirical evidence on whether this process leads to higher food prices remains inconclusive (Bentivoglio & Rasetti, 2015; Wicki, 2017; Zilberman et al., 2013).

Moreover, WBA (2025) notes that bioethanol production has stabilised, without further pressure to expand cultivated areas.

An additional issue concerns the intensification of land competition in third countries. The import of large volumes of vegetable oils for biodiesel production, for example, from Asia to EU countries, leads in exporting countries both to an expansion of oilseed cultivation and, frequently, to increased emissions associated with such production. As a result, the negative effects of competition may be observed not only in agricultural production but also in GHG emissions.

Land Use Change and Biofuel Generations

Another important aspect concerns land-use change, which may conflict with the climate objectives associated with biofuel use. The most readily observable form is direct land-use change (dLUC), which involves converting natural ecosystems, such as forests, wetlands, and grasslands, into land for energy crop cultivation. A prominent example is deforestation for oil palm plantations in Southeast Asia (Abreu et al., 2022; Chowdhury et al., 2025). Emissions from indirect land-use change (iLUC) occur when biofuel production displaces food crops. Estimates of iLUC are subject to considerable uncertainty; however, they may significantly worsen the greenhouse gas (GHG) balance of biofuels, in some cases rendering them less environmentally beneficial than fossil fuels (Börjesson, 2009; Chowdhury et al., 2025; Czyrnek-Delêtre et al., 2016; Jarosz, 2016). An alternative solution was to use set-aside land to produce raw materials for biofuels, as it happened in the European Union.

Actual CO_2 emission reductions depend on life-cycle assessment (LCA) of biofuels. When indirect land-use change (iLUC) is accounted for, the environmental benefits may be substantially reduced. For instance, an IEEP report indicates that additional biofuels promoted under EU targets may generate 81–167% more GHG emissions than fossil fuels, precisely due to iLUC effects. In response, the European Union introduced regulatory limits on food- and feed-based biofuels, as well as caps on high iLUC-risk biofuels. The share of high iLUC-risk biofuels is to be gradually reduced to zero by 2030 (PE/36/2023/REV/2). At the same time, the permitted share of first-generation biofuels blended into conventional fuels will be lowered.

Biofuels derived from food-based feedstocks are classified as first-generation biofuels (Table 1). In addition, three further generations are distinguished. Second- and third-generation biofuels rely on non-edible feedstocks, such as lignocellulosic biomass, agricultural and forestry residues, and microalgae, which do not require high-quality agricultural land. Examples include short rotation coppice systems. However, such production is typically not economically viable without additional subsidies (Zięty et al., 2022), and processing technologies remain costly and energy-intensive. A niche but promising approach in second-generation feedstock production involves using marginal, degraded, or contaminated land.

The deployment of algae-based biofuels (third generation) and genetically modified algae (fourth generation) faces numerous technological, economic, and biological barriers. As a result, while such production is technically feasible, it remains economically uncompetitive at present (Goh et al., 2019).

Table 1

Biofuels generations

Biofuel generation	Feedstocks used in production	Examples
First	Food crops containing significant amounts of starch, sugar, or oil	Sugarcane, sugar beet, maize, wheat, palm oil, rapeseed, soybean, potato
Second	Lignocellulosic biomass and other waste streams, including industrial and municipal waste	Agricultural residues, cereal straw, wood waste, agro-processing residues (e.g., walnut shells, rice husks), cellulosic plants, including those grown on marginal land
Third	Algae	Seaweeds, microalgae
Fourth	Genetically modified organisms (e.g., microalgae, yeast)	Genetically modified microalgae, yeast, and other microorganisms

Source: own elaboration based on: (Abreu et al., 2022; Broda et al., 2022; Cavelius et al., 2023; Clauser et al., 2021; Igwebuike et al., 2024; Osman et al., 2023; Patel & Singh, 2023).

The effects of taking iLUC into account in biofuel production in Poland

In Poland, iLUC is taken into account in biofuels assessment under the RED II Directive. iLUC factors for rapeseed are significantly higher (55 g CO_2eq/MJ) than for cereals (12 g CO_2eq/MJ). When iLUC is taken into account, Polish biodiesel produced from conventionally cultivated rapeseed does not meet the required emission-reduction thresholds, necessitating the adoption of more costly cultivation methods (e.g., no-tillage systems) or moving production to better soils to reach higher yields to reduce carbon emissions. This may lead to the displacement of biodiesel by bioethanol, which more easily meets emission criteria when iLUC is considered. In the long term, this is intended to support investments in technologies based on non-food feedstocks, such as lignocellulosic residues, straw, or even algae (Abreu et al., 2022; Jarosz, 2016; Millinger et al., 2018; Philippidis et al., 2018). The use of food-processing waste streams in

biogas production is also advantageous (Naglis-Liepa et al., 2022; Naglis-Liepa & Pelse, 2014).
Given the multiple benefits and constraints associated with biofuel production (Table 2), there is a need for a coherent energy–agricultural policy that reconciles climate objectives with ecosystem protection and the stability of agricultural commodity prices.
A related issue concerns the broader economic impacts of biofuel production at the local and national levels, including employment, income generation, and trade. The biofuel sector contributes to job creation and income; however, employment is often concentrated in specific segments of the agricultural supply chain, tends to be seasonal, and may offer limited labour protections, as observed in countries such as Brazil and Indonesia.

Table 2
The main advantages and disadvantages of biofuels of each generation

Biofuel generation	Advantages	Disadvantages
First	Widely available feedstocks and mature technology Cost-effective; supports farm income and employment Lower CO_2 emissions than gasoline	Competes with food production (land, water, feedstocks) Risks related to LUC and iLUC Sustainability limits expansion
Second	Limited competition with food production Uses waste and residues (resource efficiency) Higher environmental benefits; policy support (e.g., RED II)	High production and logistics costs Low technological maturity and limited scale Feedstock heterogeneity and energy-intensive processing
Third	No competition for arable land Potential for CO_2 capture High theoretical efficiency	Very high costs; early-stage technology Environmental risks Currently uncertain GHG performance
Fourth	Very high potential productivity Use of waste CO_2 streams	Regulatory constraints (GMOs) Early-stage development High R&D costs

Source: own elaboration based on: (Abreu et al., 2022; Carneiro et al., 2017; Correa et al., 2017; Igwebuike et al., 2024; Jarosz et al., 2017; Osman et al., 2023; Popluga et al., 2024; Rulli et al., 2016).

Globally, biofuel-related employment was estimated at 16.6 million jobs in 2024. In highly developed countries, including Poland, the impact on the labour market is relatively limited (IRENA & ILO, 2026; Trypolska, 2023).
Poland has pursued an increase in the share of renewable energy, including a 10% target for biofuels in transport fuels by 2020 (MG, 2009). More broadly, several country-specific conditions can be identified. Liquid biofuels (primarily bioethanol and biodiesel) are produced from agricultural feedstocks, with biodiesel playing a dominant role in Poland. The economic benefits of biofuels include improved energy security, rural development, and higher farm incomes. Environmental benefits, provided that production is sustainable, include reduced emissions and the generation of valuable by-products.

Materials and Methods

The aim of this study is to assess the extent to which biofuel production from agricultural feedstocks competes with food production for land resources in Poland and to examine its impact on feedstock availability for animal feed, export levels, and farm income.
The analysis addresses a research gap concerning the competition between biofuels and food production in Poland. Existing studies have primarily focused on the efficiency, volume, and emissions associated with biofuel production, while land-use competition has received less attention.
The empirical analysis is based on data from official statistical sources and records of feedstocks used in agricultural biogas production. The dataset includes information on the production volumes of biogas, bioethanol, and biodiesel (fatty acid methyl esters), as well as the quantities of feedstocks used in agricultural biogas plants. These data are derived from databases of Statistics Poland and reports of the National Support Centre for Agriculture (KOWR). The analysis covers the period 2005–2024. Data on feedstock consumption for agricultural biogas production are available from 2011 onwards; therefore, this shorter period is applied to the biogas analysis. The starting year reflects the fact that the official production of methyl esters in 2004 was zero (Izdebski et al., 2014).
Feedstock use for bioethanol and biodiesel production was estimated based on the energy output of biofuels. The following conversion factors were applied: 37.3 MJ per Mg of biodiesel and 26.8 MJ per Mg of bioethanol, in line with KOWR data. These values were cross-validated by comparing the quantities of biofuels in circulation (KOWR) with the corresponding energy production reported by Statistics Poland, ensuring consistency. The estimated biofuel volumes were then converted into feedstock use,

specifically cereal grains and rapeseed. An average ethanol yield of 340 litres per tonne (Michalski, 2007) and a density of 0.778 kg per dm³ were assumed. For biodiesel, an oil yield of 435 litres per tonne and an average density of 0.919 kg per dm³ were applied (Dz.U. 2025 poz. 545, 2025).

The area allocated to biofuel production was calculated based on annual feedstock consumption and the average yields of cereals, rapeseed, and other energy crops in that year. The analysis also accounts for the volume of energy crops used in biogas production and their yields. The total estimated area devoted to biofuel production was then related to Poland's total sown area in each year. The dynamics of changes over the study period were assessed using an exponential growth function.

Results and Discussion

Industrial-scale biofuel production in Poland began during the pre-accession period. Earlier, neither a political demand nor an appropriate regulatory framework existed, partly due to the need to rebuild the productive capacity of Polish agriculture following the economic transition. Data on biofuel energy production are presented in Table 3. In the initial phase, bioethanol production dominated. Until 2007, up to 200 thousand hectares (less than 2% of arable land) were allocated to biofuel feedstock production.

Table 3

Production area, share in arable land area and dynamics of biofuel crop production

Year	Area of arable land# dedicated to energy crops in ha				Share of arable land dedicated to energy crops in per cent			
	cereals for bioethanol	rapeseed for biodiesel	crops for biogas@	total	cereals	rapeseed	biogas	total
2005	86,281	59,570	–	126,819	0.8	0.5	0.0	1.3
2006	139,332	84,081	–	192,678	1.2	0.7	0.0	1.9
2007	134,512	44,426	–	149,267	1.2	0.4	0.0	1.6
2008	106,924	241,510	–	324,848	0.9	2.1	0.0	3.0
2009	149,237	296,130	–	412,447	1.3	2.5	0.0	3.8
2010	165,690	402,333	–	531,473	1.6	3.9	0.0	5.4
2011	143,969	406,132	2,311	520,654	1.4	3.8	0.0	5.2
2012	189,812	602,973	4,783	755,698	1.8	5.8	0.0	7.6
2013	194,716	551,865	6,770	710,399	1.9	5.4	0.1	7.3
2014	141,794	537,073	12,344	659,934	1.4	5.2	0.1	6.6
2015	153,712	755,020	11,234	886,059	1.4	7.0	0.1	8.6
2016	197,651	840,025	15,674	1,009,750	1.9	7.9	0.1	10.0
2017	174,601	808,728	20,072	964,885	1.6	7.4	0.2	9.2
2018	184,060	835,432	19,245	998,136	1.7	7.6	0.2	9.4
2019	207,380	888,027	16,052	1,065,713	1.9	8.0	0.1	10.1
2020	160,480	748,291	18,611	891,981	1.4	6.7	0.2	8.3
2021	204,727	770,361	21,235	951,163	1.8	6.9	0.2	8.9
2022	235,487	738,327	20,854	942,723	2.1	6.6	0.2	8.9
2023	244,354	718,488	21,716	930,657	2.2	6.4	0.2	8.8
2024	315,268	789,702	26,799	1,062,224	2.8	7.1	0.2	10.2
CAGR$ 2005-2024 in %	4.15	12.65	14.28	9.36	4.22	12.71	13.63	9.42
CAGR 2015-2024 in %	5.76	-0.95	6.51	0.63	5.24	-1.46	5.99	0.11

– The total area of arable land in Poland has been decreasing over time. In the period under analysis, it ranged from 11 to 11.4 million hectares; @ - in the years 2005-2010, no records were kept of raw material consumption for biogas production due to the very small number of biogas installations; $ - CAGR was calculated using an exponential function.

From 2008 onwards, biofuel production increased dynamically following the introduction of mandatory blending requirements in transport fuels. Energy consumption from biofuels rose from 12 TJ in 2008 to over 45 TJ annually in 2021–2024, implying a substantial increase in feedstock demand. In 2008–2010, approximately 0.47 million tonnes of cereals and 0.84 million tons of rapeseed were used annually for biofuel production; by 2022–2024, these figures had increased to 1.3 million tonnes and 2.5 million tonnes, respectively – roughly a threefold rise.

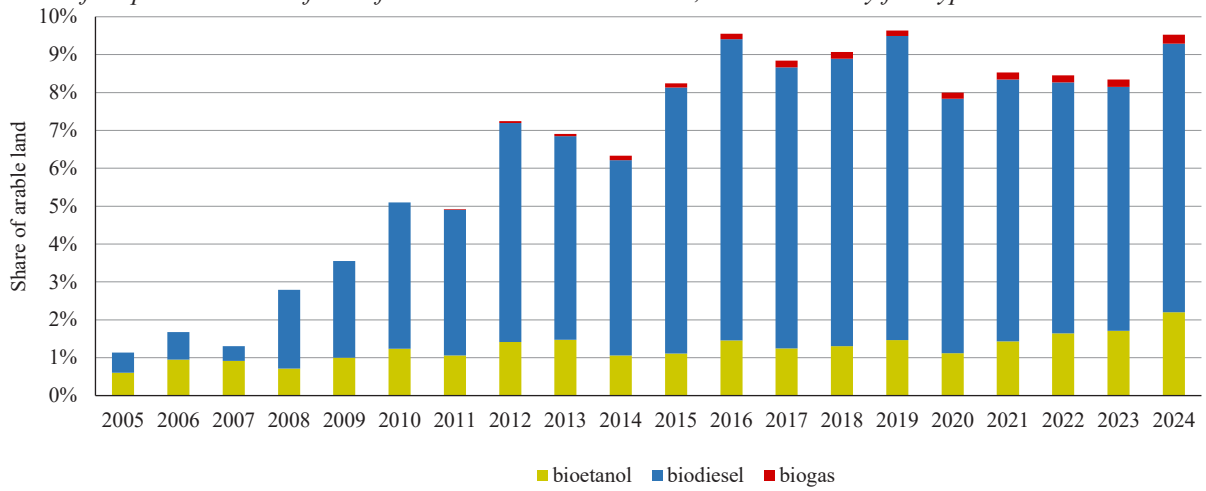
The area devoted to feedstock production increased from approximately 0.45 million hectares in 2008–2010 (4.1% of arable land) to 1.04 million hectares (9.3%) in

2022–2024. The average annual growth rate of this area was 9.8%, with the most rapid expansion occurring between 2005 and 2015, followed by a period of stabilisation. Notably, the area allocated to biodiesel feedstocks remained stable after 2015, while the area for bioethanol feedstocks grew at an annual rate of 5.7%.

As shown in Figure 1, the share of arable land used for biofuel production increased from around 3% in 2008 to over 8% in 2015, after which it stabilised. In terms of crop structure, rapeseed dominated throughout most of the period. While its share ranged from 25–40% until 2007, it increased to 70–80% after 2010. This is significant because rapeseed cultivation requires high-quality soils, which constitute less than 30% of agricultural land in Poland. This suggests competition for higher-quality land. In contrast, crops used for biogas production accounted for only around 2% of the total area, reflecting the relatively limited development of this sector due to scale requirements, investment costs, and technological specificity.

Figure 1

Share of crop area intended for biofuels in Poland in 2005–2024, broken down by fuel type



Overall, biofuel feedstock production currently occupies approximately 1.1 million hectares, or about 10% of Poland's arable land, consistent with earlier projections made at the time of introducing blending mandates (Krasowicz, 2008). Despite this, there is no clear evidence of strong, direct competition between biofuel and food production for land.

Research conducted by IUNG indicates that competition for cereals between food and biofuel uses diminishes once yields exceed 3.9 t·ha^{-1} and total production reaches approximately 30 million tonnes (Krasowicz, 2009). This threshold was surpassed in 2014, with yields subsequently increasing to nearly 4.5 t·ha^{-1} (Runowski et al., 2023). Demand for feed and food grains remained stable, while total production grew and exceeded 35 million tonnes (Statistics Poland [SP], 2025). There is also no evidence that biofuel production has driven increases in cereal prices; observed price fluctuations were linked primarily to global market conditions (e.g., in 2009 and 2022). In fact, some studies suggest that biofuel demand may stabilise markets and reduce price volatility (Kalicki, 2010). Faced with an oversupply of grain in the EU and low local and export prices in some years, which make production unprofitable, EU Commissioner C. Hansen even called for increased biofuel production to reduce competition in the grain market (Cenyrolnicze.pl, 2026).

The amount of cereal grain available after use for biofuels was 26.3 million tons between 2005 and 2009, and 28.0, 28.4 and 34.2 million tons in the subsequent five-year periods, respectively. Disposable surpluses increased, suggesting a lack of competition for land. For rapeseed, these surpluses were 1.6, 1.0, 0.2, and 0.9 million tons. On average, this was sufficient for edible oil production, but 85,000 tonnes of biodiesel had to be imported annually for transport fuel. This amount would require an additional 0.6% of arable land (approximately 63,000 hectares). In the case of rapeseed, given the lack of competition for land in Poland, such competition is also not being generated in other countries.

Biofuel production in Poland does not appear to directly compete with food production. During the same period in which first-generation biofuel production expanded, exports of agri-food products also increased (Kraciński et al., 2023). Currently, around 30% of agricultural output has to be exported, often to highly competitive markets. Agricultural exports exceed USD 58 billion, with a trade surplus of approximately USD 20 billion. This reflects rising productivity alongside relatively stable domestic demand. Earlier studies also noted a surplus of agricultural land in Poland relative to food production needs at the observed level of productivity (Roszkowski, 2008). Competition for feedstocks may therefore be more relevant in countries without such production surpluses.

The production of raw materials for biofuels, especially rapeseed, is economically attractive for farmers, as it allows relatively high economic surpluses per hectare with high sales certainty. This

indicates that production levels are strongly influenced by policy instruments, including blending mandates.

Bioethanol production has also benefited farmers, particularly through the utilisation of maize, which helps absorb surpluses in feed grain markets. Maize can be cultivated in monoculture using relatively simple technology and, due to higher yields, generates higher economic returns. The area under maize for grain in Poland increased by 0.8 million hectares between 2013 and 2024, while production rose from 2 to 9 million tonnes (Statistics Poland, 2025).

When maize yields exceed the national average, bioethanol production meets GHG emission reduction requirements under the RED Directive (Jarosz et al., 2017). Similar results have been observed for other cereals (rye, wheat, triticale) (Wiśniewski & Kistowski, 2020), although lower emissions per unit are typically associated with higher production intensity (Wicki et al., 2025). This suggests that cereal-based biofuel production can be considered sustainable under appropriate technological conditions and on high-quality soils. However, this may result in food production being displaced to less favourable land. Thus, competition for land in Poland appears to be partial and primarily concerns high-quality soils – an issue also recognised by farmers themselves (Wyszomierski et al., 2025).

While meeting emission standards is essential, it is also important to consider potential negative environmental effects, such as the expansion of maize monocultures.

A positive outcome of biofuel production is the increased availability of by-products such as rapeseed cake and distillers' dried grains with solubles (DDGS). These are valuable protein feed components and serve as substitutes for imported soybean meal (Klepacka et al., 2019). Rapeseed meal accounts for approximately 60% of the mass of rapeseed used for biodiesel production, while DDGS amounts to around 300 kg per tonne of processed grain. In total, this allows us to obtain around 2 million tonnes of high-value protein feed per year, most of which would otherwise have to be imported.

Conclusions

1. The area allocated to biofuel feedstock production in Poland increased fivefold between 2005 and 2024, reaching approximately 1.1 million hectares (9.5% of arable land), with rapeseed dominating the structure.
2. This growth was primarily driven by policy-induced demand (mandatory blending), supported by the relative profitability of energy crops and compatibility with existing production technologies.
3. No strong evidence of direct competition between biofuel and food production was identified; agricultural output exceeded domestic demand, and biofuel demand contributed to partial market stabilisation.
4. The limited land competition can be explained by productivity gains, higher yields and total output, which allowed additional production to be directed toward biofuels without reducing food supply.
5. Competition may occur for higher-quality land, as rapeseed and maize require more fertile soils, leading to unequal access to benefits among farmers.
6. While biofuel production generates benefits such as by-products for feed and income stabilisation, it also entails risks, including monoculture expansion and emission intensity under less efficient production conditions.

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ANALYSIS OF THE TAX BURDEN IN AGRICULTURAL FARMS OF VARIOUS SPECIALIZATIONS, A CASE STUDY OF LATVIA

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Abstract
The aim of the study is to investigate changes in the tax burden in agriculture and its sub-sectors in Latvia in order to determine the factors contributing to the increase in the tax burden. The hypothesis put forward for the study is that the increase in the tax burden in agriculture in Latvia is mainly caused by the increase in the tax burden on the labor force, which affects labor-intensive sub-sectors more. The article describes the composition of taxpayers in the sector, analyzes the dynamics of tax payments and benefits in the sector, and analyzes changes in the tax burden in agricultural enterprises of various specializations. The study concluded that the tax burden differs significantly in farms of various specializations. Due to the higher share of labor costs, compared to other sectors, the highest tax burden is in Vegetable Growing and Permanent Plantation Farms, and it is predicted that the tax burden could increase the fastest in these farms in the future. It should be positively assessed that the most rapid increase in support in Latvia is directly in the Horticulture and Permanent crops farms, which is related to the priority opportunities for these specialized farms to receive support payments when evaluating the projects submitted by support applicants, as well as a significant increase in support specifically for vegetable growing and fruit growing.
Keywords: agricultural taxes, tax reliefs, tax burden, agricultural sub-sectors.

Introduction

In recent years, agriculture, like other sectors in Latvia, has faced various challenges - as a result of the geopolitical situation, production costs have significantly increased, inflationary pressure and the lack of an adequate workforce contribute to a rapid increase in labor costs, crops have been lost due to climatic conditions, etc. However, there are significant differences between farms of different sizes and specializations in the sector. Subsidies and tax reliefs are one of the main fiscal instruments for supporting the agricultural sector. The sector is subsidized mainly using EU support payments, while national support for the sector is in the form of tax reliefs and discounts. However, despite the fact that farmers in Latvia receive very significant tax reliefs, the tax burden in agriculture is increasing.

The aim of the study is to investigate changes in the tax burden in agriculture and its subsectors in Latvia in order to determine the factors contributing to the increase in the tax burden. The hypothesis put forward is that the increase in the tax burden in agriculture in Latvia is mainly caused by the increase in the tax burden on labor, which affects labor-intensive subsectors more. The tasks set for the study: 1) to characterize the composition of taxpayers in the sector, 2) to analyze the dynamics of tax payments and benefits in the sector, and 3) to analyze changes in the tax burden in agricultural subsectors.

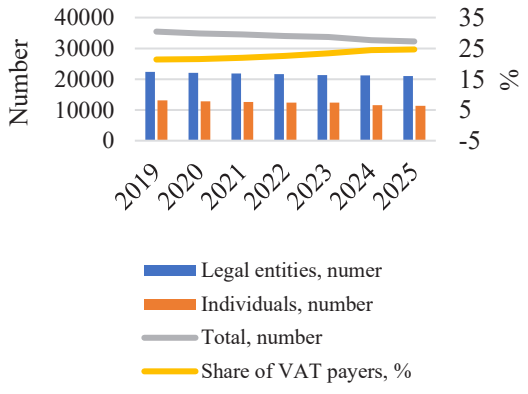
Materials and Methods

The empirical framework of this research relies on the monographic and descriptive methods, supplemented by structural analysis and synthesis, as well as statistical and graphical data processing. The present research is based on various scientific publications, information available in databases and other sources. It covers the period from 2019 to 2025, although in some cases the period is shorter due to data unavailability.

Results and Discussion

The number of agricultural enterprises (NACE A01 Crop and animal husbandry, hunting and related support activities) in Latvia at the beginning of 2025 is 32,247; however, it has been decreasing every year (Figure1), over the last 6 years by an average of 1.6% per year. This is mainly due to the closure of small farms as a result of competition, as well as generational change, as fewer and fewer young people choose to continue the farming started by their parents. As researchers acknowledge, despite the policy instruments introduced in Latvia after joining the EU to support young farmers and promote early retirement of farm owners, the aging process of farm owners and managers is occurring relatively rapidly (Nipers & Pilvere, 2020).

Figure 1
Changes in the number and type of taxpayers in agriculture (NACE A01) at the beginning of 2019 - 2025



Source: authors' calculations based on the data of the SRS.

The structure of enterprises is also changing, with the proportion of legal entities gradually increasing - from

63.1% in 2019 to 65.0% in 2025, while the proportion of natural persons (homestead farms) is decreasing accordingly. It should be positively assessed that both the number and proportion of value added tax (VAT) payers are increasing, from 21.4% to 24.6%, respectively. However, it is still very small, which means that approximately ¾ of farmers' economic activity turnover is less than 50 thousand euros per year, which is the VAT payer registration threshold.

At the beginning of 2025, mixed farming (crop growing and livestock farming, NACE A0150) constituted the most prevalent form of agricultural activity in Latvia, accounting for 61.2% of all registered holdings. However, as the specialization of farms increases, the proportion of these farms decreases, as in 2019 they were 65.0% of farmers. The largest increase is in growing of cereals, legumes and oilseeds (NACE A0111), i.e. from 9.8% to 11.4% of farmers. Moreover, this specialization exhibits the highest concentration of VAT payers, comprising 50.4% (more than half) of all farmers at the beginning of 2025. The number and share of other animal breeding (NACE A0149) farms has also increased from 2.31% to 2.6%, as well as the number and share of other cattle breeding (NACE A0142) farms from 2.1% to 2.3%, and the number and share of sheep and goat breeding (NACE A0145) farms from 0.6% to 0.7%. In turn, the number of pig breeding (NACE A0146) farms is decreasing, maintaining its share of 0.2%. However, it should be noted that these represent relatively larger farms, as VAT payers accounted for 46.2%. of the sector the beginning of 2025. The most significant decrease in the number and proportion is for Dairy farming (NACE A0141) farms, i.e. their number has decreased by 11.7% in the study period. As of early 2025, they are only 6.2% of farms. The proportion of Vegetable growing (NACE A0113) farms has increased slightly (from 4.4% to 4.7%); however, their number has also decreased by 4.4% in the study period. It can be predicted that the specialization of farms and the increase in the proportion of VAT payers will continue in the coming years.

The fact that most agricultural enterprises are very small is also confirmed by the low proportion of employers in the sector, in 2024 only 15.0% of farms are employers, which has only slightly increased compared to 14.0% in 2019. The largest proportion of employers is in pig farming enterprises 42.1%, in other livestock enterprises it fluctuates around 20%, in grain farming 35.5%, in vegetable farming 13.8%, in mixed specialization farms 10.2%. The number of paid jobs also continues to decrease in the agricultural sector (Table 1), i.e. from 2019 to 2024 by 6.1%. The most rapid decrease in the number of employees is in livestock farming and vegetable farming, while it has increased in grain farming (+6.7). The largest number of people working in the sector are employed in mixed agricultural holdings (36.1%) and in cereal farming (27.5%), dairy farming (9.3%) and vegetable farming (5.1%). The decrease in the number of employees indicates both an increasing trend in the use of technology and a more intensive use of labor. Wages are increasing accordingly. However, there are significant differences between different agricultural sub-sectors. As researchers acknowledge, the labor intensity decreases with expanding farm scale; nevertheless, a greater divergence is evident among distinct types of agricultural production. The greatest demand for labor in Latvia is for perennial crops, vegetable and potato growing and dairy farming, while the least is for energy crops and grassland systems (Veipane et al., 2025).

Table 1

Changes in the number of jobs and gross wages in the agricultural sector as a whole and in subsectors with the largest number of employees in 2019 and 2024

NACE code, sector, class	Number of jobs where income was earned				Average monthly gross income, EUR			
	2019	2024	*2024/ 2019*	*from the industry total (%)*	2019	2024	2024/ 2019 (%)	from the industry total (+/-, %)
A 01 Crop and livestock farming, hunting and related support activities	21,142	19,851	*-6.1*	*100.0*	664	1,092	*64.4*	*0.0*
0150 Mixed farming	8,162	7,165	*-12.2*	*36.1*	569	974	*71.1*	*-10.8*
0111 Cultivation of cereals, pulses and oilseeds	5,108	5,449	*6.7*	*27.5*	753	1,175	*55.9*	*7.6*
0141 Dairy farming	2,045	1,842	*-10.0*	*9.3*	570	1,036	*81.8*	*-5.1*
0147 Poultry farming	1,410	1,361	*-3.4*	*6.9*	1,175	1,723	*46.6*	*57.8*
0113 Vegetable farming	1,124	1,021	*-9.2*	*5.1*	575	982	*70.7*	*-10.1*
0146 Pig farming	597	486	*-18.5*	*2.4*	1,032	1,675	*62.2*	*53.4*

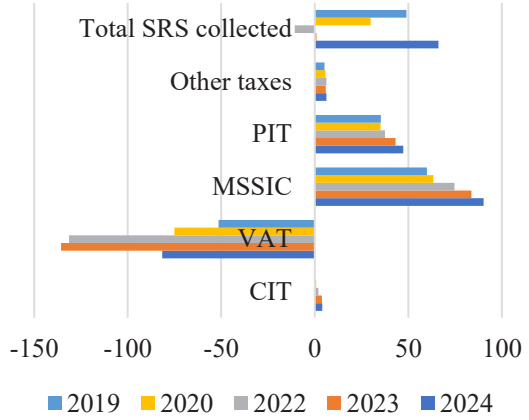
Source: authors' calculations based on the data of the SRS.

Wages in agricultural enterprises remain relatively low, averaging 1,092 EUR per month in 2024 (Table 1), which constitutes 75.0% of the national average in Latvia. Nevertheless, this represents an improvement compared to 2019, when agricultural earning stood at just 71.6%. The highest wages in the sector are in poultry farming (1,723 EUR in 2024) and pig farming (1,675 EUR), which also significantly exceeds the national average. However, comparing 2024 to 2019, the growth in these sub-sectors (+46.6% and 62.2%, respectively) is less rapid than in the sector as a whole (+64.4%). The fastest wage increase was in dairy farming (+81.8%), mixed farming (+71.1%) and vegetable farming (+70.7%), which can be assessed as very rapid. Nevertheless, it should be noted that the increase in gross wages in the country as a whole during this period is also rapid (+56.8%), which is mainly caused by the increase in inflation and the increasing shortage of qualified labor.

When evaluating the statistical data of the State Revenue Service (SRS), the largest tax payments in agriculture are made up of labor taxes (Figure 2), i.e. more than 90% of the taxes administered by the SRS are related to mandatory state social insurance contributions (MSSIC) and personal income tax (PIT) for employees and farmers themselves as self-employed persons. VAT payments are not taken into account in the calculations, because they do not constitute a tax burden for entrepreneurs, as they are consumption taxes paid by buyers. In addition, reverse charge is applied to the sale of cereals in Latvia, which means that the seller of cereals does not calculate VAT, but he has the right to use VAT input tax, which significantly reduces the costs of his economic activity. Considering that grain and mixed agricultural enterprises are the largest taxpayers in the sector, overall VAT payments in the agricultural sector are negative. Negative VAT payments are also made by vegetable growers, because since 2020 a reduced VAT rate has been applied to vegetables (5% in 2020-2023, 12% since 2024). As a result, the calculated VAT is less than the input tax, and farmers have a VAT overpayment, which they recover from the state budget or use to pay other taxes. The largest VAT refunds for the sector were 131.3 million euros in 2022 and 135.6 million euros in 2023, which resulted in the total tax payments administered by the SRS for the sector being negative (-10.8 million euros in 2022) or very small (1.0 million euros in 2023). This effect is also caused by the fact that farmers are very actively using EU support for the modernization of farms, purchasing new machinery and technologies, using the opportunity to recover input VAT on their purchase. It can be predicted that the effect of VAT overpayment in the sector will continue, because in order to achieve the set goals in environmental protection, the need for greater financial support is increasing, including financing for advanced technologies to help offset the costs of transformation (Beizitere, 2025). When analyzing the tax burden, it should be noted that the SRS calculations do not take into account real estate tax, because it is collected by municipalities, but it must be recognized that it creates increasingly large costs for farmers.

Figure 2

Tax payments in the agricultural sector (NACE A01) (excluding real estate tax) in 2019 - 2024, mln EUR



Source: authors' calculations based on the data of the SRS.

To promote the reinvestment of profits for the development of the company, a tax reform was carried out in Latvia in 2018, shifting the calculation of corporate income tax (CIT) from the profit earned to the moment when the profit is distributed in dividends or when expenses not related to economic activity are incurred. As a result, in the first years after this reform, CIT payments decreased rapidly or in some cases were even negative, receiving CIT overpayments from the state budget for previous years. Only gradually did CIT payments return to the pre-reform level. According to the assessment of some specialists, the tax reforms implemented in Latvia in 2018 can also be assessed positively for the bioeconomy sectors. The most significant investments of these sectors are in CIT payments and in the field of social security, as the bioeconomy sectors account for 24% and 20% of the state budget tax revenues, respectively (Upite et al., 2022). However, the authors of this study only partially concur with this assertion. In agriculture - a key sector of the bioeconomy - tax payments were relatively unaffected by the tax reform due to the substantial tax reliefs granted to farmers both prior to and following its implementation.

Overall, during the analyzed period, the sector's tax payments increased relatively rapidly by 47.3%; however, this growth rate trailed the national average of 53.4% across all economic sectors in Latvia. This rapid increase in the sector was mainly caused by 50.7% increase in social security contributions, which constitute the largest single tax payments both at the national level and within the agricultural sector (where contributions reached 90.3 million euros in 2024). The rapid increase in the amount of social security contributions is associated with the increase in the

minimum wage (430 euros in 2019 to 700 euros in 2024) and the increase in the minimum social security contribution rate for the self-employed from 5% to 10% on 1 July 2021, as well as with the increase in wages described above. For these reasons, the increase in the MSSIC is expected to continue. The second fastest growth in tax payments is CIT (35.4%); however, the amounts are relatively small (4.0 million euros in 2024), since the proportion of large farms and, consequently, the proportion of CIT payers in agriculture is small. Most agricultural enterprises still do not exceed the turnover of 300 thousand euros per year and therefore pay PIT on income from economic activities. The increase in PIT payments is also relatively rapid (by 33.9%). The increase in both CIT and PIT payments was mainly caused by the increase in farmers' income, which was facilitated by both the increase in agricultural product prices and labor productivity. Although sectoral data for 2025 is not yet available, fiscal yield from these two tax categories is expected to diminish. This projected decline is linked to suppressed agricultural profits, precipitated by a reduction in the gross agricultural product under the influence of adverse climatic conditions.

Farmers' tax payments are reduced by tax incentives and rebates specifically granted to the sector (Table 2). Sector-specific tax incentives are available in almost all taxes. The exception is the natural resources tax (NRT), which is paid for the use of natural resources, environmentally harmful activities and the use of packaging materials by all taxpayers under the same rules. In turn, any taxpayer, regardless of the sector, can reduce NRT payments by using environmentally friendly technologies and taking measures to reduce the impact on the environment. The agricultural sector in Latvia is the only one to which such significant tax incentives are applied, their aim is to promote the production of agricultural products and ensure farmers' income support and sustainable operations. The excise tax, company car tax and vehicle operation tax rebate depend on the amount of agricultural income in a particular company, so sometimes farmers cannot use them in full, especially in years unfavorable for agricultural production. The labor tax relief for fruit and vegetable growers is positively evaluated, i.e. the opportunity to employ seasonal workers under preferential terms, applying a lower tax rate, which allows reducing the increase in the tax burden in the sector. Compared to 2019, the number of employers hiring seasonal agricultural workers under preferential terms experienced a more than twofold increase by 2024, rising from 230 to 473. The number of agricultural workers themselves has increased slightly, i.e. from 3240 to 3823, or only by 18.0%, which can be explained by the fact that one agricultural worker can work for several farmers at the same time, working a few hours a day or a few days a month.

Table 2

Tax reliefs in agriculture in Latvia in 2026

Type of tax	Reliefs for farmers
CIT	The CIT taxable object is reduced by 50% of the subsidies received per year
PIT	Tax-exempt income from EU and national subsidies for agriculture and rural development. Relief for income from agriculture and rural development ≤ 3,000 EUR/year
MSSIC	Tax-exempt: EU and state subsidies for agriculture and rural development. Self-employed farmers pay a reduced rate of 10% of annual income if income is less than the minimum wage. Farmers of retirement age, disabled persons of Groups 1 and 2 are exempt from social security contributions
Labour taxes	In growing fruit trees, berries and vegetables, picking stones, smaller tax is paid for seasonal agricultural workers - 15% of gross wage (of which 10% are redistributed as PIT and 90% as MSSIC)
VAT	Entities not paying VAT receive a 14% compensation on agricultural produce supplied to processing companies or cooperatives. A reduced VAT rate of 12% applies to fruits, berries and vegetables, as well as temporarily (1.07.2026.–30.06.2027.) to the sale of milk, poultry meat, eggs
Excise	Lower tax – 15% from rate is paid for diesel fuel, according to the norm set for each sector (liters/ha) if the income from agriculture is at least 450 EUR/ha, for organic farms 270 EUR/ha
VOT	For trucks farmers pay 25% of the tax amount if income from agriculture ≤ 5,000 EUR per car, 70,000 EUR for each subsequent car
CCT	Exempt from tax on company`s vehicles (cars) if income from agriculture ≤ 5,000 EUR per car, 70,000 EUR for each subsequent vehicle

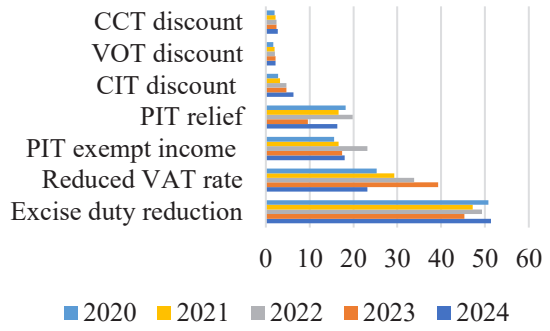
IPT - Immovable property tax, VOT – Vehicle operation tax, CCT – Company car tax.
Source: author's construction based on the tax laws of the Republic of Latvia.

The Ministry of Finance's data by sector is available for the period from 2020 to 2024 (Figure 3). The largest discount amounts are the reduced excise tax rate (15% of the full rate) for diesel fuel, which in 2019 reduced farmers' costs by 40.2 million euros, but in 2024 by 51.4 million euros.

The next largest impact on state budget revenues is the reduced VAT rate for fruits, berries and vegetables.

However, as already mentioned above, VAT and its rate reduction do not have a direct impact on the farmer's costs. It affects the consumption of these products, and it should reduce the price of these products and promote greater consumption of them. However, as researchers observe, the most significant impact on price reduction of the reduced VAT rate was only in the first year after the rate reduction (Nipers, 2019).

Figure 3
Tax reliefs in agriculture in Latvia 2020 – 2024, mln EUR



Source: authors' calculations based on the data of the Ministry of Finance.

PIT discounts are very important for small farmers. The opportunity not to pay PIT for income up to 3,000 euros per year can be used by every small farmer; however, often the actual income of the farmer, excluding subsidies, is less than this amount, so the discount is not always used in full. In a year favorable for farmers, income and, consequently, the possibilities of using the discount increase. It is difficult to explain why the PIT rebate for EU and state support for agriculture and rural development (subsidies) received decreased in 2023 (only 9.5 million euros, while in 2024 it was already 16.3 million euros again), because in previous years it increased steadily. In addition, the amount of subsidies received has also increased every year. It is possible that this can be explained by the application of the cash principle in filling out the annual income declaration and calculating PIT, because during the taxation period only the amounts actually received are recognized as income, including from subsidies. The CIT rebate is relatively small (6.3 million euros in 2024), because the proportion of CIT payers in the sector is small, as they are only large agricultural enterprises (13.9% in 2024) (Table 3). However, the amount increases every year, because these farmers have accumulated a large amount of retained earnings. This is also evidenced by the rapidly increasing amount of positive equity in the companies of the sector (+60.0%), which significantly exceeds the increase in net turnover (+34.8%). In the year 2024, the amount of profit even decreased (- 17.9%), while the amount of losses increased 2.6 times.

Table 3
Dynamics of the number of annual report submitters and financial results in the annual reports of agricultural companies in 2019 and 2024

Year	Number of annual reports	% of taxpayers in the sector	Thousand EUR						
			Net turnover	Profit	Loss	Long-term investments	Curent assets	Equity (positive)	Equity (negative)
2019	4,135	*11.7*	1,360.0	233.2	-27.1	2,303.2	897.2	1,653.0	-44.0
2024	4,492	*13.9*	1,833.5	191.4	-98.4	3,329.4	1,314.3	2,644.6	-44.4
2024/ 2019	*8.6*	*19.4*	*34.8*	*-17.9*	*263.8*	*44.6*	*46.5*	*60.0*	*0.9*

Source: authors' calculations based on the data of the SRS.

Despite the poorer results in the sector, in 2024, long-term investments (+44.6%) and working capital (+46.5%) increased significantly, which was ensured by the favorable 2022 and 2023 for farmers, as well as the targeted use of subsidies. Per agricultural enterprise, the largest amount of long-term investments at the end of 2024 is in poultry farming (3920 thousand euros) and pig farming (3258 thousand euros), which demonstrates large investments for long-term development. Enterprises in other sub-sectors have significantly smaller volumes - in agriculture an average of 741 thousand euros per enterprise. Per company that has submitted an annual report, the equity capital in the agricultural sector is higher than the average in Latvia (579 and 412 thousand euros, respectively), in the agricultural sector it is highest in pig farming (3214 thousand euros) and poultry farming (2799 thousand euros). It should be noted that these indicators do not characterize the sector as a whole, since only a small part of farmers submit annual reports; however, the number and proportion of these companies increase every year, which indicates an increase in the net turnover of companies, since farms must prepare an annual report if their income from economic activities exceeds 300 thousand euros per year. There are significant differences between sub-sectors. The highest proportion of those submitting annual reports is in pig farming (38.5% in 2024), grain farming (35.0%) and poultry farming (24.8%), which indicates an increasing concentration of production in larger companies.

The concentration of agricultural production is also

shown by Farm Data Accounting Network (SUDAT, 2026) data. Between 2019 and 2023, the calculated economic size of a farm increased by 1.7 times on average (EUR), most rapidly in mixed specialization (2.0 times), pasture livestock breeding (1.8 times), permanent crops (1.8 times) and dairy farming (1.7 times) farms. In turn, the highest economic size on average is estimated in pig farming and vegetable farming farms; however, significant differences between farm size groups should be considered.

Using SUDAT data (2026), it is also possible to analyze the production support received and the tax burden in enterprises of various specializations (Table 4). Significantly higher production support has been in cattle rearing and fattening, sheep and goats and mixed livestock (573.6 and 449.5 EUR per 1000 EUR of output, respectively). A positive development within the sectoral framework is the rapid expansion of funding for horticulture and permanent crops; allocations in 2023 represented a 6.6-fold and 2.7-fold increase, respectively, relative to 2019 levels. This is due to the priority opportunities for these specialization farms to receive support payments, evaluating the projects submitted by support applicants, as well as a significant increase in support specifically for vegetable growing and fruit growing in Latvia since 2023. In addition, the tax burden (excluding VAT) for farms in this specialization is also the highest – more than 11% of net turnover, which is associated with higher labor costs compared to farms in other specializations. In turn, the increase in labor costs results in a faster increase in the tax burden, in vegetable growing by 1.4 times compared 2019 to 2023. While mixed livestock saw an even sharper increase of 2.1 times in tax burden, their total tax contributions remain the lowest in the agricultural sector.

Table 4

Production support and tax burden on farms of various specializations in 2023 compared to 2019

Farm specialization	Tax burden (excluding VAT)/ net, %		Production aid per output 1000 EUR	
	2023, %	*2023/2019*	2023, EUR	*2023/2019*
All farms	*7.2*	*1.04*	203.9	*1.1*
Permanent crops	*11.4*	*1.08*	277.6	*2.7*
Horticulture	*11.1*	*1.40*	13.1	*6.6*
Mixed cropping	*8.9*	*1.01*	139.0	*1.0*
Mixed farming	*8.6*	*1.17*	239.0	*0.9*
Dairying	*8.0*	*0.93*	220.0	*1.0*
Cattle rearing and fattening, sheep and goats	*7.8*	*0.92*	573.6	*1.3*
Pigs and poultry	*6.5*	*1.06*	80.8	*1.1*
Field crops	*6.4*	*1.08*	185.4	*0.9*
Mixed livestock	*5.4*	*2.10*	449.5	*2.3*

Source: authors' calculations based on the data of SUDAT, 2026.

It must be acknowledged that EU support payments play a very important role in the economic growth of farms. As researchers point out, the support of the Common Agricultural Policy (CAP) has contributed not only to the increase in the net income of farms, but also to the increase in the value of their total production (Nipers et al., 2025). The CAP support policy in Latvia must be further adjusted in order to achieve more efficient use of resources, increase labor productivity per employee and per hectare of arable land, as well as promote sustainable agriculture, thus achieving a balance between agricultural efficiency, productivity and environmental sustainability (Pilvere et al., 2025). However, the authors of the article emphasize that in order to promote the development of the sector, it is important not only to adjust the CAP support policy, but also to significantly evaluate the tax reliefs existing in Latvia and their effectiveness in achieving the set goals. The practice applied so far, to exempt all support payments for agriculture and rural development from taxation, contributes to the income inequality that is already characteristic of Latvia. Inequality is also promoted in a regional context (Leibus et al., 2022). Allocating a greater share of direct support payments to vegetable and fruit farms would promote a more equitable regional distribution of income. Furthermore, it would attract labor to rural regions, enhance rural landscape diversity, and improve consumer access to locally produced vegetables and fruit.

Conclusions

1. In Latvia, the total number of farms in the agricultural sector continues to decrease, which is caused by the cessation of operations of very small farms. In turn, larger farms are strengthening, which is evidenced by the increase in the proportion of legal entities and VAT payers. These changes are most rapidly observed in grain growing and dairy farming enterprises.

2. The number of paid jobs in the sector continues to decrease. In turn, wages, although still lower than the average in Latvia, are increasing more rapidly. However, there are significant differences between

different agricultural sub-sectors. The fastest increase in wages is in dairy farming, mixed farming and vegetable growing farms.

3. The largest tax payments are made up of labor taxes, and their burden is expected to increase in the future due to the annual increase in the minimum wage and the shortage of appropriately qualified labor. In accordance with higher labor costs, compared to other sectors, the heaviest tax burden is concentrated within vegetable growing and permanent plantation farms. Furthermore, projections indicate that these specific farm types will continue to experience the most rapid escalation of their tax burden in the future.

4. State support for agriculture is mainly expressed in the form of tax incentives and discounts, as a result of which the tax burden in agriculture is significantly lower than in other sectors. The most significant tax incentives are the excise tax discount for the purchase of diesel fuel and tax-free income from agricultural production and subsidies.

5. The EU and state support has contributed to a significant increase in long-term investment and equity capital of agricultural enterprises, especially in pig farming and poultry farming enterprises.

6. Significantly higher production support, calculated on 1000 euros of output, has been in cattle rearing and fattening, sheep and goats and mixed livestock. Since 2023, the most rapid increase in support has been in horticulture and permanent crops farms, which is associated with the priority opportunities for these specialization farms to receive support payments when evaluating the projects submitted by support applicants, as well as a significant increase in support specifically for vegetable and fruit growing.

7. The results of the study confirm the hypothesis put forward - the tax burden is higher on farms with higher labor costs. Therefore, the redirection of larger support payments to horticulture and perennial crop farms is positively assessed. Such targeted funding would foster a more equitable regional income distribution, attract labor to rural regions, enhance the rural landscape diversity, and provide consumers with locally produced vegetables and fruit.

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RETHINKING HUMAN CAPITAL INDICATORS IN REGIONAL ANALYSIS BASED ON EVIDENCE FROM LATVIA

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Abstract
This study addresses the critical problem of interpreting human capital indicators arising from a structural mismatch between administrative territories and functional labour markets. While traditional socio-economic indicators are statically aggregated within official administrative boundaries, increasing institutional and physical mobility increasingly decouples an individual's place of residence from their actual site of economic activity. The study aims to evaluate this structural mismatch between administrative and functional human capital indicators by developing a comprehensive conceptual framework for their recontextualisation, introducing the 'Regional Living Space' model. Using Latvian experimental statistics (NPV03x) dataset for the period from 2017 to 2022, functional integration is systematically assessed through key spatial metrics: regional self-containment, functional mismatch, and net commuting balance. The empirical results reveal pronounced geographical disparities across Latvian statistical regions: the Pieriga region exhibits an exceptionally high functional mismatch (72.5%), reflecting a deep, symbiotic metropolitan integration, while peripheral areas like Latgale show high self-containment rates (>70%) combined with negative commuting balances, clearly indicating spatial isolation. Concurrently, Riga City emerges as a powerful net labour attractor with low self-containment, driven by employment redistribution far beyond its administrative borders. These findings robustly demonstrate that workplace-based indicators often reflect complex inter-territorial spatial flows rather than localized development capacities. Consequently, the study concludes that contemporary regional development policies and European Union Cohesion fund allocation mechanisms must urgently shift from rigid territorial metrics toward functional spatial perspectives.
Keywords: human capital, regional living space, functional mobility, commuting flows, spatial mismatch.

Introduction

Regional development research has long relied on the assumption that administratively defined territories provide an adequate analytical framework for understanding socio-economic processes (Pike et al., 2007). Within this framework, population size, educational attainment, and employment levels are routinely aggregated at sub-national levels to assess regional performance and competitiveness (Iammarino et al., 2019; European Commission, 2022). Human capital occupies a central position in this tradition and is commonly treated as a territorially embedded resource, implicitly assuming that its formation and utilisation occur within the same spatial units (Diebolt & Hippe, 2022).

However, the increasing spatial decoupling of place of residence and place of work poses a significant challenge to this static perspective. The 'new mobilities' paradigm argues that static spatial theories fail to capture the complex movements of people, objects, and information that define contemporary social life (Sheller & Urry, 2006). In contemporary functional labour markets, daily commuting and mobility patterns connect administratively distinct territories into integrated socio-economic systems, as demonstrated in comparative studies of European capital city-regions (Wicht et al., 2019; Ubarevičienė et al., 2025). As a result, traditional regional indicators may generate a structural mismatch between statistical territories and the spaces in which economic value is actually created (Rodríguez - Pose, 2013, 2018). This mismatch is further complicated by the Modifiable Areal Unit Problem (MAUP), whereby statistical outcomes may vary depending on how territorial boundaries and spatial aggregation levels are defined (Openshaw, 1984).

This interpretative gap carries substantial policy implications, as it leads to a systematic misidentification of regional development needs. Within the framework of European Union Cohesion Policy, regional development capacity is still largely assessed through administratively aggregated, residence-based indicators, which may categorize functionally integrated and mobile regions as lagging simply because their economic output is captured elsewhere (Vedrine & Le Gallo, 2021). Recent policy reviews increasingly acknowledge the limitations of this approach in functionally integrated labour markets, where mobility and spatial interaction routinely transcend formal territorial boundaries (European Commission, 2022; OECD, 2020; EPRS, 2024). Under such conditions, reliance on residence-based indicators may lead to inaccurate diagnoses of regional development gaps and, consequently, to the misallocation of structural and investment funds (Vedrine & Le Gallo, 2021). These risks are particularly pronounced in Eastern European and Baltic regions, where demographic decline and processes of peripheralisation coexist with high levels of functional mobility towards a limited number of dominant economic centres (Hazans, 2018; Krumins & Berzins, 2025).

To address these challenges, this study introduces the concept of a 'regional living space' as an analytical lens for interpreting regional development under conditions of systematic labour mobility. Rather than treating regions as closed containers, this perspective emphasises functional spatial configurations that emerge through interactions between places of residence and work. In doing so, it aligns with recent calls for more spatially sensitive and functionally oriented approaches to territorial governance (Krišjāne et al., 2023).

The aim of this study is to evaluate the structural

mismatch between administrative and functional human capital indicators by developing a conceptual framework for their recontextualisation within a functional spatial perspective. To achieve this aim, the study addresses the following research question: how does functional labour mobility affect the validity of administratively bound human capital indicators in regional analysis? To address this research question, the study undertakes two primary objectives: 1) to quantify the decoupling between residence-based human capital and workplace-based utilisation using experimental commuting statistics; 2) to develop the 'regional living space' conceptual framework as a tool for interpreting regional development in functionally integrated contexts. Drawing on experimental statistics on Latvian commuting flows (NPV03x series) for the period 2017–2022 and residence-based employment stocks derived from experimental statistics, the analysis demonstrates that traditional regional measures often reflect inter-territorial labour flows rather than regionally embedded development potential (Central Statistical Bureau of Latvia, 2024). By reframing regional performance through the lens of functional integration, this paper contributes to a more nuanced understanding of regional competitiveness in shrinking and structurally peripheral regions and supports the development of more analytically robust approaches to interpreting regional development in functionally integrated contexts (OECD, 2025).

Materials and Methods

The empirical analysis adopts a quantitative analytical approach based on experimental statistics provided by the Central Statistical Bureau of Latvia (CSB). To ensure methodological consistency and functional validity, the study prioritises datasets that explicitly capture spatial interaction between places of residence and employment, offering higher analytical precision for functional regional analysis than conventional territorially aggregated indicators.

The core empirical dataset used in this study is the CSB experimental statistics series NPV030 (Functional Flows), covering the period 2017 - 2022. This dataset links declared places of residence with tax-registered workplaces, thereby capturing inter-territorial commuting flows and enabling the analysis of functional labour market integration across regions. While the Covid-19 pandemic catalysed a transition to remote work, Latvia's functional labour market structure remained largely unchanged. Analysis of SC_i and FM_i values across the 2017 - 2022 period shows year-to-year variations of less than 1,5 percentage points. This high degree of temporal stability justifies the use of 2022 as a representative reference year, as functional integration patterns appear to be structural rather than transitory. Unlike traditional employment statistics aggregated by administrative units, NPV030 allows for the identification of residence-based employment totals and their spatial redistribution through daily mobility.

Employment figures used in this study are derived directly from the residence-based employment totals published in NPV030 (Central Statistical Bureau of Latvia, Metadata Code: NPV030). The dataset reports pre-calculated employment counts by combinations of place of residence and place of work, as documented in the official CSB metadata. This structure allows for the identification of all employed residents registered in a given territory, irrespective of their actual workplace location. Accordingly, the residence-based employment total for Riga (City) encompasses both internal employment (Riga → Riga) and inter-territorial commuting flows (e.g., Riga → Pieriga, Riga → Vidzeme). These residence-based employment totals are treated as a harmonised input and serve as the baseline denominator for the calculation of regional self-containment (SC_i) and functional mismatch (FM_i) indicators. All data processing, matrix aggregation, and indicator calculations were performed using the R statistical computing environment (R Core Team, 2024).

A methodological limitation of the NPV series is its reliance on formal employment records, which may underestimate the mobility of self-employed individuals and participants in non-standard forms of work. However, this limitation does not undermine the functional interpretation adopted in this study. Instead, it reinforces the relevance of a conceptual framework that explicitly distinguishes between residence-based employment stocks and workplace-based utilisation, particularly in the context of increasing labour market flexibility and spatial mobility (Eurofound, 2024).

Latvia provides a particularly illustrative case for analysing functional labour market integration due to its pronounced monocentric spatial structure and persistent regional disparities. Although administratively divided into five planning regions, economic activity is strongly concentrated in the Riga Metropolitan Area, which accounts for the dominant share of national GDP and employment (European Commission, 2022). This configuration reflects a clear core-periphery structure in which Riga functions as the primary centre of employment and economic utilisation, while surrounding regions increasingly supply labour through commuting and mobility flows (Krišjāne et al., 2021). Such a high degree of monocentricity intensifies the spatial decoupling between places of residence and places of economic utilisation, generating functional mismatches that are more pronounced than those typically observed in Western European polycentric systems. Comparative evidence from European capital city regions indicates that post-socialist and Central and Eastern European contexts tend to exhibit stronger functional asymmetries and socio-economic polarisation, reinforcing the relevance of Latvia as an empirical laboratory for examining the decoupling of residence-based indicators from actual economic performance (Kunhardt, 2025; Ubarevičienė et al., 2025).

To assess the degree of functional integration between

regions, the Regional Self-Containment ratio (SC_i) is calculated as the share of intra-regional employment flows relative to the total resident workforce:

$$SC_i = \frac{F_{ii}}{\sum_j F_{ij}} \quad (1)$$

where F_{ii} denotes the number of employed residents working within their region of residence (the diagonal element of the commuting matrix), and F_{ij} represents the total employed population residing in region i, including both internal and outward commuting flows. This indicator follows the commonly used approach in the analysis of functional urban areas and labour market regions, where self-containment serves as a key criterion for functional cohesion. In the context of this study, the residence-based self-containment indicator is used because the analytical focus lies on the spatial utilisation of human capital stocks observed at the place of residence. While functional labour market delineations often consider both supply-side and demand-side self-containment, the residence-based formulation is sufficient for capturing the extent to which regional human capital is utilised within or outside the region.

Accordingly, Functional Mismatch FMi is defined as the inverse of self-containment:

$$FM_i = 1 - SC_i \quad (2)$$

Higher values of FM_i indicate stronger integration into interregional labour market flows and a greater structural dependence on external economic centres, reflecting the extent to which a region's human capital is utilised outside its administrative boundaries.

To evaluate whether a region functions as a net sender or receiver of human capital, the Net Commuting Balance NB_i is calculated as:

$$NB_i = \sum_k F_{ki} - \sum_k F_{ik} \quad (3)$$

where $kFki$ represents total inflows of workers into region i, and $kFik$ denotes total outflows. A positive balance indicates net attraction of labour, while a negative balance signals net human capital leakage. This balance serves as a proxy for a region's economic gravity and ability to overcome structural disparities (Kühn, 2015; Ganesch, 2018).

To assess temporal robustness, self-containment rates (SC_i) were examined for the period 2017 - 2022. Across all regions, year-to-year variation remained below 1.5 percentage points, including during the Covid-19 period. This stability justifies the selection of 2022 as a representative reference year for the empirical analysis.

The analytical procedure follows three sequential steps. First, residence-based employment totals derived from NPV030 are used as a harmonised baseline input. Second, inter-regional commuting flows are analysed to identify divergences between residence-based employment and workplace-based utilisation. Third, functional integration and imbalance are quantified using self-containment and net commuting balance indicators to capture the spatial redistribution of labour resulting from daily mobility.

Results and Discussion

The analysis of regional development indicators for 2022 reveals a pronounced divergence between demographic capacity, human capital stocks, and functional labour market integration across Latvian statistical regions. These relationships are captured through a set of residence-based employment and commuting-derived functional indicators (Table 1). The longitudinal analysis of commuting flows between 2017 and 2022 demonstrates that the observed functional structure is not merely a snapshot, but rather a persistent regional characteristic.

Table 1

Regional Living Space Indicators (2022)

Statistical region	Employed residents (residence-based)	Intra-regional employment	Self-Containment (SC_i)%	Functional mismatch (FM_i)%	Net commuting balance (NB_i)
Riga (City)	559794	260557	46.5	53.5	16778
Pieriga [a]	184803	50824	27.5	72.5	-14937
Vidzeme	157668	88968	56.4	43.6	-1862
Kurzeme	140800	101651	72.2	27.8	-2538
Zemgale	126646	71284	56.3	43.7	313
Latgale	112464	85364	75.9	24.1	2246

[a] *Pieriga represents a structurally dependent commuter region.*

Source: Author's calculations based on CSB experimental statistics (NPV030).

Despite the external shocks of the Covid - 19 pandemic, the Self-Containment (SC) of Riga City remained stable, fluctuating only within a 1.2 percentage point range (from 47.7% in 2017 to 46.5% in 2022). Similarly, the Functional Mismatch (FM) in Pieriga showed a consistent upward trend, increasing from 69.8% to 72.5%, indicating that the pandemic-induced shift toward remote work did not reverse the long-term spatial integration of the metropolitan labour market; rather, it reinforced the role of Pieriga as a primary residential base.

The inclusion of Net Commuting Balance (NB) values

further clarifies regional roles. Riga (City) acts as the primary national attractor (16778), effectively capturing human capital from its surroundings. In contrast, Pieriga shows the deepest negative balance (-14937), confirming its role as a residential hinterland. Interestingly, the positive net commuting balance in Latgale (2246) reflects its status as a relatively closed functional system; due to the significant distance from the capital, its urban centres function as localized attractors for their immediate rural hinterlands rather than participating in daily national-scale flows. Conversely, the negative balances in Kurzeme (-2538) and Vidzeme (-1862) indicate a steady, albeit smaller, outflow of human capital toward the metropolitan core. Figure 1 illustrates this functional asymmetry - the decoupling of residence and workplace is not a sign of regional decline but an indicator of high spatial integration within the metropolitan system. Figure 2 conceptualizes this relationship, showing that value creation is a shared process within a 'regional living space' that transcends administrative boundaries.

Riga (City) statistical region stands out with by far the largest employed residents (residence-based: 559794), reflecting its dominant demographic and human capital concentration within Latvia. In contrast, the remaining statistical regions - Vidzeme, Zemgale, Kurzeme, and Latgale, exhibit considerably smaller employment stocks, broadly aligned with their population size and peripheral position within the national settlement system.

However, the distribution of intra-regional employment (i.e. employed residents working within their region of residence) reveals a more nuanced pattern. Peripheral regions such as Latgale (75.9%) and Kurzeme (72.2%) display high levels of self-containment, indicating that the majority of their employed residents work within their region of residence. Vidzeme and Zemgale occupy an intermediate position, combining moderate self-containment with noticeable outward commuting.

In contrast, Riga (City) records a comparatively low self-containment rate (46.5%), despite its strong economic position. This indicates that a significant proportion of Riga's labour force is engaged in out-commuting, as they are employed in territories beyond the city's administrative boundaries. Rather than signalling limited economic capacity, this pattern reflects the spatial fragmentation of the metropolitan labour market across adjacent administrative units. While Table 1 provides a comparative overview of individual statistical regions, it remains a static representation that does not fully capture the dynamic internal structure of the Riga metropolitan system.

In this context, residence and workplace locations are not merely points on a map but are distributed across closely interconnected and functionally interdependent territories.

To address this analytical limitation, Figure 1 focuses explicitly on the functional relationship between Riga (City) and Pierīga - two territories that, despite their administrative merger into a single statistical region in 2024, continue to exhibit sharply distinct and complementary commuting roles.

Figure 1

Metropolitan-scale functional interpretation (Riga-Pieriga)

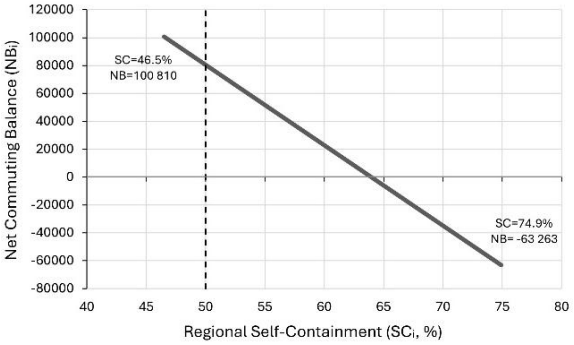
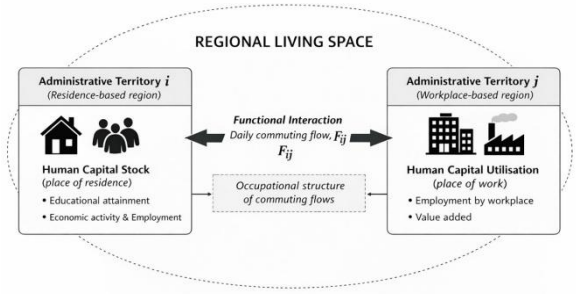


Figure 1 visualizes the fundamental functional asymmetry that defines the capital region's labour market. By positioning Riga (City) and Pieriga in opposing quadrants - specifically as a net attractor and a net sender - the analysis illustrates that their traditional administrative separation is analytically artificial and fails to reflect the underlying economic reality. The spatial distance between their functional coordinates in the diagram represents more than just a mobility flow, it quantifies the intensity of the 'metropolitan bond'. This bond signifies a process where human capital value is generated and socially reproduced in one jurisdiction (Pieriga) but economically realized and taxed in another (Riga City). Consequently, this visual evidence serves as a critical argument for transitioning from rigid administrative boundaries toward functional regionalism in national development planning and Cohesion policy.

Figure 2

Conceptual framework of a regional living space linking residence-based human capital stocks with workplace-based utilisation through daily commuting



These observations confirm that administrative units no longer function as self-contained economic entities. Traditional indicators often reflect a region's functional position within a spatial hierarchy rather than its intrinsic development capacity. Reliance on residence-based stocks alone results in a systematic

misinterpretation of regional potential, as value creation is distributed across interconnected systems.

To bridge this analytical gap, the study introduces the Regional Living Space framework (Figure 2). It defines a functionally coherent system where human capital stocks (residence) and utilization (workplace) are spatially decoupled but analytically inseparable due to systematic commuting flows.

The conceptual framework presented in Figure 2 synthesizes these findings by defining the 'regional living space' as a bridge between fixed stocks and dynamic flows. It illustrates that traditional indicators overlook the 'utilization' phase of human capital when it occurs across administrative borders. By explicitly linking residence - based potential with workplace - based outcomes through commuting as the primary mechanism, Figure 2 provides a replicable logic for re-evaluating regional competitiveness in any functionally integrated context.

The empirical evidence from Latvia validates this framework, confirming a profound mismatch between administrative boundaries and functional economic realities. With Riga City's self-containment at only 46.5% and Pieriga's functional mismatch at 72.5%, the results demonstrate that these territories operate as a single, integrated regional living space. The study concludes that residence - based human capital indicators alone provide a distorted view of regional development. Therefore, regional policy and European Union Cohesion assessments must shift from bounded territorial metrics toward functional spatial perspectives that account for labour mobility and inter - regional connectivity.

Conclusions

1. This study confirms that administratively defined regional indicators are insufficient for capturing the functional realities of contemporary labour markets. The empirical analysis demonstrates that residence-based employment and human capital measures, when interpreted without accounting for spatial mobility, fail to reflect how regional development capacity is functionally organised and economically realised.

2. A systematic divergence exists between residence-based employment patterns and functional labour market integration. Values of (SC_i), (FM_i), and (NB_i) confirm that Latvian regions do not operate as self-contained economic units, but as interdependent functional systems structured by daily mobility. This is most evident in the Riga - Pierīga area, where Riga City acts as a net labour attractor, while Pieriga exhibits very low self-containment (27.5%) and persistent net outflows. In peripheral regions like Latgale, higher self-containment (75.9%) reflects spatial isolation rather than functional autonomy.

3. The results highlight the limitations of territorially fixed performance metrics. Regions with strong human capital endowments may appear economically underperforming if assessed only through workplace-based indicators, as core regions capture value created by labour residing elsewhere. Thus, regional performance cannot be reliably assessed without accounting for functional integration.

4. Methodologically, the study proves the value of combining residence-based employment data with commuting-derived functional flows. This approach provides a transparent and replicable framework for identifying functional positions within national labour markets.

5. Conceptually, the 'regional living space' framework serves as an analytical overlay linking residence-based human capital stocks with workplace-based utilisation through commuting flows. This provides a coherent lens for analysis without necessitating administrative boundary changes.

6. Finally, the study demonstrates that residence-based human capital, functional connectivity, and economic outcomes form an integrated system. This establishes the conceptual foundation for future research to develop a comprehensive human capital index that aligns measurement with the functional realities of contemporary, mobile labour markets. While this study focuses on Latvia, the observed patterns align with the 'new mobilities' paradigm and reflect processes seen in other post-socialist Central and Eastern European capital regions. Future research should apply this framework in comparative contexts to further validate its generalizability across different European regional systems.

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CAP SUPPORT AND BALANCED AGRICULTURAL DEVELOPMENT IN LATVIA: EVIDENCE FROM EXPERT EVALUATIONS AND FARM-LEVEL DATA

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Abstract
As agricultural policy increasingly shifts towards sustainability, evaluating the distribution and impact of financial instruments becomes essential for national development. The present research evaluates the impact of Common Agricultural Policy (CAP) support on farm performance and identifies strategic priorities for fostering balanced agricultural development in Latvia. The research identified whether current financial instruments effectively reached diverse farm holdings to ensure long-term sector resilience. The research employed a mixed-methods approach, combining a quantitative analysis of Farm Accountancy Data Network (FADN) indicators for the period 2014-2022 with a qualitative expert survey based on the Analytical Hierarchy Process (AHP). The key results demonstrated a significant relationship between support intensity and the economic stability of large-scale farms, while small and medium-sized holdings exhibited a higher reliance on targeted payments to maintain social viability. The expert evaluations via AHP prioritised the economic pillar but highlighted a perceived imbalance and a substantial implementation gap regarding rural vitality and environmental diversification. Furthermore, the evaluation of development scenarios suggested that achieving a balanced model is contingent upon enhancing redistributive support instruments and reducing administrative barriers. The research concluded that while the implementation of the CAP in Latvia provides a solid economic foundation, a more integrated and targeted approach is necessary to ensure truly balanced agricultural development. These findings offer evidence-based recommendations for policy adjustments to ensure a sustainable transition for the Latvian agricultural sector.
Keywords: CAP support payment, farm performance, environment.

Introduction

The CAP is one of the most important European Union (EU) policies aimed at achieving steady agricultural development and the continuity of food production. Historically, the main objectives of the CAP have been to stabilise farm incomes, increase agricultural productivity, and ensure the availability of food in Europe. In recent years, however, reforms have increasingly focused on integrating sustainable development principles into agricultural policies, especially environmental protection, thus achieving climate goals and balanced rural development (European Commission, 2021; Pe'er et al., 2020; Heyl et al., 2022). As scientists have found, CAP socio-economic objectives such as rural vitality and income stability might conflict with environmental requirements, as stricter ecological requirements can increase costs and place a burden on small and medium-sized farmers (Féret et al., 2023). Severini et al. (2021) have concluded that subsidies not only stabilise incomes for individual farmers but also provide wider support to the rural economy as a whole. Paun & Ivascu (2021) argue that the agricultural support system helps to stabilise rural areas by contributing to stable income flows and the development of the local economy. However, addressing fundamental policy bottlenecks and ensuring that the agricultural objectives of the European Green Deal are achieved requires a multidimensional sustainability evaluation and appropriate, specific national policies (Muska et al., 2025).

At the same time, the impact of CAP support instruments can vary across EU Member States, as the structure of agriculture, farm sizes, and historical and regional development differ significantly. Some research studies have shown that CAP support payments can affect farm development in different ways, depending on farm structure, investment opportunities, and market orientation (Staniszewski & Borychowski, 2020; Galluzzo, 2023). Larger farms are more likely to use support instruments for investment and productivity gains, while smaller farms rely more on support payments as an income stabilisation mechanism. In Latvia, the agricultural sector is characterized by significant differences in farm size, production specializations, and regional development. Such structural differences indicate that the impact of CAP support instruments on farm development can be uneven, affecting not only farm economic performance but also broader rural development processes (Nipers et al., 2017).

In view of the growing need to develop sustainable, environmentally and climate-friendly, and resilient agriculture in the EU, the question of how much CAP support contributes to the balanced development of agriculture is becoming relevant. Therefore, the present research aims to evaluate the role of CAP support in the development of balanced agriculture in Latvia by analysing both farm performance and expert ratings of future agricultural policy priorities. To achieve the research aim, the following specific research tasks have been set: 1) to identify the socio-economic and environmental impact of CAP support based on farm-level data; 2) to evaluate scenarios for CAP support based on an expert evaluation.

Materials and Methods

To assess the role of CAP support in the development of Latvian agriculture, the research analysed data from the Latvian FADN, as well as sector-level statistics on agricultural income and subsidies. The analysis

covered the period from 2014 to 2022, enabling identification of both the sector's overall trends and the importance of support payments across different farm groups. The research applied an approach that combines quantitative analysis of farm-level data with a structured expert evaluation. The analysis included economic, social, and environmental indicators. The data were analysed comparatively over the analysis period using statistical methods to determine correlations between support intensity and farm performance.

The AHP (Saaty & Vargas, 2001) has been used to evaluate the priorities of the CAP, thereby structuring the potential development of agriculture at four levels: the goal, three groups of criteria with nine detailed evaluation criteria, and three alternative scenarios. The experts were selected deliberately to ensure representation of perspectives from different agricultural sub-sectors, including both practicing farmers representing farms of different sizes and institutional experts involved in the development (Ministry of Agriculture (MoA)) and administration (Rural Support Service (RSS)) of CAP support instruments in Latvia. This makes it possible to combine practical farm experience with a policy-making and implementation perspective. The profile of the experts and the areas represented are summarised in Table 1.

The expert ratings were based on pairwise comparison, thereby calculating relative priorities and verifying the coherence of ratings.

The individual results were aggregated to obtain a common distribution of priorities for the scenarios. The research interprets balanced agricultural development as a balance between socio-economic, environmental, and regional dimensions, comparing the actual impact of CAP support with the strategic priorities identified by the experts.

Table 1

Expert profiles, interview data and areas represented for the AHP evaluation

Expert designation	Characteristics of the area represented	Interview date
Expert 1	Manager of a large farm	27/03/2025
Expert 2	Manager of a small farm	31/03/2025
Expert 3	Member of the Council of the Latvian Association of Organic Agriculture	01/04/2025
Expert 4	Representative of the RSS Zemgale Regional Agricultural Administration	31/03/2025
Expert 5	MoA high-level expert on direct payment policy	03/04/2025

Results and Discussion

CAP support and farm-level performance in Latvia

Changes in agricultural income in Latvia indicate a significant shift in the economic structure of the agricultural sector. In 2014-2022, total income from agricultural activity increased 2.1 times, while the amount of CAP support payments increased steadily (by 28%). This indicates that the CAP support instruments continue to play an important role in the agricultural sector and in stabilising farm incomes. At the same time, it can be observed that as market income increases, the agricultural sector's economic resilience also gradually increases. Although support payments still represent a significant share of income, the development of the agricultural sector indicates a gradual shift towards a larger role of market income, as the share of CAP support payments in total agricultural income decreases.

During the analysis period, agricultural incomes were largely dependent on support payments in some years. For example, in 2015, subsidies accounted for about 96%, in 2016 – 90% of total agricultural income, which indicated a very high dependence of the agricultural sector on support policy instruments. The share gradually decreased in subsequent years, and in 2022, the share of subsidies was approximately 48 %, thereby indicating gradual stabilisation and an increased role of market income (Figure 1).

The calculation of the correlation coefficient between net income and CAP support payments, on average per farm, in Latvia in 2014–2022 revealed a value of 0.35, indicating a positive but weak linear correlation.

Regarding the overall development of the agricultural sector, significant differences could also be found between the different size groups of farms. The FADN data showed that the share of CAP support payments in farm income was, on average, significantly higher for small and medium-sized farms over the entire analysis period, at 41% and 52%, respectively. This indicates that smaller farms relied much more heavily on CAP support instruments as an income stabilisation mechanism (Figure 2).

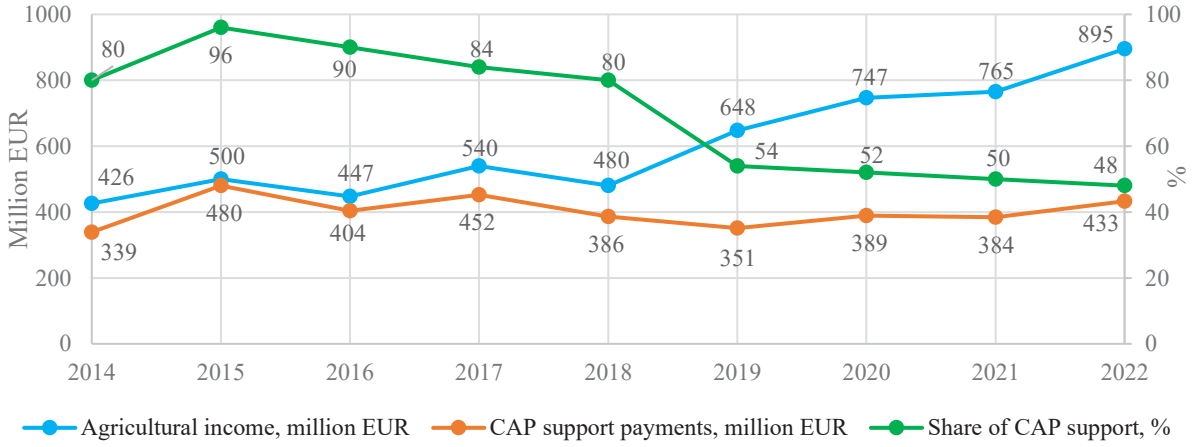
A comparison of the economic indicators of farms revealed that large farms usually achieved higher production efficiency and higher output. Such farms were more likely to use CAP support for investments in technology, modern production facilities, and farm development. In contrast, support payments for smaller farms were more likely to have a stabilising function, helping to compensate for market fluctuations and maintain economic viability in rural areas.

In addition to the economic and structural aspects, environmental sustainability objectives are also increasingly important under the CAP. The instruments contributing to sustainable land management, the preservation of biodiversity, and the efficient use of resources are playing an increasingly important role in agricultural policies. In Latvia, such instruments include various environmental payments

and support for organic farming, which encourage sustainable farming practices. However, the impact of the instruments on farm economic performance could vary across farm groups. In some cases, the introduction of environmental requirements can increase production costs, while in other cases, it could contribute to a more efficient use of resources and the development of more sustainable farms.

Figure 1

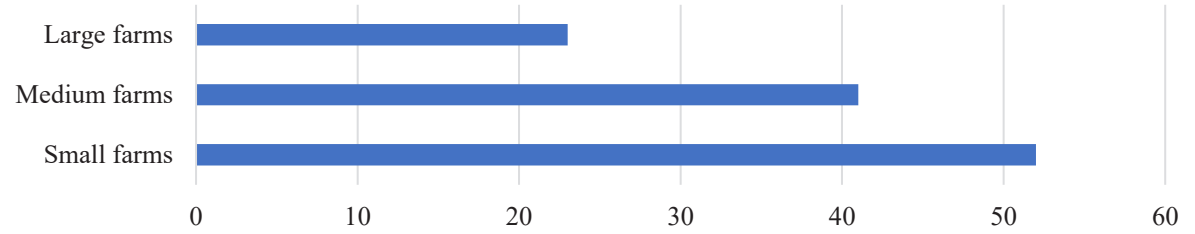
Changes in agricultural income and CAP support payments for agriculture, EUR, and a share of CAP support in total agricultural income in Latvia, %, in 2014-2022



Source: authors' calculations based on FADN (2025) and the MoA (2025).

Figure 2

Share of CAP support in total farm income by farm size group in Latvia in 2014-2022, %*



*Large farms – standard output ≥100 thou. EUR, medium farms – standard output 25–<100 thou. EUR, small farms – standard output 4–<25 ... thou. EUR.
Source: authors' calculations based on FADN (2025).

To examine in depth the relationship between CAP support and farm economic performance, a correlation analysis was performed between the amount of subsidies received by farms of different sizes and their main economic, social, and environmental performance indicators. The results showed a positive correlation between support payments and net farm income, yet differences between farm size groups tended to be significant, which pointed to the role of CAP support in income stabilisation. At the same time, there was also a moderate correlation between support and productivity indicators, e.g., agricultural output and labour efficiency. The results of the correlation analysis between CAP support and key farm performance indicators are summarised in Table 2.

Overall, the analysis of FADN data confirmed that in Latvia, CAP support payments were significant for the agricultural sector. At the same time, the results demonstrated that the impact of CAP support was not the same across farm groups. Small farms used CAP support to stabilise their incomes to a greater extent, while large farms were more likely to use it to increase productivity and investments.

In addition to the economic impact, the analysis of FADN data also revealed broader structural trends in the agricultural sector in Latvia. Differences between farm size groups indicated that the impact of CAP support instruments was not uniform, as the CAP support was used differently across farm groups: small farms were more likely to achieve income stability and farm survival, while large farms more often used it for investments and increasing production efficiency. This indicates that the impact of CAP instruments on agricultural development was strongly related to farm structure and the scale of production (Staniszewski & Borychowski, 2020).

Table 2

Correlations between CAP support and selected farm performance indicators for various farm size groups in Latvia in 2014-2022

Indicator	Correlation with CAP subsidies, EUR		Interpretation
	Correlation coefficient interval (r)	Correlation characteristics	
Economic indicators			
Net income per farm, EUR/farm	-0.1 to 0.9	weak - strong positive	CAP support contributes to the stability of farm income
Agricultural output, EUR/farm	-0.2 to 0.9	medium	A stronger correlation was found for large farms
Labour productivity, EUR/AWU*	-0.7 to 0.3	medium	Pertains to investment and technology capacity
Social indicators			
Employment in agriculture, AWU	-0.2 to 0.1	weak	Employment was mainly affected by structural change and mechanisation
Labour force efficiency, EUR/AWU	-0.7 to 0.2	weak–negative	Higher subsidies did not always correlate with higher productivity
Wage and social tax payments, EUR/farm	0.1 to 0.7	medium	More labour use increases employment-related payments
Environmental indicators			
Green and environmental support subsidies, EUR/farm	0.4 to 0.9	moderate - strong positive	Environmental payments contribute to sustainable farming practices
Environmental costs, EUR/farm	-0.6 to 0.1	weak	Environmental costs are rising, yet their correlation with subsidies was not significant

*AWU – agricultural work unit – one man-year (1840 hours).

Source: authors' calculations.

To complement the empirical results and evaluate priorities for the CAP in the long term, the researchers performed an expert evaluation using the AHP method.

Scenarios for CAP support development in Latvia

The AHP hierarchy was structured at four levels (Figure 3), including the goal – sustainable and balanced development of agriculture in Latvia – three groups of criteria (economic interests of farmers, environmental protection interests, and national development interests), nine detailed criteria, and three alternative scenarios. Three scenarios were created and offered to the experts for evaluation:

1. Maintaining the current support system entails the continuation of current policies without substantial changes. Stability and security for farmers are ensured, yet the objectives of sustainability and the European Green Deal are achieved to a limited extent.

2. Prioritising environmental goals emphasizes the importance of sustainable practices, biodiversity, and the reduction of GHG emissions. In this scenario, financial incentives are targeted at promoting environmental protection, even if this means compromising income or output.

3. Economic development and regional growth focus on increasing competitiveness, modernising farms, raising incomes, and reducing regional inequalities. The introduction of environmental requirements is implemented gradually, thus ensuring flexibility and balance with economic goals.

The four-level hierarchy provides a clear and systemic basis for evaluating the scenarios, thereby allowing for the determination of the pathway of development that would best contribute to the achievement of the goal: sustainable and balanced development of agriculture in Latvia. The present research considers balanced development as the ability of CAP instruments to simultaneously ensure the economic viability of farms, promote environmental sustainability, and strengthen regional resilience. The ratings of the second-level groups of criteria revealed both the structure of the priorities and a significant dispersion of the expert opinions.

The aggregate AHP results showed that the highest average rating was given to the economic interests of farmers (0.360), followed by national development interests (0.339) and environmental protection interests (0.302).

The average ratings showed that economic stability was still perceived as an essential prerequisite for the development of the agricultural sector.

At the same time, the high coefficient of variation for the national development dimension (77.2%) and the significant dispersion for economic interests (61.6%) indicated different opinions of the experts on policy consistency and the effectiveness of support instruments across farm groups. The relative priorities of the groups of criteria and the distribution of ratings are summarised in Table 3.

Figure 3
Hierarchy of criteria for evaluating the sustainable and balanced agricultural development scenarios in Latvia

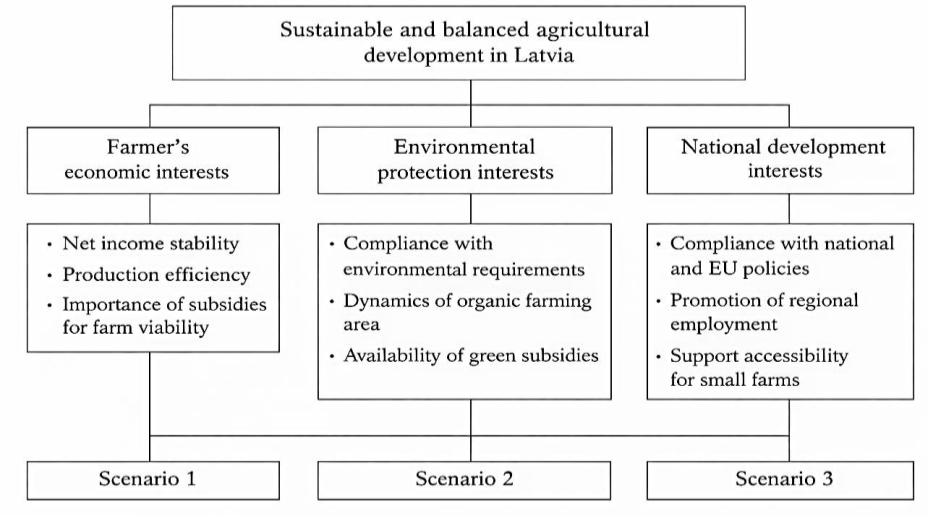


Table 3
Expert ratings of second-level criteria groups and variation coefficients, %

Criteria groups	Experts/ratings						Variation coefficient
	1	2	3	4	5	average	
Economic interests of farmers	0.637	0.110	0.429	0.156	0.467	0.360	61.625
Environmental protection interests	0.105	0.323	0.429	0.185	0.467	0.302	51.399
National development interests	0.258	0.567	0.143	0.659	0.067	0.339	77.170

Source: authors' calculations.

A comparison of the structural distribution of priorities with the total rating of the scenarios showed significant analytical tensions. While the economic pillar received the highest relative weight at the criteria level, the scenario for prioritising environmental goals was given the highest rating in the combined scenario evaluation (0.38). This was followed by the scenario of economic development and regional growth (0.35), while the lowest rating was given to the scenario of maintaining the current support system (0.27) (Table 4).

Table 4
Overall rankings of the CAP development scenarios based on an AHP evaluation

Scenario	AHP weight	Rank
Prioritising environmental goals	0.38	1
Economic development and regional growth	0.35	2
Maintaining the current support system	0.27	3

Source: authors' calculations.

The difference between the significance of criteria and the choice of final scenarios suggests a gradual shift towards sustainability-oriented policy mindset, with environmental goals being perceived as strategically important in the context of long-term competitiveness and public confidence. At the same time, the AHP analysis results made it possible to identify tensions between different agricultural development goals. Although economic interests gained the highest relative weight at the criteria level, the scenario of prioritising environmental goals was given the highest priority. This revealed that the experts considered economic stability to be a necessary basis for agricultural development, while emphasizing the need to strengthen environmental sustainability aspects in agricultural policies.

The dispersion of expert ratings of criteria also reflected their divergent opinions on the effectiveness of CAP support instruments in practice. The particularly high coefficient of variation in the group of national development criteria indicated a different understanding of the role of agriculture in regional development and in strengthening the socio-economic resilience of rural areas. Such differences might relate to the diverse structure of agriculture in Latvia (Galluzzo, 2023) and significant differences between farm size groups.

Comparing the expert ratings with the results of the farm-level data analysis, the link between policy priorities and the actual situation in the agricultural sector also becomes apparent. The FADN data showed that CAP support continued to play an important role

in stabilising farm incomes, especially for small and medium-sized farms. However, the AHP analysis results pointed to the need to further strengthen support instruments in the future, which simultaneously contribute to economic stability, environmental sustainability, and the balanced development of rural areas.

The expert ratings also revealed structural tensions between ensuring economic viability and expanding environmental requirements. Economic stability is perceived as a prerequisite for any transformation, while the implementation of environmental priorities is often seen as an administratively and financially challenging process. The experts' comments highlighted implementation challenges – administrative complexity, frequent policy changes, and insufficient targeting of support instruments for small and medium farms. This indicates a potential imbalance between the declared sustainability goals and the practical implementation of the policy. Balanced agricultural development in Latvia is possible only with a more differentiated and redistributive application of CAP support, which simultaneously strengthens economic resilience and contributes to a gradual transition to environmentally friendly farming.

Conclusions

1. The analysis of FADN farm-level data confirmed that CAP support payments played a key role in stabilising farm incomes in Latvia. During the analysis period, support payments accounted for a significant share of agricultural incomes and served as an essential mechanism for ensuring economic resilience. This was particularly true for small and medium-sized farms, as the CAP support significantly contributed to their economic and social viability.

2. The research results confirmed the different importance of CAP support in the development of farms of different sizes. Large farms often used CAP support for investments, technological development, and increasing productivity, which contributed to their competitiveness. For smaller farms, in contrast, support payments largely served as a mechanism for stabilising incomes and ensuring the continuity of farm activities.

3. The empirical analysis revealed a positive correlation between the intensity of CAP support and the economic performance of farms. The correlation analysis results indicated that support payments related to the stability of net farm incomes, as well as moderately correlated with output and labour productivity. This confirmed the importance of CAP support for promoting the economic stability and development of farms.

4. Using the AHP method, the expert ratings revealed some tension between the declared policy priorities and their practical implementation. Although economic stability was considered an essential prerequisite for agricultural development, the ratings of the scenarios suggested that long-term agricultural sector development was increasingly linked to prioritising environmental goals. This pointed to the need to improve the implementation of the CAP support instruments to ensure more balanced economic, environmental, and regional development in agriculture.

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THE ROLE OF PUBLIC-PRIVATE PARTNERSHIPS IN REGIONAL DEVELOPMENT, SUSTAINABILITY, CHALLENGES AND FUTURE PROSPECTS IN LITERATURE

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Abstract
Public-private partnerships (PPPs) have become an important governance and financing mechanism for providing infrastructure and public services around the world. Governments are increasingly using PPP agreements to attract private investment, improve infrastructure quality and address fiscal constraints associated with large-scale infrastructure development. Despite the growing body of research on PPP governance and implementation, the role of PPPs in regional development and sustainability remains an important topic of academic discussion. The aim of this study is to analyze theoretical foundations, development potential, and sustainability impact of public-private partnerships in the context of regional development, utilizing a comprehensive literature review. The study is based on a structured analysis of scientific publications dedicated to PPP governance, institutional framework, infrastructure development and sustainability aspects. The results show that PPP research has evolved from primarily examining financial and contractual aspects to broader issues related to governance systems, institutional frameworks, and socioeconomic impacts. The analysis shows that PPPs can support regional development by modernizing infrastructure, improving public services, and fostering innovation. At the same time, the effectiveness of PPP initiatives depends on the quality of governance, institutional capacity and the ability to coordinate cooperation between public and private stakeholders. The study's conclusions emphasize that PPPs are an important tool for supporting regional development and sustainable infrastructure systems, provided that appropriate governance mechanisms and institutional frameworks are in place.
Keywords: public-private partnerships, regional development, sustainability, governance, infrastructure.

Introduction

Public-private partnerships (PPPs) have become widely used instruments for providing infrastructure and public services in both developed and developing countries. PPPs typical involve long-term cooperation agreement between government agencies and private entities in which responsibilities risks, and financial investments are shared to implement infrastructure projects or provide public sector (Ma et al., 2019). The growing use of PPPs is closely linked to rising global demand for infrastructure development and the financial constraints faced by governments. Many countries face significant infrastructure investment gaps that exceed available public funding. As a result, policymakers are increasingly relying on PPP agreements to mobilize private-sectors investment and improve the efficiency of infrastructure provision (Fu et al., 2023). Over the past two decades, PPPs have attracted significant academic attention. A broad body of research has emerged evaluating PPP governance, contract structures risk- sharing mechanisms, financial models and project outcomes. Comprehensive literature reviews indicate that governance structures, risk allocation, procurement mechanisms, financial viability, contract management, and performance evaluation are the dominant research themes in PPP studies (Ma et al., 2019; Fu et al., 2023). However, despite the extensive literature on PPP implementation and management academic debates regarding the broader impact of PPPs on development remain fragmented. Earlier studies primarily focused on the management and financial aspects of PPP implementation, whereas more recent studies increasingly emphasize the integration of sustainability institutional governance systems and the socioeconomic impacts of PPP projects (Adebayo et al., 2023). Sustainability has become an increasingly important topic in PPP research, particularly in the context of infrastructure development. PPP projects have the potential to promote sustainable development by integrating economic, environmental and social objectives into infrastructure planning and implementation. Recent studies also highlight the growing importance of PPPs in supporting low-carbon and climate resilient infrastructure systems (Casady et al., 2024; Adebayo et al., 2023). However, research indicates that sustainability principles are not always effectively integrated into PPP governance systems (Adebayo et al., 2023). Another important issue concerns the institutional and political factors that influence PPP implementation. Empirical studies indicate that PPP investments can be influenced by political incentives, governance structures, and institutional capacity which may affect project selection and the allocation of investments across sectors (Zhang et al., 2026). Furthermore, recent studies highlight the growing complicity of PPP governance systems. PPP projects involve numerous stakeholders, including governments, private companies, financial institutions, and local communities. The interaction among these participants creates complex governance networks that require effective coordination and institutional oversight (Zhao et al., 2026). Despite the growing body of research on PPP governance and sustainability, there remains a need to synthesize existing studies to better understand how PPPs contribute to reginal development and sustainable infrastructure transformation. Therefore, the aim of this study is to review the academic literature on public private

partnerships to analyze their theoretical foundations, role in regional development and sustainability as well as the main challenges and future research directions identified in the literature.

The study addresses the following research objectives:

1. To identify the dominant theoretical foundations used in PPP research.
2. To assess how PPPs contribute to regional development and sustainability.
3. To analyze the governance and implementation challenges associated with PPP projects.
4. To identify future perspectives and research directions in the PPP literature.

Materials and Methods

This study employs a structured literature review methodology to synthesize existing academic research on public-private partnerships (PPPs) and the role in regional development and sustainability. The literature review is based on peer-reviewed journal articles, systematic reviews, theoretical studies and empirical studies examining PPP governance, institutional frameworks, infrastructure development, and sustainability outcomes. To understand the evolution of PPP research, two comprehensive review studies were used as a foundation. These studies analyze PPP publications over an extended period and identify dominant research trends in this field. Their results indicate that governance structures, risk allocation, procurement mechanisms, financial models and project performance evaluation are the most frequently studied topics in PPP research (Ma et al., 2019; Fu et al., 2023). In addition to review studies, the analysis includes theoretical studies that evaluate PPP governance and contractual terms. Contract theory studies highlight the role of incomplete contracts and asymmetric information in PPP relationships, emphasizing that infrastructure projects are characterized by long-term uncertainty and that contact terms cannot be fully specified in advance (Schmitz, 2025). The review also includes empirical studies that evaluate the implementation of PPPs in various sectors and regional context. These studies provide insight into how institutional systems, governance capacity policy incentives and market conditions influence PPP investment decisions and project outcomes (Dominguez et al., 2025; Zhang et al., 2026; Saneimoghaddam et al., 2025; Zhao et al., 2026).

Results and Discussion

Research in the Development of PPPs

Over the past few decades, the academic literature on public-private partnerships (PPPs) has expanded significantly.

Earlier systematic reviews also emphasized the growing diversity of PPP applications and the increasing importance of governance and public value considerations in PPP research (Roehrich et al., 2014). Early research on PPPs focused primarily on financial structures, procurements mechanisms, and risk allocation in the context of infrastructure projects. In these studies, PPPs were viewed primarily as financial instruments to address the lack of infrastructure investment and improve the efficiency of public sector project implementation (Grimsey & Lewis, 2004; Ma et al., 2019). As the implementation of PPPs expanded globally, researchers increasingly began to analyze the management and institutional aspects of PPP projects. Studies have shown that PPPs are a hybrid governance mechanism that combines elements of public administration and private sector management (Hodge & Greve, 2007). Later studies further emphasized that effective PPP governance requires balancing efficiency objectives with public accountability, transparency and public value creation (Hodge et al., 2017). This perspective emphasizes the need to understand PPPs not only as contractual arrangements but also as institutional mechanisms that facilitate interaction between government agencies and private actors. Recent systematic literature reviews indicate that PPP research has gradually evolved toward broader research themes, including governance systems, institutional capacity stakeholder coordination, and sustainability considerations (Fu et al., 2023). These studies highlight the growing recognition that PPP projects affect not only performance at the project level but also broader socioeconomic and regional development outcomes. Furthermore, the expansion of PPP programs in many countries has spurred research into the political and institutional context that influence PPP implementation.

Researchers are increasingly examining the role of governance structures, regulatory systems and the policy environment in shaping the success or failure of PPP projects. To summarize the main areas of PPP research examined in this study, Table 1 presents the key publications analyzed in this literature review, highlighting their research focus, methodological approach and main conclusions. The studies summarized in Table 1 show that PPP research encompasses several analytical perspectives, including financial analysis, institutional governance systems, innovation systems and political – economic approaches. Taken together these perspectives indicate that PPP outcomes are influenced not only by financial arrangements but also by institutional capacity and governance structures.

PPP Theoretical Foundations of PPP Management

The theoretical foundations of PPP governance can be understood through several complementary perspectives including contract theory, institutional theory and the analysis of governance networks. Contract theory provides a fundamental analytical framework for understanding PPP agreements. Infrastructure projects implemented through PPP contracts typically involve long-term investment commitments and uncertain future conditions.

Table 1
Key studies on public-private partnerships cited in this literature review

Authors	Research focus	Method	Main findings
Ma et al. (2019)	Evolution of PPP research (2008 – 2018)	Literature review	PPP research focuses on governance, risk allocation, and procurement mechanisms
Fu et al. (2023)	Global PPP research trends (2012-2021)	Literature review	Emerging research themes include sustainability, governance complexity and innovation
Adebayo et al. (2023)	Sustainable PPP infrastructure governance	Literature review	Institutional frameworks and policy rules are critical for sustainable PPP implementation
Schmitz (2025)	PPP contract theory	Economic analysis	Incomplete contracts and information asymmetry influence PPP efficiency
Zhao et al. (2026)	PPP collaboration networks	Network analysis	PPP governance operates through complex multi-actor networks
Dominguez et al. (2025)	PPP innovation systems	Case study	PPPs facilitate technological development and knowledge transfer
Zhang et al. (2026)	Political incentives and PPP investment	Literature review	Political factors influence infrastructure investment decisions
Saneimoghaddam et al. (2025)	PPP infrastructure modernization	Case analysis	Institutional capacity affects PPP implementation outcomes
Hodge & Greve (2007)	PPP governance performance	International review	PPP represent hybrid governance arrangements combining public and private actors
Grimsey & Lewis (2004)	Risk allocation in PPP projects	Policy analysis	Effective risk allocation is essential for successful PPP implementation
Yescombe (2018)	PPP financing structures	Infrastructure finance analysis	Financial design and governance frameworks influence PPP sustainability
Klijn & Teisman (2003)	PPP decision-making networks	Governance study	Multi-actor coordination in essential in PPP project management
Iossa & Martimort (2015)	Economic theory of PPPs	Economic modeling	PPP efficiency depends on incentive structures and contract design
Hodge et al. (2017)	Global PPP governance	Policy analysis	PPP governance must balance efficiency, accountability and public value

Source: developed by the authors based on the literature reviewed in this study.

As a result, PPP contracts are inherently incomplete as it is impossible to precisely identify all possible future contingencies at the time of contract signing (Schmitz, 2025; Iossa & Martimort, 2015). Incomplete contracts create potential problems related to information asymmetry between public authorities and private partners. Private participants may have a better grasp of project costs, technological solutions, or operational efficiency. Therefore, PPP governance systems must include oversight mechanisms and incentive structures that reduce this information asymmetry and align the interests of both parties. Institutional theory further emphasizes the importance of regulatory systems and governance structures in shaping PPP performance outcomes. Institutional systems establish the rules and procedures governing PPP procurement, contract management and performance evaluation (Adebayo et al., 2023). Strong institutional capacity promotes transparency, enhance accountability and supports a balanced distribution of risk between public and private partners. Furthermore, governance network approaches highlight the multi-stakeholder nature of PPP systems. PPP projects involve interactions among private companies, financial institutions, consultants and local communities. These participants operate within governance networks that influence decisions-making processes and projects outcomes (Klijn & Teisman, 2003; Zhao et al., 2026; Atutxa et al., 2026). Thus, network-based perspectives emphasize the importance of collaboration, coordination and trust among stakeholders. Effective governance networks facilitate knowledge exchange, reduce coordination failures and enhance the resilience of PPP systems.

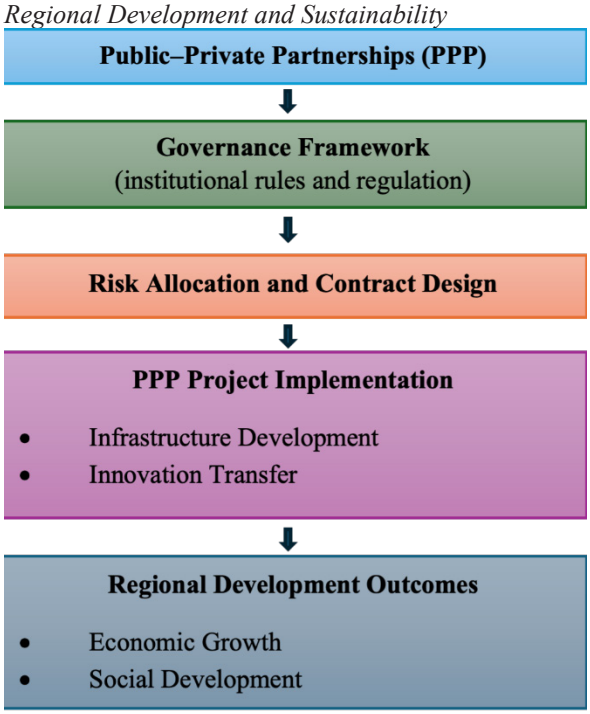
Public-private Partnerships and Regional Development

Public private partnerships are playing an increasingly important role in regional development by supporting infrastructure investments and improving the delivery of public services. Infrastructure systems, such as transport networks, energy supply, digital infrastructure and water management systems are a vital foundation for regional economic growth and competitiveness. PPP agreements allow governments to attract private capital and expertise to infrastructure development projects that might otherwise face financial or administrative constraints. Through long-term contractual cooperation and risk-sharing mechanisms, PPPs facilitate the implementation of

large-scale infrastructure projects that promote regional economic development (Yescombe, 2018; Saneimoghaddam et al., 2025). In addition to infrastructure development, PPP initiatives can also foster innovation and technological progress in regional economies. Partnerships between public research institutions and private companies create opportunities for knowledge exchange, technology transfer and joint research activities. Empirical studies show that PPP programs in sectors such as agriculture, technology development and infrastructure innovation can support the diffusion of new technologies and strengthen regional innovation systems (Dominguez et al., 2025). Furthermore, PPP infrastructure projects often generate indirect economic benefits by improving regional accessibility, strengthening links between economic centers and attracting private investment into regional economies. Improved infrastructure can promote trade, increase productivity and support the development of regional industries. In addition to infrastructure development, public-private partnerships can improve the accessibility and quality of public services - including in transportation, healthcare, education, and utilities - thereby promoting social well-being and regional cohesion. In addition to economic benefits, PPPs can contribute to the achievement of broader sustainability goals.

Figure 1

The Conceptual Framework for PPPs Contribution to Regional Development and Sustainability



Source: developed by the authors based on the literature reviewed in this study.

Sustainable PPP projects increasingly incorporate environmental and social considerations into infrastructure planning, including resource efficiency, climate resilience, environmental protection, and improved access to public services. Recent studies indicate that PPP governance frameworks can support the integration of sustainability principles into infrastructure development, particularly when institutional arrangements, stakeholder participation, and long-term performance targets are clearly embedded in project design (Adebayo et al., 2023; Casady et al., 2024). Thus, PPPs can simultaneously promote economic development, social well-being, and environmental sustainability at the regional level. The relationship between PPP governance mechanisms and regional development outcomes is illustrated in Figure 1, which depicts a conceptual framework linking governance structures, infrastructure development processes and sustainability outcomes.

The conceptual model shown in Figure 1 highlights the importance of governance structures and contractual agreements in shaping the implementation of public-private partnerships (PPP) projects. These governance mechanisms influence infrastructure development innovation processes and service delivery which collectively contribute to regional development outcomes.

Governance and Sustainability Challenges

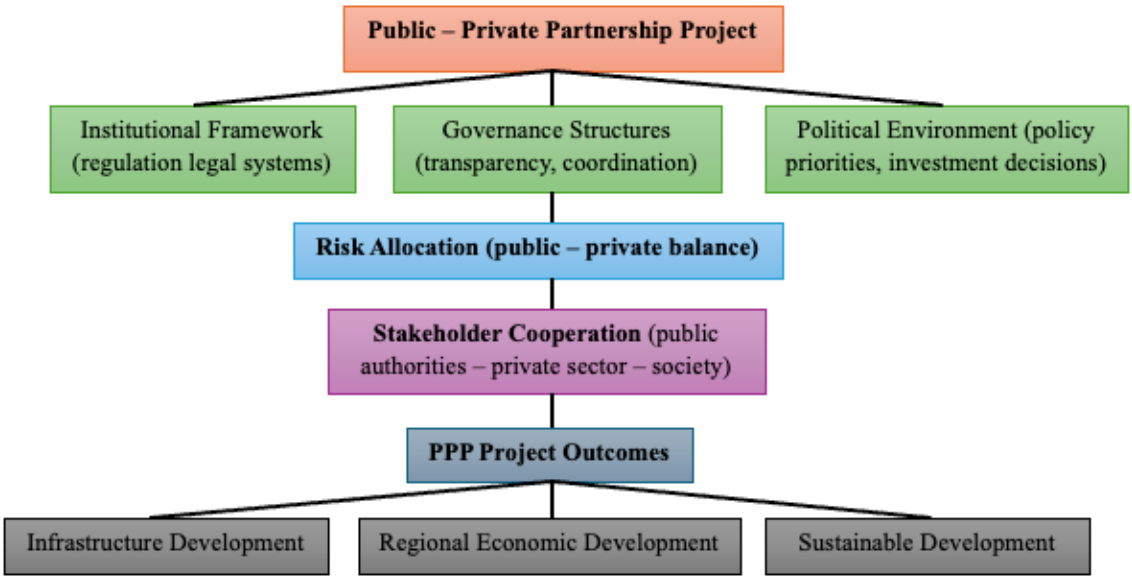
Despite the potential benefits of public-private partnerships, the literature highlights several governance and sustainability challenges that can affect the effectiveness and long-term success of PPP projects. These challenges are primarily related to the institutional framework, governance structures the political environment and the coordination of the numerous stakeholders involved in the partnership agreement. One of the most important factors influencing PPP implementation is the institutional environment in which PPP projects operate. Institutional frameworks establish the legal regulatory and administrative rules governing cooperation between public authorities and private-sector partners. Well-developed institutional systems help ensure transparency in the decision-making process, establish clear contractual responsibilities and support effective monitoring of project outcomes. In contrast, weak institutional frameworks can increase uncertainty, complicate contract management and reduce the effectiveness of PPP implementation (Adebayo et al., 2023). Governance structures also play crucial role in determining PPP outcomes. Effective governance requires transparent procurement procedures, clear accountability mechanisms and a balanced allocation of risk between public and private partners. Risk allocation is particularly important in PPP projects as infrastructure investments are typically characterized by long time horizons, high capital costs and significant operational uncertainty (Chen et al., 2024; Grimsey & Lewis, 2004; Yescombe, 2018). Studies emphasize that an inappropriate allocation of risks among project partners can reduce the motivation for effective project management and negatively impact project outcomes (Grimsey & Lewis, 2004;

Yescombe, 2018). In addition to institutional and governance factors, the political environment can significantly influence the implementation of PPP projects. Government priorities, policy strategies and political incentives can influence decisions regarding infrastructure investments and the selection of PPP projects. Empirical studies show that political motives can sometimes influence the distribution of PPP projects across sectors and regions, particularly when governments seek to achieve visible economic development outcomes or demonstrate policy achievements (Zhang et al., 2026).

Another key challenge relates to the coordination of stakeholders involved in PPP projects. PPP initiatives involve collaboration among multiple participants, including government agencies, private companies, financial institutions and local communities. These actors operate within complex governance network that influence decision-making processes and project implementation. Therefore, effective coordination and communication among stakeholders are essential to mitigate governance conflicts and ensure successful project implementation (Klijn & Teisman, 2003; Zhao et al., 2026). The relationship among these key factors influencing the effectiveness of PPP projects are illustrated in Figure 2.

Figure 2 illustrates the key institutional governance and political factors that influence the effectiveness of public-private partnerships projects. The figure highlights that institutional systems, governance structures and political environment influence risk allocation and level of cooperation among stakeholders in PPP systems. Together, these factors shape the implementation process of PPP projects and ultimately determine their outcomes.

Figure 2
Key factors influencing the effectiveness of public-private projects



Source: developed by the authors based on the literature reviewed in this study.

As shown in Figure 2, the effective implementation of PPPs requires a balanced interaction between regulatory authorities, governance mechanisms and stakeholder cooperation. Strong institutional capacity and transparent governance systems support effective risk sharing and improve coordination between public and private partners. At the same time constructive cooperation among stakeholders improves project efficiency and promotes knowledge sharing and the pooling resources. Ultimately these governance conditions influence the broader outcomes of PPP projects, including infrastructure modernization, regional economic development, and sustainable development goals. Therefore, strengthening institutional frameworks, improving governance transparency, and incorporating sustainability are essential for achieving long-term project success.

Conclusions

1. A review of the literature confirms that research on public-private partnerships has evolved from focusing primarily on financial structures, procurement procedures and risk sharing in infrastructure projects to broader research areas, including governance systems, institutional capacity and the socioeconomic impact of PPP implementation.
2. The study shows that PPP governance mechanisms play a significant role in the implementation of infrastructure projects, ensuring long term cooperation between public authorities and private sector actors such as transport, energy and public services.
3. The results indicate that the PPP initiatives can foster regional development by improving the quality and accessibility of public services supporting infrastructure development and promoting

technological innovation within regional economic systems.

4. The analysis highlight that the effectiveness of PPP projects depends largely on institutional capacity, transparent governance systems, balanced risk-sharing mechanisms and the ability to coordinate the activities of multiple stakeholders, while integrating sustainability considerations into infrastructure planning and development.

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ANALYSIS OF PUBLIC-PRIVATE PARTNERSHIPS INSTITUTIONAL ENVIRONMENT FOR REGIONAL DEVELOPMENT AND SUSTAINABILITY

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Abstract
Public-private partnerships (PPPs) are increasingly used to finance and deliver infrastructure and public services under conditions of fiscal pressure and rising development needs. Their effectiveness, however, depends not only on projects design but also on the institutional environment in which they are implemented. This study analyses the institutional environment of public-private partnerships in the context of regional development and sustainability, with particular emphasis on Latvia. The research applies literature analysis, institutional and comparative analysis. The study examines the legal and governance framework of PPPs, identifies the main institutional determinants of PPP development, and compares Latvia's experience with broader international and Baltic practice. The results show that PPP development is strongly influenced by regulatory quality, governance capacity institutional coordination and the quality of risk allocation. Although Latvia has established a formal legal framework for PPP implementation, actual PPP practice remains limited compared with countries that have stronger institutional coordination and accumulated implementation experience. The analysis indicates that Latvia's main constraints are not the absence of law, but rather limited administrative capacity fragmented strategic planning, weak project continuity and a narrow financing and knowledge base. The study concludes that strengthening institutional coordination, improving public sectors competence and embedding PPPs in clearer strategic development framework would increase the contribution of PPPs to sustainable regional development in Latvia.
Keywords: public-private partnerships, institutional environment, regional development, sustainability, Latvia.

Introduction

Public-private partnerships (PPPs) have become an important instrument for the development of infrastructure and public services in countries seeking to combine public goals with private finance, expertise and managerial capacity (Dao et al., 2020; Gupta & Sharma, 2023). In practical terms, PPPs are long-term cooperative arrangements in which public and private actors share resources, responsibilities and risks in order to provide infrastructure or services that serve public needs (Public – Private Partnership Law, 2009; Brusbārde, 2024). The international expansion of PPPs has been driven by several factors. Governments face increasing pressure to modernize transport, energy, healthcare, housing and public service systems while operating under fiscal constraints. PPPs offers a way to mobilize private capital, spread costs over time and potentially improve efficiency through innovation and lifecycle-oriented project management (Dao et al., 2020; Brusbārde, 2024). At the same time research shows that PPPs do not succeed automatically. Their results depend heavily on the institutional environment, including legal rules, governance quality, regulatory predictability, administrative competence and broader trust relations between public and private actors (Gupta & Sharna, 2023; Saad et al., 2021; Reynaers & Parrado, 2017). The literature has analyses PPPs from several complementary perspectives, one strand emphasizes institutional quality, demonstrating that government effectiveness regulatory quality political stability and corruption control influence private investment in PPP infrastructure projects (Gupta & Sharma, 2023). Another strand focuses on risk and relational governance, showing that PPP performance depends not only on formal contracts but also on trust, flexibility and the ability of partners to manage relational risk over the time (Saad et al., 2021; Reynaers & Parrado, 2017). A third strand highlights legitimacy and institutional linkages arguing that PPPs operate not only as financing tools but also as institutional arrangements through which private actors gain legitimacy by aligning themselves with public goals and state structures (Marschilich & Ingenhoff, 2022; Žuvela et al., 2023). Recent research also stresses institutional distance and network positioning, showing that private partners adapt to unfamiliar institutional environments by building stronger collaborative linkages and brokerage positions in PPP networks (Wang et al., 2026). Although this literature is extensive an important gap remains. Most empirical research focuses on large economies, broad international samples or mature PPP markets. Far less attention has been paid to smaller regional economies where a legal PPP framework exists but implementation remains thin and discontinuous. This is particularly relevant for Latvia. On paper, Latvia has formal PPP framework that defines PPP types, procedures, institutional responsibilities and risk-sharing principles (Public – Private Partnership Law, 2009). In practice, however, PPP implementation has remained limited and uneven especially in comparison with neighboring Lithuania, which has built a broader and more institutionally coordinated PPP practice (Brusbārde, 2024). This difference is analytically important. It suggests that the existence of legal norms, administrative capacity, strategic coordination, project preparation and financial ecosystem maturity interact within a broader institutional environment. This study addresses that problem. The aim of the study is to analyse the institutional environment influencing the development of public-private partnerships and to evaluate its significance for regional development and sustainability in Latvia.

To achieve this aim, the study addresses three research questions:

1. Which institutional factors most strongly influence PPP development and performance in the context of regional development and sustainability?
2. How is the PPP institutional framework structured in Latvia, and how does it support or limit the use of PPPs for sustainable regional development?
3. Which institutional barriers explain Latvia's comparatively limited PPP implementation and reduce the potential contribution of PPPs to regional development and sustainability?

The study contributes in two ways. First, it synthesizes fragmented strands of PPP literature into a single institutional framework applicable to Latvia. Second, it uses the Latvian case to show why PPP development depends not only on legal regulation but also on governance capacity, strategic continuity, and institutional coordination.

Materials and Methods

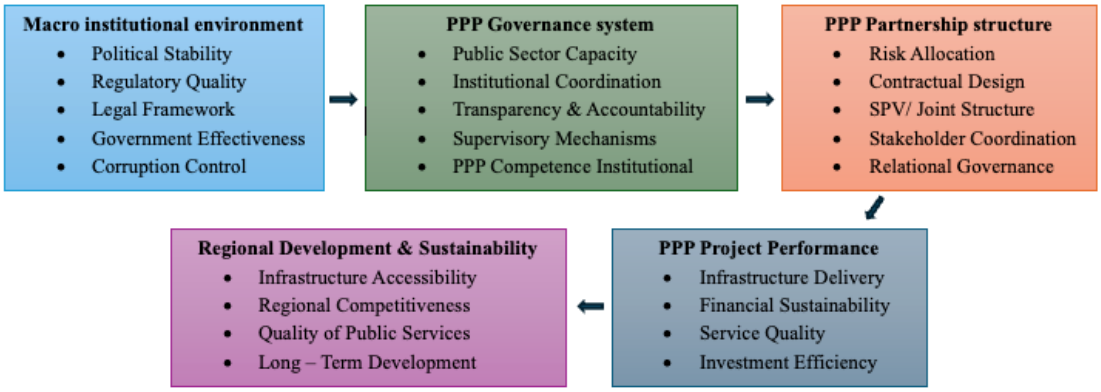
The study use a qualitative research design based on literature analysis, institutional and comparative analysis. The literature review covers 16 sources used in the study. These sources include international academic studies on institutional quality, PPP governance, relationship risk, legitimacy, network positioning, investment efficiency, and model development, as well as Latvian legislation and policy documents. The literature was analyzed to identify recurring explanatory variables related to PPP development, including institutional quality, governance capacity, risk allocation, legitimacy, coordination mechanisms, and financing structure (Dao et al., 2020; Gupta & Sharma, 2023; Saad et al., 2021; Reynaers & Parrado, 2017; Wang et al., 2026). The main variables used in the analysis were institutional quality, regulatory predictability, public-sector administrative capacity, inter-institutional coordination, transparency and accountability, risk allocation, financial system maturity, stakeholder trust, project continuity and alignment with regional development and sustainability objectives. The institutional models were identified, compared and interpreted according to six analytical criteria: legal and regulatory framework, public-sector governance capacity, institutional coordination mechanisms, risk allocation and contract management, financial and investment capacity and the expected contribution of PPPs to regional development and sustainability. The regional development dimension was assessed through references to infrastructure accessibility, regional competitiveness, public service quality and long-term development capacity. The sustainability dimension was interpreted through the ability of PPP systems to support long-term project continuity, efficient resource use, transparent governance and socially beneficial infrastructure outcomes. The institutional analysis focuses on Latvia's Public-Private Partnerships Act and the associated governance mechanisms. This analysis evaluates how Latvian legislation defines PPPs, distinguishes between contractual and institutional PPPs, structures concession and partnership agreements, allocates risks, and assigns supervisory functions to public authorities (Public-Private Partnerships Law, 2009). A comparative analysis is used to compare Latvia with international and Baltic practices. Special attention is paid to global PPP trends and Lithuania as a regional comparison, as Lithuania has established a broader and more sustainable PPP portfolio under a more coordinated institutional model (Brusbārde, 2024). Methodologically, the study does not statistically test causal relationships. Instead, it identifies and interprets institutional models from various sources, using Latvia as the main case study and international experience as a comparative reference point. This approach aligns with the article's objective, which is analytical and focused on system development rather than econometric. During the preparation of this work, artificial intelligence tools were used for text translation, as well as for improving sentence style and grammar. These tools were used solely for the purposes of language editing and improving textual accuracy; the research concept, analysis, interpretation, and conclusions, however, represent the authors' independent academic contribution.

Results and Discussion

Institutional environment framework of public-private partnerships

The reviewed literature clearly demonstrates one thing: PPPs are not simply contracts or financing mechanisms. They are deeply entrenched institutional systems. Their effectiveness depends on the interaction between legal frameworks, governance capacity, institutional coordination, risk allocation at the project level, as well as the ability of public and private actors to collaborate over the long term (Gupta & Sharma, 2023; Saad et al., 2021; Reynaers & Parrado, 2017). At the macro level, institutional quality is important because it creates transparency for investors: government effectiveness, regulatory quality, control of corruption, and political stability—all of these influence whether private companies are willing to invest long-term capital in PPP projects (Gupta & Sharma, 2023). At the micro level, public administration capacity is important because PPPs require government agencies capable of conducting project selection, procurement planning, contract supervision, and financial evaluation (Wang, 2015; Dao et al., 2020). At the project level, risk allocation and partnership structure are important, as improperly allocated risks, weak oversight, or overly strict contracts reduce project effectiveness and create incentives to renegotiate contracts and lead to conflicts (Saad et al., 2021; Reynaers & Parrado, 2017; Van Ham & Koppenjan, 2016). These multi-level relationships are summarized in Figure 1. This model suggests that the institutional environment influences regional development indirectly by affecting PPP governance and project outcomes.

Figure 1
Institutional environmental framework of public-private partnerships



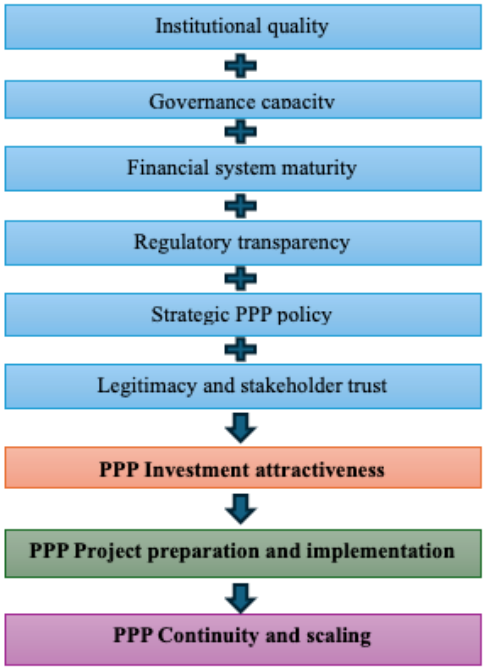
Source: developed by the author based on Gupta & Sharma (2023), Saad et al. (2021), Rynaers &Parrado (2017), Wang et al. (2026), Dao et al., (2020) and Public – Private Partnership Law (2009).

This is important for Latvia because it means that policymakers must focus not only on 'whether PPPs are permitted by law' but also on 'whether the governance system is capable of ensuring the implementation of viable PPP projects'. In the context of regional development, this means that public-private partnerships (PPPs) should be evaluated not only by the number of projects implemented, but also by their ability to improve infrastructure accessibility, regional competitiveness, the quality of public services, and long-term development opportunities. In the context of sustainability, the institutional environment is crucial, as weak coordination, inadequate risk sharing, and limited project continuity reduce the ability of PPPs to deliver stable, long-term public benefits.

Determinants of PPP development

In all 16 sources, five factors are repeatedly cited as the most important for the development of PPPs. First, institutional quality influences the attractiveness of PPPs to private partners. A country with stricter regulations, more predictable government action, and better control of corruption is better able to attract private investment (Gupta & Sharma, 2023; Dao et al., 2020). Second, governance capabilities in the public sector are crucial. Governments must be able to identify suitable projects, select appropriate PPP models, prepare sound procurement procedures, and oversee project implementation (Wang, 2015; Reynaers & Parrado, 2017). Third, the quality of risk allocation is crucial; PPPs are most effective when risks are assigned to the party best equipped to manage them. Inappropriate risk allocation leads either to excessive government exposure to risk or to private sector withdrawal, opportunism, or poor service outcomes (Saad et al., 2021; Wang, 2015; Brusbārde, 2024). Fourth, institutional legitimacy and stakeholder trust foster long-term cooperation. PPPs are not sustained by formal clauses alone. Informal institutional conditions, such as trust, legitimacy, and a sense of socially accepted and perceived fairness, influence whether partnerships remain stable over time (Marschilich & Ingenhoff, 2022; Reynaers & Parrado, 2017). Fifth, strategic policy continuity and coordination mechanisms are important. Countries with specialized PPP competence centers, accumulated project experience, and a clearer project plan typically implement PPPs more effectively (Brusbārde, 2024; Wang, 2015). These determinants are synthesized in Figure 2.

Figure 2
Determinants of public-private partnership development



Source: developed by the author based on Dao et al. (2020), Gupta & Sharma (2023), Saad et al. (2021), Marschilich & Ingenhoff (2022), Wang (2015) and Brusbārde (2024).

This indicator is useful from an analytical perspective because it shows that PPP development is cumulative. A country with only one piece of legislation but lacking coordination capacity, a project pipeline,

financial stability, and stakeholder trust is capable of creating a fully-fledged PPP environment.

Global PPP practice and institutional framework of PPPs in Latvia

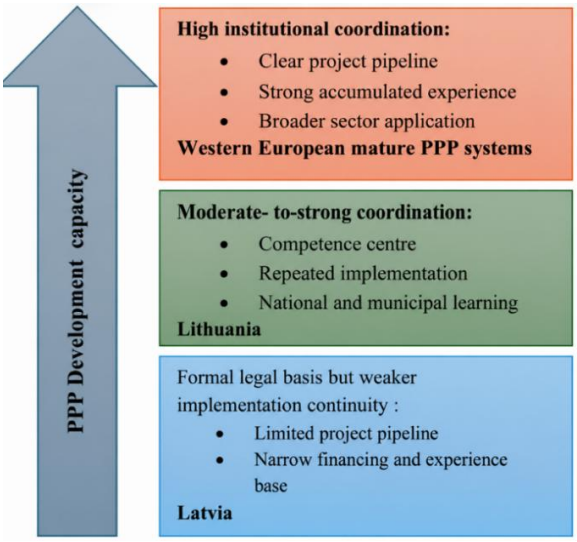
International practice shows that public-private partnerships (PPPs) are used in many sectors, but the transportation sector continues to play a dominant role (Brusbārde, 2024; World Bank Group, 2024). Brusbārde (2024) notes that, both globally and in Europe, transport infrastructure has historically accounted for the largest share of the total value of PPPs, while healthcare, education, environmental protection, and information and communication technologies (ICT) are also significant sectors. The United States provides examples of a long-standing use of PPPs in road, urban development, and service infrastructure, while France and Germany illustrate how PPPs have been integrated into investments in transportation, station renovations, healthcare, and education (Brusbārde, 2024). At the same time, international experience cautions against simplistic optimism. PPPs can improve project implementation, spread costs over time, and foster innovation, but they can also lead to transparency issues, high transaction costs, and poor value-for-money outcomes if risks are poorly allocated or contracts are poorly drafted (Brusbārde, 2024; Dao et al., 2020). European audit experience cited in Latvian policy discussions shows that ineffective risk allocation and excessive private profit are real governance risks, not abstract possibilities (European Court of Auditors, 2018; Brusbārde, 2024). Latvia has established an official legal framework for public-private partnerships (PPPs) (Public – Private Partnership Law, 2009; Ministry of Finance of the Republic of Latvia, 2020). The Public-Private Partnerships Act defines a PPP as a long-term collaboration between the public and private sectors characterized by the joint use of resources, a long duration of operation, as well as shared responsibility and risks. The law distinguishes between contractual PPPs and institutional PPPs, and recognizes both partnership procurement contracts and concession contracts as the main legal forms (Public-Private Partnerships Law, 2009). This is not a weak or incomplete legal definition. On the contrary, the law provides a relatively clear framework for implementing PPPs, including definitions of public and private partners, forms of concessions, demand and availability risks, joint venture structures, and oversight responsibilities. It also designates the Ministry of Finance, the Procurement Monitoring Bureau, and the designated supervisory authority as the responsible parties for supervising the PPP process (Public-Private Partnership Law, 2009). Thus, the analytical problem is not a legal deficiency. It is a weakness in implementation, despite the legal framework. Brusbārde (2024) shows that Latvia's PPP practice has developed in intermittent phases. Before the global financial crisis, several PPP-type contracts were concluded, many of them concessions. After the crisis, PPP development slowed sharply, and the hiatus lasted more than ten years. By 2023, only one major PPP project had been implemented: the Ķekava bypass. Several additional projects were in the planning or financial evaluation phase, but their implementation was curtailed (Brusbārde, 2024). This pattern confirms the research gap identified in the introduction. Latvia demonstrates that a country can have a formal legal framework yet still fail to establish a mature PPP ecosystem. The question is: why? This is particularly important in the case of Latvia. Latvia does not need 'more PPPs at any cost'. It needs institutionally sounder PPPs, developed selectively in those areas where governance and financing conditions justify them. The most telling comparison is with Lithuania. According to Brusbārde (2024), by the end of 2023, 73 PPP contracts had been concluded in Lithuania, of which 50 were still in force. These projects spanned the sectors of transportation, energy, waste management, healthcare, public safety, culture, sports, and others. This diversity is significant because it indicates not only a greater number of projects but also a broader institutional normalization of PPPs as a development tool. The wider use of PPPs in Lithuania also creates greater opportunities to improve regional infrastructure, access to public services, and local economic development, thereby strengthening the contribution of PPPs to achieving sustainable regional development outcomes. Brusbārde (2024) attributes part of Lithuania's best results to the existence of a PPP competence center, the continuity of projects, and the accumulation of implementation experience at both the national and local government levels. Lithuania also benefited from the clearer integration of PPP thinking into strategic development planning. Latvia, on the other hand, has been weaker in terms of continuity, with fewer projects and fewer opportunities to build institutional experience through repeated implementation. This difference is illustrated in Figure 3.

This comparison does not mean that Latvia should simply copy the mechanisms used in Lithuania or Western Europe. The issue is more specific and practical: Latvia's task is institutional maturation, not merely legal adaptation.

Policy Implication for PPP development in Latvia

Analysis of the institutional environment for public-private partnerships in Latvia reveals several important policy implications aimed at strengthening PPP governance and improving the effectiveness of infrastructure development strategies. First, institutional coordination mechanisms must be strengthened. International experience shows that in countries where PPPs are successfully implemented, specialized PPP competence centers or coordinating bodies are often established. These entities are responsible for supporting project preparation, providing methodological guidelines, and fostering cooperation between government agencies and private partners (Gupta & Sharma, 2023; Brusbārde, 2024; European PPP Expertise Centre, 2021).

Figure 3
Comparative PPP development model: Latvia and international practice



Source: developed by the author based on Brusbārde (2024), Public – Private Partnership Law (2009) and international studies by Dao et al. (2020), Gupta & Sharma (2023) and Wang (2015).

Establishing such an institutional coordination structure in Latvia could improve project continuity and strengthen administrative capacity. Second, the public sector's expertise in PPP project preparation must be expanded. PPP projects require complex financial modeling, legal expertise, and risk assessment capabilities. Strengthening training programs for government officials and establishing specialized PPP advisory units could significantly improve project preparation and contract management (Wang et al., 2015; Reynaers & Parrado, 2017). Third, PPP projects should be more clearly integrated into national and regional development strategies. This is particularly important for regions where infrastructure deficits, limited fiscal capacity, and unequal access to public services constrain long-term development potential. In such cases, public-private partnerships can promote sustainability only if projects are selected in accordance with clear regional development priorities and if their expected social, economic, and environmental benefits are assessed prior to implementation. International experience shows that successful PPP systems typically operate within structured project pipelines that align infrastructure investments with long-term development planning (Dao et al., 2020). A clearer strategic framework for PPP implementation in Latvia could increase investor confidence and improve the transparency of PPP opportunities. Fourth, the development of the financial ecosystem must be promoted; the limited experience of financial institutions in PPP financing has been identified as a barrier to the expansion of PPPs in Latvia (Brusbārde, 2024). Promoting cooperation among government agencies, commercial banks, development finance institutions, and international financial organizations could help expand financing opportunities for PPP infrastructure projects. Finally, institutional learning mechanisms must be strengthened. PPP systems typically evolve through iterative learning processes in which government agencies refine regulatory frameworks, procurement procedures, and risk-sharing models based on experience from previous projects (Reynaers & Parrado, 2017). Supporting knowledge exchange and institutional learning could improve the sustainability of PPP governance in Latvia. Overall, these policy recommendations emphasize that the future development of PPPs in Latvia will depend not only on maintaining the existing legal framework, but also on strengthening institutional capacity, governance coordination, and strategic planning.

Conclusions

1. Public-private partnerships are an institutional governance mechanism that allows governments to combine public policy objectives with private-sector resources in infrastructure development. The literature indicates that the effectiveness of PPPs depends not only on the contract structure but also on the broader institutional environment, including the quality of regulation, governance capacity, and stakeholder trust.
2. Analysis shows that countries with stronger institutional coordination, accumulated administrative experience, and clear PPP strategies achieve higher PPP implementation rates. Effective PPP systems require not only a legal framework but also institutional experience, governance capacity, and well-structured risk-sharing mechanisms.
3. Latvia has a formal legal framework governing PPP implementation; however, actual PPP practice remains limited compared to neighboring countries, such as Lithuania. This discrepancy indicates that the main constraints are institutional rather than legislative, including limited administrative capacity, fragmented policy coordination, and a narrow spectrum of the financing ecosystem.
4. Strengthening inter-agency coordination, improving the public sector's expertise in preparing PPP projects, and more clearly integrating PPPs into national and regional development strategies could significantly increase the contribution of PPPs to sustainable regional development in Latvia.
5. Future research should empirically examine the link between PPP institutional capacity and measurable regional development outcomes in Latvia and the Baltic region. Future research could compare PPP project plans, governance models, and sustainability indicators in Latvia, Lithuania, and Estonia, as well as assess how PPPs impact infrastructure accessibility, service quality, investment attraction, and the long-term sustainability of regions.

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SYNERGY OF RURAL AREA REVITALIZATION AND AGRICULTURAL PRODUCTION DEVELOPMENT IN THE CONTEXT OF WAR AND POST-WAR CHALLENGES IN UKRAINE: MANAGERIAL ASPECT

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Abstract
This study examines governance mechanisms that strengthen the synergy between rural revitalization and agricultural production development under wartime and post-war conditions in Ukraine. Rural territories perform important economic, social, and demographic functions, while agriculture remains a key contributor to national food security and economic resilience. Descriptive statistics, SWOT and PESTEL analyses were applied to identify the major challenges and development opportunities affecting rural territories and agricultural producers. The findings indicate that labor shortages, infrastructure destruction, limited access to finance, and institutional instability are the most significant barriers to sustainable rural development. At the same time, farmers demonstrate considerable adaptive capacity, willingness to cooperate, and interest in innovation. The study operationalizes synergy through three dimensions: economic, social, and institutional. Economic synergy is reflected in employment creation, investment attraction, and market diversification; social synergy is associated with community resilience and human capital development; institutional synergy emerges through stakeholder cooperation and governance effectiveness. Based on empirical findings, the paper proposes an evidence-based Governance Synergy Framework that integrates agricultural, infrastructural, social, and institutional recovery measures. The results emphasize that sustainable post-war recovery requires coordinated actions by public authorities, local communities, agricultural enterprises, financial institutions, and international partners. Strengthening such interactions can enhance rural resilience, support food security, and improve the long-term competitiveness of rural territories in Ukraine.
Keywords: rural revitalization, agricultural development, governance synergy, management mechanisms, post-war recovery.

Introduction

Rural territories represent complex socio-economic systems that perform multiple functions extending beyond agricultural production. They contribute to food security, employment, environmental sustainability, demographic stability, and territorial cohesion. In Ukraine, rural areas account for a substantial share of agricultural output and play a strategic role in maintaining national economic resilience. Consequently, the sustainable development of rural territories and the competitiveness of agricultural production are increasingly viewed as interdependent policy objectives rather than separate development domains.

The full-scale Russian invasion has significantly intensified long-standing structural challenges affecting rural territories. Military actions have resulted in the destruction of infrastructure, disruption of logistics chains, contamination of agricultural land, labor shortages, and increased investment risks. Simultaneously, rural communities have experienced population displacement, demographic decline, and reduced access to public services. These challenges have undermined both agricultural productivity and the socio-economic viability of rural territories, creating the need for integrated recovery approaches that simultaneously address economic, social, and institutional dimensions of development.

Despite these adverse conditions, the agricultural sector has demonstrated considerable resilience and remains one of the key contributors to Ukraine's economic stability and export revenues. However, the sustainability of agricultural production increasingly depends on broader territorial factors, including infrastructure quality, institutional capacity, labor availability, access to finance, and the effectiveness of local governance. This interdependence suggests that agricultural development and rural revitalization should not be analyzed separately but rather as mutually reinforcing processes.

In this study, rural revitalization is understood as a comprehensive process of restoring and enhancing the economic, social, environmental, and institutional capacity of rural territories. Agricultural development, in turn, is viewed not only as an increase in production volumes but also as a catalyst for local economic growth, job creation, innovation diffusion, and community resilience. The interaction between these processes generates what is conceptualized in this paper as synergy.

Unlike previous studies, synergy is not treated as a rhetorical concept but as an analytical category. It is defined as the mutually reinforcing interaction between agricultural production development and rural revitalization that generates outcomes exceeding those achievable through isolated interventions. From a governance perspective, synergy emerges when coordinated actions of public authorities, local communities, agricultural enterprises, financial institutions, and international partners simultaneously strengthen economic performance, social cohesion, and institutional capacity. Accordingly, three dimensions of synergy are distinguished in this research:

- economic synergy – manifested through employment growth, investment attraction, business diversification, and increased local revenues;
- social synergy – reflected in community resilience, demographic stabilization, human capital development, and improved quality of life;
- institutional synergy – generated through effective governance, stakeholder cooperation, public-private partnerships, and enhanced access to development resources.

This conceptualization provides a theoretical framework for analyzing the interaction between agricultural production and rural revitalization under wartime and post-war conditions.

A substantial body of literature has examined the consequences of the Russian invasion for Ukrainian agriculture and rural development. M. Nehrey and R. Finger (2024) analyzed the initial impact of the war on Ukrainian agriculture and emphasized the importance of human capital development, support for small and medium-sized farms, integration into international markets, and digital transformation as prerequisites for post-war recovery (Nehrey & Finger, 2024).

O. Garafonova, H. Zhosan, V. Khudolei, N. Tiukhtenko, I. Tymkiv, and N. Riabets highlighted the role of diversified financing mechanisms, investment support, and innovative development models in revitalizing de-occupied territories. Their findings suggest that post-war reconstruction should be viewed as an opportunity for structural modernization rather than merely compensation for losses (Garafonova et al., 2023).

The growing role of digitalization in agricultural development has also attracted considerable scholarly attention. N. Zelisko, N. Raiter, N. Markovych, H. Matskiv, and O. Vasylyna demonstrated that the adoption of artificial intelligence, Big Data, blockchain technologies, drones, and precision farming systems contributes to greater efficiency, competitiveness, and economic security in agribusiness (Zelisko et al., 2024).

Similarly, R. Finger argues that digital innovations enhance productivity while simultaneously 1. strengthening the resilience and sustainability of agricultural systems. These findings indicate that technological modernization represents an important component of post-war rural recovery strategies (Finger, 2023).

Other studies emphasize the broader economic and geopolitical significance of Ukrainian agriculture. T. Glauben and co-authors demonstrated that disruptions in Ukrainian agricultural production have significant implications for global food security, particularly for countries dependent on grain imports from the Black Sea region (Glauben et al., 2022).

At the territorial level, I. Zamkova, I. Romaniuk, H. Zhosan, H. Matskiv, and O. Bodnar identified new development opportunities for affected communities through innovative approaches such as military tourism, emphasizing the importance of community engagement, local initiatives, and employment creation (Zamkova et al., 2025).

Thus, the analysis of existing studies indicates that scholars have extensively examined individual aspects of the problem, including the losses of the agricultural sector caused by the war, governmental responses to the crisis, financial mechanisms for post-war recovery, tools for the digitalization of agribusiness, as well as certain directions of revitalization of de-occupied territories (Boikivska & Honchar, 2024; Fedchyshyn et al., 2023; Abramiuk, 2023).

However, a comprehensive approach that would reveal the synergy between the revitalization of rural territories and the development of agricultural production during wartime and post-war periods, with particular emphasis on managerial aspects, remains underdeveloped. In particular, issues related to the coordination of actions among the state, local communities, businesses, and investors; the integration of agricultural, social, infrastructural, and digital components of recovery; and the formation of a holistic governance model capable of ensuring the long-term resilience and competitiveness of rural territories in Ukraine remain insufficiently explored. This gap determines the relevance of the chosen topic and defines the scientific niche of the proposed study.

The study aims to assess the synergy between revitalizing rural territories and developing agricultural production in the context of wartime challenges and post-war reconstruction in Ukraine, from a governance perspective. To achieve this aim, the following research objectives are defined:

1.To assess the impact of wartime conditions on the development strategies of small farming enterprises in Ukraine.

2. To identify the key economic, institutional, social, and infrastructural factors affecting both agricultural production and rural revitalization.

3.To determine governance mechanisms capable of strengthening the synergy between the development of agricultural production and the processes of rural revitalization.

Materials and Methods

This study employs an integrated mixed-methods research design aimed at identifying and assessing the synergy between rural revitalization and agricultural production development under wartime and post-war conditions in Ukraine. Given the multidimensional nature of rural development, the research combines quantitative and qualitative approaches, including sociological survey analysis, descriptive and inferential statistical methods, SWOT analysis, and PESTEL analysis.

The empirical basis of the study consists of a sociological survey conducted among 200 small farming enterprises located in different regions of Ukraine. The survey covered five macro-regions: Western, Central, Northern, Southern, and Eastern Ukraine. The regional distribution of respondents

enabled the identification of territorial differences in wartime impacts and development priorities.

A purposive sampling approach was employed to ensure the inclusion of farms differing in production specialization, scale of activity, and geographical location. Although the sample does not provide proportional representation of all Ukrainian farming enterprises, it adequately reflects the diversity of small-scale agricultural producers operating under wartime conditions.

The questionnaire consisted of 24 questions grouped into four thematic blocks: 1) general characteristics of farming enterprises; 2) wartime impacts on agricultural activities; 3) development priorities and strategic adaptation measures; 4) cooperation, governance, and future development expectations. The survey instrument included closed-ended, open-ended, and mixed-format questions. Most attitudinal and perception-based variables were measured using a five-point Likert scale ranging from 1 ('very low importance/impact') to 5 ('very high importance/ impact').

Prior to the main survey, the questionnaire was reviewed by three experts in rural development and agricultural economics to assess content validity. A pilot survey involving 15 farming enterprises was conducted to evaluate clarity, consistency, and relevance of the questions. Minor modifications were introduced based on respondents' feedback before the final data collection stage.

The collected data were processed using IBM SPSS Statistics 21. Descriptive statistical methods, including frequency distributions, percentages, means, and standard deviations, were used to identify the most significant challenges, development priorities, and strategic orientations of farming enterprises.

To strengthen analytical interpretation, cross-tabulation analysis and Pearson's Chi-square tests were applied to examine relationships between regional location and perceived development challenges, as well as between development strategies and willingness to participate in cooperative initiatives. Statistical significance was assessed at the 0.05 level.

In addition, a Synergy Assessment Framework was developed to operationalize the concept of synergy introduced in the theoretical section. The framework evaluates three interrelated dimensions:

- economic synergy, reflected in production expansion intentions, investment needs, market diversification, and employment generation;
-social synergy**,** reflected in cooperation readiness, knowledge exchange, human capital development, and community engagement;
- institutional synergy, reflected in demand for governance support, participation in development programs, and interaction with local institutions.

The empirical findings were interpreted through these dimensions to identify mechanisms linking agricultural development and rural revitalization.

To complement the survey analysis, SWOT and PESTEL methodologies were employed.

The SWOT analysis was used to evaluate internal and external factors affecting the sustainable development of rural territories. Unlike traditional descriptive applications, the SWOT framework was structured according to methodological principles distinguishing internal factors (strengths and weaknesses) from external factors (opportunities and threats).

The PESTEL analysis was applied to assess the influence of political, economic, social, technological, environmental, and legal factors on rural recovery and agricultural development under wartime conditions. Particular attention was paid to wartime-specific challenges, including infrastructure destruction, labor migration, security risks, institutional instability, and access to international support programs.

Based on the integration of survey results, statistical analysis, SWOT and PESTEL findings, an evidence-based Governance Synergy Framework was developed. The model conceptualizes synergy as the outcome of interactions among economic, social, and institutional mechanisms that simultaneously stimulate agricultural development and rural revitalization.

The framework identifies governance mechanisms through which public authorities, local communities, agricultural enterprises, financial institutions, and international development partners contribute to strengthening territorial resilience and supporting post-war recovery.

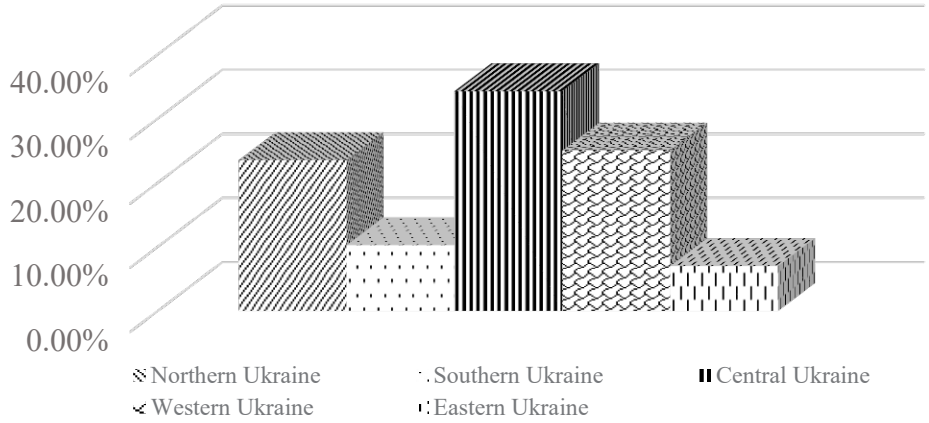
Several limitations should be acknowledged. First, the sample includes a higher proportion of respondents from relatively secure regions, reflecting wartime restrictions on data collection in frontline territories. Consequently, the results should be interpreted with caution when generalized to all rural regions of Ukraine. Second, the study relies primarily on self-reported perceptions of respondents, which may be influenced by subjective assessments. Nevertheless, the combination of quantitative survey data and strategic analytical tools provides a robust basis for identifying key governance challenges and opportunities for rural recovery.

Results and Discussion

The study of key aspects of rural development through the lens of the strategic priorities of small-scale farming served as the basis for a sociological survey of 200 farming enterprises across different regions of Ukraine, aimed at identifying regional specificities. The surveyed farms covered all five macro-regions of Ukraine. In particular, 33.00% of respondents represented the Western region (Lviv, Ternopil, Ivano-Frankivsk, Volyn, Rivne, Khmelnytskyi, Chernivtsi, and Zakarpattia oblasts); 30.25% the Central region (Vinnytsia, Kirovohrad, Poltava, and Cherkasy oblasts); 23.50% the Northern region (Zhytomyr, Kyiv, Chernihiv, and Sumy oblasts); 6.25% the Southern region (Zaporizhzhia, Kherson, Odesa, and Mykolaiv

oblasts); and 7.00% represented the Eastern region (Kharkiv and Dnipropetrovsk oblasts) (Figure 1).
Although the proportion of respondents from frontline regions was lower due to wartime security constraints, the sample reflects the diversity of Ukrainian small-scale farming and provides valuable insights into rural development processes under conditions of crisis and uncertainty.
According to the specialization of their activities, the surveyed farming enterprises exhibit significant diversity in production profiles, ranging from the cultivation of various crop products to livestock farming and processing of agricultural products (Figure 2).

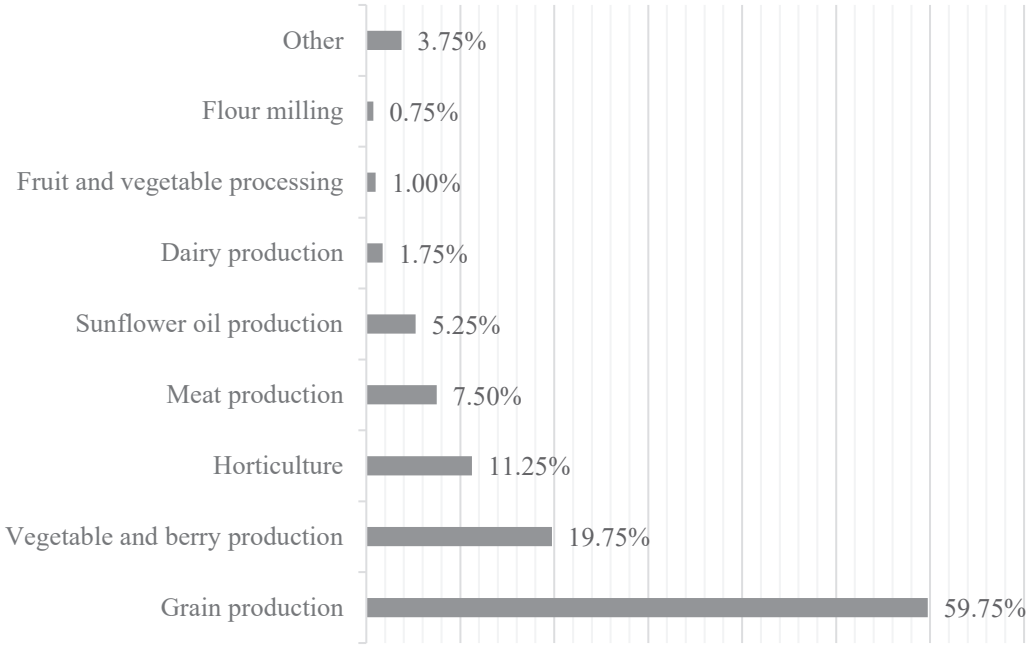
Figure 1
Geographic distribution of surveyed respondents representing farming enterprises



Source: compiled by the authors.

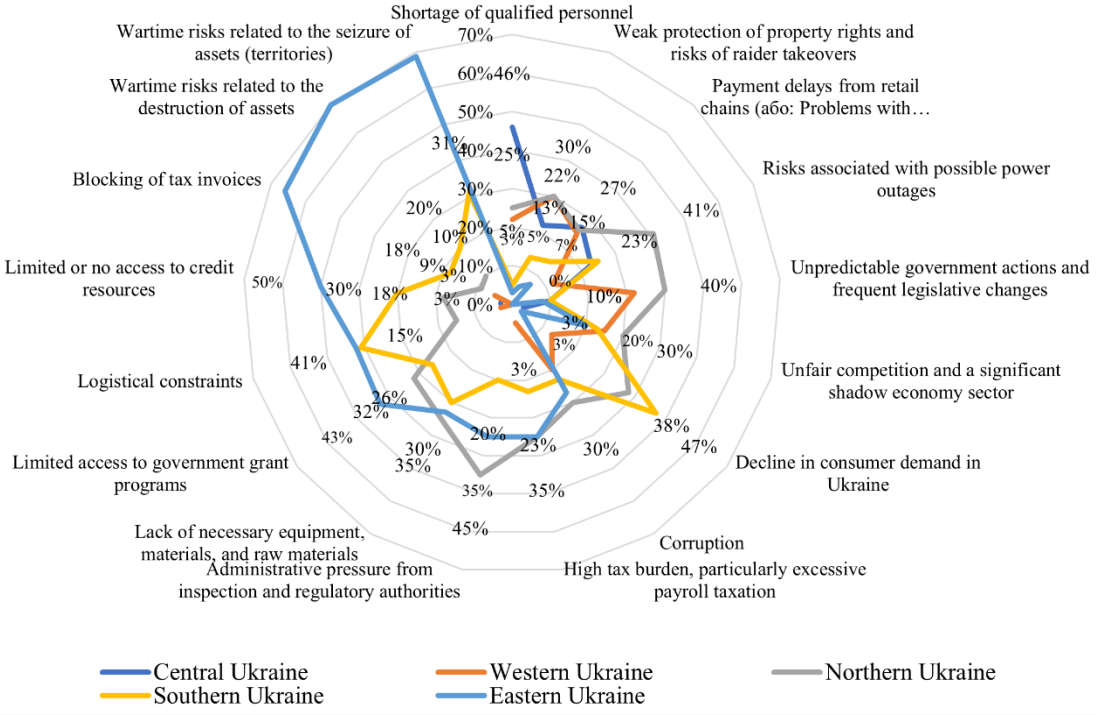
Grain production constituted the dominant activity (59.75%), followed by vegetable and berry production (19.75%), horticulture (11.25%), and livestock production (7.50%). Smaller shares of respondents were engaged in sunflower oil production, dairy farming, agricultural processing, and flour milling. Such diversity enables a comprehensive evaluation of the relationship between agricultural activities and broader rural development processes.
The analysis of strategic orientations demonstrates a predominance of adaptive rather than expansion-oriented behavior. Nearly half of the surveyed enterprises (46%) identified stabilization of current activities as their primary strategic objective, while 26.5% reported intentions to improve performance and expand business operations. In contrast, only 6.25% indicated plans to scale down activities or temporarily conserve assets. These findings indicate that despite severe wartime disruptions, the majority of small farms remain economically active and continue to play an important stabilizing role within rural communities. From the perspective of the proposed synergy framework, such behavior contributes to economic synergy, as the preservation of agricultural activity supports local employment, maintains value chains, and prevents further economic decline of rural territories.
The analysis of development challenges revealed substantial regional differences (Figure 3). The most frequently reported constraint was the shortage of qualified personnel, particularly in Eastern and Southern Ukraine. The problem is largely associated with labor migration, military mobilization, and demographic decline. Similar findings have been reported by Bohdanov, who emphasized the critical role of human capital in sustaining rural development. (Bohdanov, 2017).
A statistically significant association was observed between regional location and the perceived severity of labor shortages (χ^2, $p < 0.05$), indicating that farms operating closer to conflict-affected territories experience considerably greater workforce constraints than enterprises located in relatively secure regions.
Another important challenge identified by respondents concerns the protection of property rights and the risk of raider takeovers. More than one-third of surveyed enterprises considered institutional instability a serious barrier to development. Weak enforcement of property rights reduces investment attractiveness and increases uncertainty regarding long-term business planning. Consequently, institutional deficiencies negatively affect both agricultural competitiveness and territorial resilience.
Financial constraints constitute another critical barrier. Respondents reported payment delays from retail chains, difficulties in accessing credit resources, and limited participation in government support programs. Approximately 78.3% of surveyed farms indicated a need for external financial support, while 52.3% estimated their investment requirements at between UAH 500 thousand and UAH 5 million. These findings highlight the dependence of post-war rural recovery on accessible financing mechanisms and targeted support instruments.

Figure 2
Main specialization of the surveyed farming enterprises



Source: compiled by the authors.

Figure 3
Key challenges in the development of the surveyed farming enterprises



Source: compiled by the authors.

The survey also identified infrastructure-related challenges as a significant determinant of development prospects. Frequent electricity disruptions, logistical bottlenecks, and transportation difficulties negatively affect production efficiency, storage capacity, and market access. Such constraints are particularly problematic for farms engaged in processing activities, where uninterrupted energy supply is essential for maintaining product quality and competitiveness.

At the same time, the survey results demonstrate considerable potential for strengthening social and institutional synergy. Approximately 76% of

respondents expressed willingness to participate in knowledge-sharing activities and professional cooperation networks. Although only 39% were prepared to engage in joint projects, this finding nevertheless indicates substantial opportunities for developing local partnerships and cooperative initiatives. Cross-tabulation analysis revealed a positive relationship between willingness to cooperate and intentions to expand production, suggesting that farms with stronger growth ambitions are also more likely to participate in collective development activities.

The findings further indicate a substantial demand for advisory and consulting services. More than half of respondents (55%) reported the need for support in financial management, investment attraction, supply-chain development, and market expansion. Such demand highlights the importance of institutional support mechanisms capable of facilitating access to knowledge, financial resources, and innovation.

The strategic priorities identified by respondents provide additional evidence supporting the existence of synergy between agricultural development and rural revitalization. While 43% of farms plan to maintain their current scale of operations, 28% intend to expand production and 19.5% seek entry into new markets, including the European Union. However, only eight surveyed enterprises currently consider themselves fully prepared for international market participation. This gap reflects not only production-related limitations but also institutional and infrastructural deficiencies that constrain broader territorial competitiveness.

Consequently, the sustainable development of rural territories depends not only on supporting agricultural production itself but also on strengthening the governance mechanisms that facilitate interaction among farms, local authorities, communities, financial institutions, and development partners. These findings provide empirical support for the proposed concept of economic, social, and institutional synergy and establish the foundation for the subsequent SWOT and PESTEL analyses (Hutorova et al., 2023; Stepanets, 2024; Vdovichen et al., 2016) (Table 1, Table 2).

The findings suggest that rural revitalization and agricultural production should not be viewed as parallel processes. Instead, they function as mutually reinforcing components of a broader territorial development system. The ability of governance institutions to coordinate these interactions determines the scale of synergistic effects and the long-term resilience of rural territories (Babenko, 2020; Harastovska et al., 2023).

From the perspective of the proposed Governance Synergy Framework, the combined results of SWOT and PESTEL analyses provide empirical evidence for the existence of three interconnected dimensions of synergy.

Based on the integration of survey results, statistical analysis, SWOT assessment, and PESTEL evaluation, an evidence-based Governance Synergy Model was developed (Figure 4).

Table 1

SWOT matrix of synergy-based rural development under wartime conditions in Ukraine

Strengths	**Weaknesses**
1. High agricultural potential and fertile land resources. 2. Significant experience and professional knowledge of farmers. 3. Strong local identity and community cohesion. 4. Diversified agricultural production structure. 5. Existing experience in adaptation to crisis conditions.	1. Aging population and demographic decline in rural areas. 2. Insufficient transport, energy, and social infrastructure. 3. Limited access to financial resources and investment capital. 4. Low level of technological modernization among many small farms. 5. Dependence on external financial and humanitarian assistance.
Opportunities	**Threats**
1. EU integration and access to European support programs. 2. International reconstruction and donor funding initiatives. 3. Development of digital agriculture and smart-village solutions. 4. Expansion of agricultural exports and market diversification. 5. Growth of public-private partnerships and local development projects.	1. Continued military actions and security risks. 2. Destruction of infrastructure and logistical networks. 3. Labor shortages caused by migration and mobilization. 4. Environmental degradation and land contamination. 5. Macroeconomic instability and investment uncertainty.

Source: compiled by the authors.

Table 2

PESTEL matrix of rural revitalization and agricultural development under wartime conditions in Ukraine

Category	Positive impacts	Negative impacts	Strategic actions
Political	International support in the form of grants and humanitarian assistance; government programs for rural recovery.	Military conflict leads to infrastructure destruction and security threats; political instability complicates long-term strategic planning.	Involvement of international partners in rural recovery; integration of security measures into development strategies.
Economic	Strong export demand for Ukrainian agricultural products; support for small and medium-sized businesses through international programs.	Destruction of logistics routes and rising fuel prices; limited access to financing for farmers and rural communities.	Development of local markets; attraction of investment in cooperatives and agricultural processing.
Social	Community cohesion encourages mutual support; willingness to implement local recovery initiatives.	Large-scale migration of the working-age population; psychological stress caused by war; limited access to education and healthcare in remote rural areas.	Implementation of psychological support programs; investment in education and healthcare for rural communities.
Technological	Introduction of modern agricultural technologies (drones, automation); development of digital platforms for farmers; use of renewable energy.	Limited access to advanced technologies due to wartime conditions; high cost of implementing innovative solutions.	Attraction of international technical assistance for innovation implementation; training farmers to use modern technologies.
Environmental	Potential for the development of renewable energy; application of environmentally friendly agricultural practices.	Land contamination due to mining and military activities; destruction of natural ecosystems.	Implementation of soil and land restoration programs; development of environmental standards for agriculture.
Legal	Integration into international legal standards, particularly EU regulations; opportunities to update the regulatory framework to support farmers.	Insufficient protection of land property rights; weak enforcement of environmental and agricultural legislation.	Reform of land legislation to simplify access to resources; strengthening legal protection of property rights and creating incentives for investors.

Source: compiled by the authors.

Unlike normative conceptual frameworks frequently presented in previous studies, the proposed model directly reflects the empirical findings of the present research (Tomashuk, 2023; Tymoshenko, 2018).

The model demonstrates how wartime challenges influence agricultural enterprises and rural communities, how governance mechanisms mediate these impacts, and how coordinated interventions generate economic, social, and institutional synergy contributing to sustainable post-war recovery.

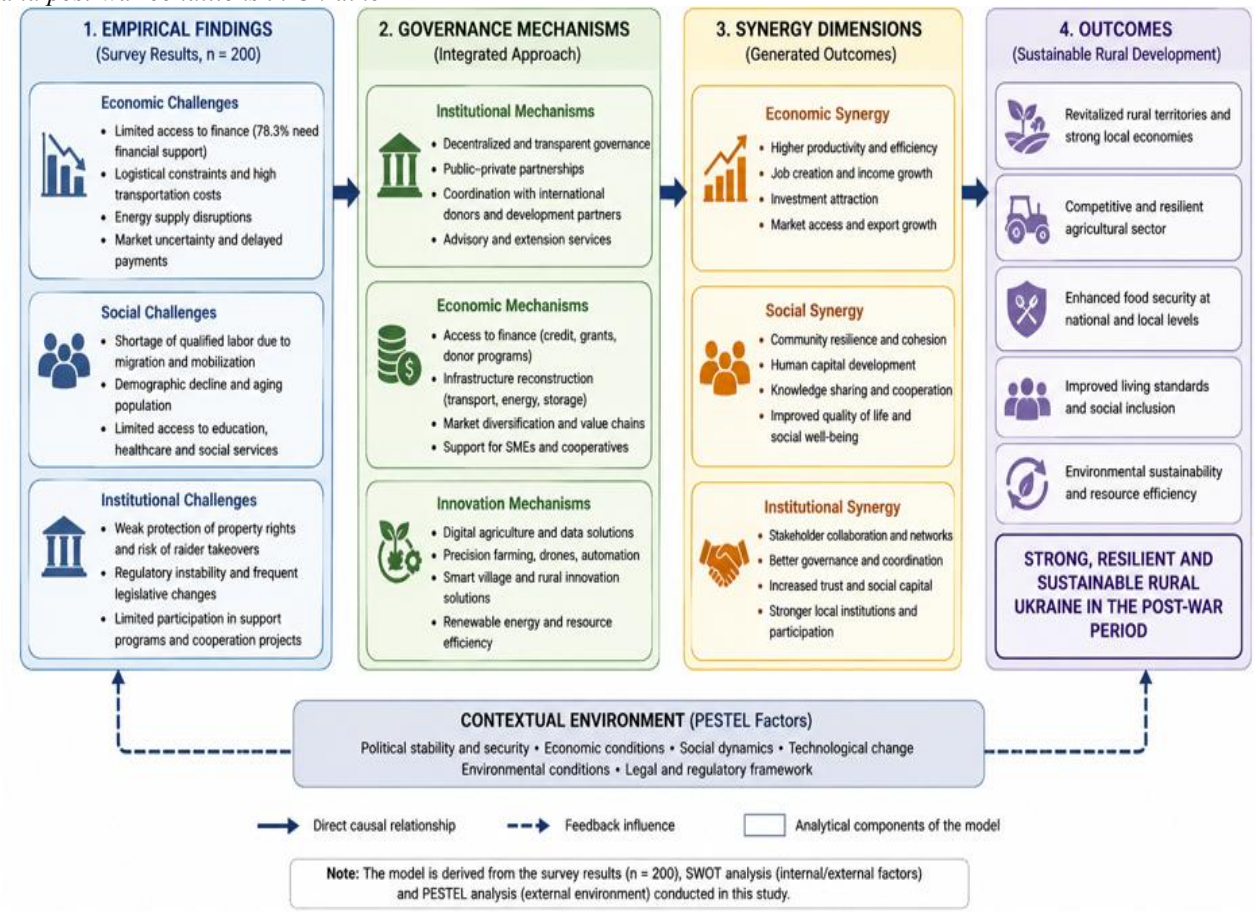
Conclusions

Based on the survey of farming enterprises and the results of SWOT and PESTEL analyses, the research provides empirical evidence that agricultural development and rural revitalization represent mutually reinforcing processes rather than independent development trajectories. The sustainable development of rural territories under wartime and post-war conditions depends on the interaction between agricultural production, local socio-economic systems, and governance institutions.

1. A key contribution of the study is the operationalization of the concept of synergy through three interconnected dimensions: economic synergy, reflected in production stability, employment generation, investment attraction, and market diversification; social synergy, reflected in community cohesion, knowledge exchange, local entrepreneurship, and human capital development and institutional synergy, reflected in stakeholder cooperation, governance effectiveness, public-private partnerships, and access to financial and advisory support.

Figure 4

Evidence-based governance synergy model for rural revitalization and agricultural development under wartime and post-war conditions in Ukraine



Source: compiled by the authors.

2. The SWOT and PESTEL analyses reveal that the future development of rural territories will largely depend on the ability of governance institutions to transform existing strengths and external opportunities into sustainable development outcomes while mitigating wartime threats and structural weaknesses. In particular, labor shortages, infrastructure destruction, limited access to finance, and institutional instability remain the most significant barriers to the formation of synergistic effects.

3. Based on the research findings, several policy priorities can be identified: strengthening targeted financial support programs for small and medium-sized farms; accelerating the reconstruction of transport, energy, and digital infrastructure in rural territories; improving legal protection of property rights; expanding advisory services and managerial training programs for farmers; increasing the involvement of international donors and development agencies in community-based recovery projects; promoting digital transformation and innovation adoption within the agricultural sector.

4. The scientific contribution of this study lies in the conceptualization and empirical interpretation of synergy between rural revitalization and agricultural development as a multidimensional governance phenomenon. Unlike previous studies that examined these processes separately, this research provides an integrated analytical framework linking agricultural production, rural development, and governance mechanisms.

5. Future research should focus on the development of quantitative synergy indicators, comparative analysis of regional recovery trajectories, and assessment of the role of digital and green transformations in strengthening the long-term resilience of rural territories.

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CONVERGING TRENDS IN AGRICULTURAL PERFORMANCE BETWEEN WESTERN AND EASTERN EUROPE

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Abstract
Agriculture is an important industry in the EU, yet there is still some agricultural development gap in Eastern European Member States compared with Western ones. The research aimed to identify trends in the performance of the agricultural industry across Western and Eastern Europe in the period 2005-2023. The research analysed employment and labour productivity in the agricultural industry and identified a correlation between the two variables. The research results revealed that Eastern European Member States tended to converge with Western European ones in terms of agricultural employment and labour productivity, with Latvia progressing the least among the Eastern European Member States. A positive change, i.e., a decrease in agricultural employment as a share of total employment, occurred in all EU Member States due to technological progress. The number of agricultural employees increased in two Member States, potentially due to changes in the structure of agricultural output (shift to labour intensity) and the availability of cheaper labour after many Eastern European countries joined the EU after 2004. There was still more than a 10-fold disparity in agricultural labour productivity across the EU, with the fastest increases in productivity being characteristic of Eastern European Member States, which nevertheless requires targeted government policies. The research found a strong correlation (-0.63) between changes in agricultural labour productivity and agricultural employment measured in annual work units, thereby indicating progress in the agricultural industry.
Keywords: agricultural employment, labour productivity, EU Member States.

Introduction

The economic, incl. agricultural, backwardness of Eastern Europe compared with Western Europe has been a well-known problem since the second half of the 20th century, due to communism and a mobilized command economy imposed after WW2, which prevented Eastern Europe from developing economically on a par with Western Europe. Even 35 years after the transition to a market economy, Eastern Europe lags behind Western Europe economically. Nonetheless, there has been significant progress in Eastern European countries after joining the EU due to unrestricted access to the markets of other EU Member States, funding from the EU Funds, free labour movement within the EU, etc.

Structurally, agricultural employment tended to decrease globally, especially in advanced economies. A decrease in agricultural employment, at least in the long term, is viewed as a positive trend because the current technological progress replaces labour, and agriculture is no exception. New industries emerge, which require labour, and the labour needs to move from the "old" industries, including agriculture, to the new ones. The more technologically advanced a country is, the smaller the share of agricultural employment, thus indicating better agricultural performance in terms of labour productivity, which is key to farm incomes.

Nowadays, agriculture is still an important industry because of its specificities and other reasons, including the fact that agriculture produces low-value-added goods. Therefore, the agricultural industry is supported in many countries, thus contributing to farmer incomes, and agricultural policies are persistently on the agenda. Due to economic disparities between Western and Eastern Europe, Eastern European states require broad-based economic growth - particularly within their agricultural sectors - especially given their financial resources to support farming. Accordingly, the present research aims to focus on trends in the performance of the agricultural industry between Western and Eastern Europe.

Based on the research aim, the following specific research tasks were set: 1) to identify long-term trends in agricultural employment in EU Member States; 2) to determine a correlation between changes in agricultural employment and changes in agricultural real factor income in EU Member States.

Materials and Methods

The present research used the following sources of information: Eurostat databases, research papers, and the European Commission. The research employed analysis and synthesis, document analysis, logical construction, and correlation analysis. The research aimed to identify a correlation between changes in agricultural employment, measured in both persons and annual work units (AWU), and labour productivity.

The present research is limited to two major indicators of agricultural performance: agricultural employment and agricultural real factor income per AWU. The latter is defined as the income generated by farming, which is used to remunerate borrowed or rented factors of production (capital, wages, and land rents) as well as own production factors (own labour, capital, and land). Ultimately, this metric can be interpreted as a measure of labour productivity in agriculture (Eurostat).

Results and Discussion

In the EU, agriculture is an important but insignificant industry, as it contributed 1.2% to the EU's GDP in 2024, about the same share as fifteen years earlier (Eurostat, 2026, February 6). Agriculture is still significantly supported in the EU. The expenditure of

the Common Agricultural Policy (CAP) as a share of the EU budget has decreased over the past 40 years, from 73.2% in 1980 to about 24.6% in 2023 (European Commission, 2024). Nevertheless, financial support for agriculture indicates low labour productivity in this industry, which is a global problem. Economists refer to the agricultural productivity gap (APG), meaning that value added per worker is significantly lower in agriculture than in the non-agricultural industries of an economy. The APG implies the misallocation of labour, and even after considering differences in hours worked and human capital per worker, as well as alternative measures of agricultural output, a puzzlingly large gap remains (Gollin et al., 2013). In addition, Gollin et al. (2025) have established that relatively faster physical productivity growth in the non-agricultural sector has, in many countries, offset the movement of labour out of agriculture, leading to persistently lower value added per worker in agriculture.

In relative terms, financial support for agriculture varies across EU Member States, with advanced economies providing more domestic support to their agricultural industries. Nevertheless, the less-developed Eastern European Member States are progressing economically, including in agriculture, thereby contributing to agricultural efficiency and productivity. This enables farms to earn more revenue, and the farmers can earn higher incomes, while Eastern European governments can provide more financial support to the farms. For example, Baer-Nawrocka et al. (2026) show that agricultural labour productivity is converging across the EU, with the economically largest farms exhibiting the fastest rate of convergence.

However, according to Zalo (2024), the agricultural productivity and efficiency of Central and Eastern European countries, including Hungary, are relatively low compared to those of Western Europe. Agricultural productivity and efficiency involve employment, i.e., labour input, and farmer income. Less labour input leads to higher labour income for the same output.

According to Garrone (2019), CAP subsidies reduce the outflow of labour from agriculture. This is, in the opinion of the author, a negative trend leading to agricultural stagnation or even a potential decrease in agricultural productivity and efficiency.

Besides, Nordin (2014) has found that a permanent increase in agricultural employment could be attributed to the Decoupling Reform, thus negatively contributing to agricultural productivity and efficiency.

González-Moralejo (2016) found a negative relationship between agricultural employment and productivity, and wages. An increase in labour productivity leads to higher wages, while at the same time decreases labour input, which is a global trend.

Cuerva (2012) found that there is a very slow process of absolute convergence in productivity among EU agricultural industries, where productivity growth is driven by agricultural out-migration and higher levels of physical capital. CAP support to the agricultural sector did not seem to have contributed to the productivity growth.

Jurkenaite et al. (2022) have found that in many EU countries, the remarkable increase in average farm size enabled the attraction of capital and the replacement of the labour force with technology, thus contributing to a decrease in agricultural employment.

According to Smedescu et al. (2024), while some nations exhibit high levels of productivity, reflecting advanced agricultural practices and efficient use of resources, others, though improving, still lag, with productivity varying almost tenfold.

Herman (2025) has found a structural shift in EU agriculture between 2010 and 2020 toward larger, more productive, and capital-intensive farms, alongside a decline in small-scale and subsistence farming and increased agricultural incomes, with persistent challenges such as rural depopulation, declining employment, and ongoing poverty.

The above-mentioned authors emphasize low agricultural productivity in Eastern Europe, the negative impact of agricultural subsidies on the outflow of labour from agriculture and agricultural productivity growth, a slow process of agricultural productivity convergence within the EU, and some other associated problems such as rural depopulation because of fewer employment opportunities there.

The above allows for a conclusion that countries lagging behind in terms of agricultural performance should focus on increasing agricultural productivity through decreasing agricultural employment.

In the present research, an analysis of agricultural employment is based on data from Eurostat (2026, January 30), category ‘Crop and animal production, hunting and related service activities’.

Next, the research analyses agricultural employment - expressed as a percentage of total employment - in 2005, immediately following the EU’s largest enlargement wave, and 2023, the most recent year with complete data available for all Member States. As shown in Figure 1, the EU Member States with the highest agricultural employment as a percentage of total employment in 2023 (above 5%) represented mostly Eastern Europe, except Greece and Portugal. In Romania and Bulgaria, it was the highest, indicating some economic backwardness in the agricultural industry; however, both Member States have made significant progress since 2005. Poland has also made significant progress, as has Slovenia. Among the seven Member States with the highest agricultural employment (above 5%), Latvia made the least significant progress during this period. Croatia and Lithuania also made significant progress, with their agricultural employment comprising less than 5%.

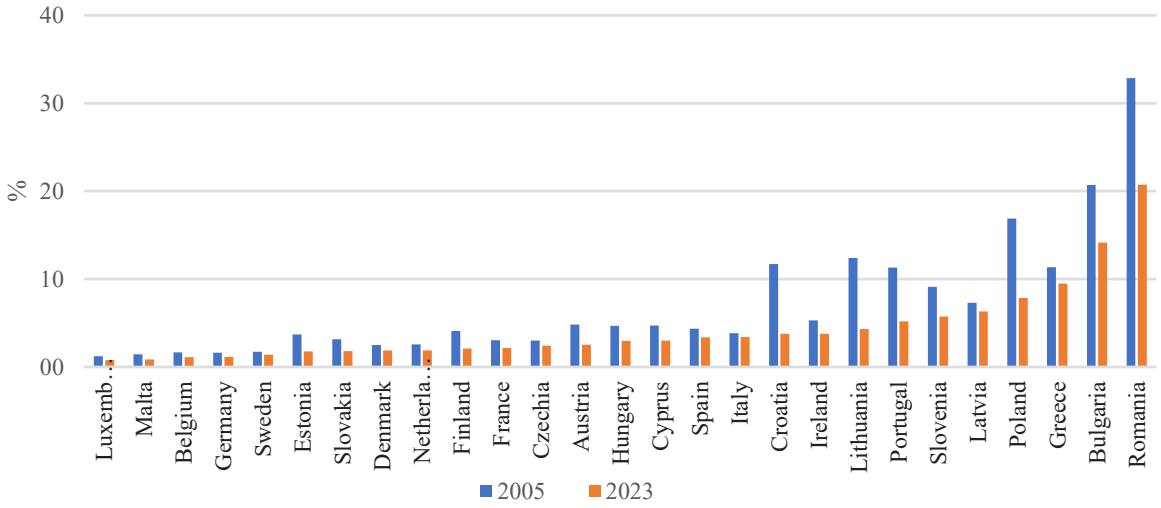
Farming can be specific; for example, in mountainous areas, fields are small, thereby requiring more agricultural employment. Some segments of the

agricultural industry are labour-intensive, whereas others are capital-intensive. Nevertheless, a positive change, i.e., a decrease in agricultural employment as a share of total employment, was observed in all EU Member States in the period 2005-2023 due to technological progress and the expansion of other industries needing labour.

Among Eastern European Member States, Estonia and Slovakia have achieved the most progress, now ranking among Western European Member States in terms of agricultural employment as a share of total employment. Czechia and Hungary also belong to this group.

Figure 1

Agricultural employment as a % of total employment in EU Member States in 2005 and 2023



However, the positive change in agricultural employment as a share of total employment does not fully reflect the actual situation, as total employment in the economy tends to fluctuate over the long term. There are Member States with a growing population and labour force, whereas other Member States experience an opposite trend. Therefore, an analysis of agricultural employment as a share of total employment needs to consider changes in total employment in the economy, as well as changes in the utilised agricultural area, because the utilised agricultural area can also change over a long period.

Next, the research performs a more detailed analysis of agricultural employment, particularly changes in agricultural employment (measured in persons and as a share of total employment in the economy), which is adjusted for changes in the utilised agricultural area (UAA) in 2023 compared with 2005.

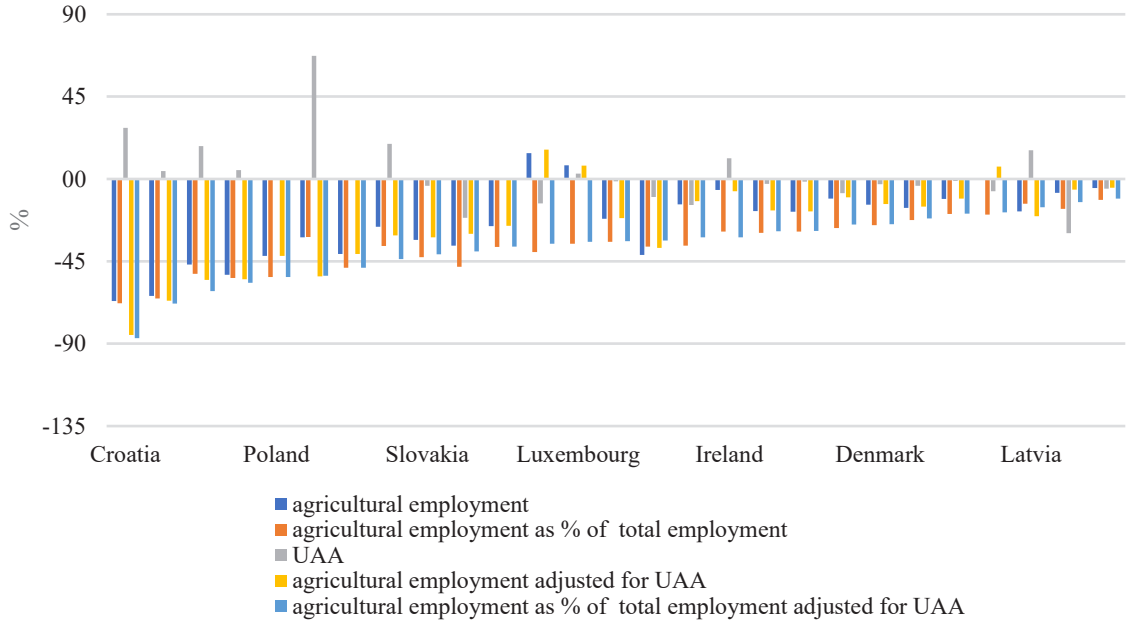
As shown in Figure 2, in 2023 compared with 2005, the largest increases in the UAA were reported in Bulgaria at 67%, followed by Croatia (28%), Hungary (19%), Estonia (18%) and Latvia (16%), which could be explained by increased economic activity in agriculture after joining the EU, which provided unlimited access to the EU single market. In contrast, the UAA decreased the most in Greece (30%) and Austria (21%).

In 2005 compared with 2023, changes in the number of agricultural employees were negative, i.e., agricultural employment decreased, which was a positive trend, almost in the entire EU, except in Malta and Luxembourg. In Malta, agricultural employment increased from 2.33 thou. in 2005 to 2.66 thou. or by 14.2% in 2023, while in Luxembourg it increased from 2.73 thou. to 4.01 thou. or by 7.5% (Table 1). The increases in agricultural employment in the economies of both Member States could be explained by changes in the structure of agricultural output (shift to labour intensity) and the availability of cheaper labour after many Eastern European countries joined the EU after 2004. In contrast, the most significant decrease occurred in mostly Eastern European Member States (Croatia, Lithuania, Estonia, Poland, and Romania), as well as in Finland, Austria, and Portugal. Latvia performed quite poorly with a decrease of only 18%; for comparison, in the neighbouring Member States – Estonia and Lithuania – the decreases were 47% and 64%, respectively.

Changes in agricultural employment expressed as a share of total employment were negative, i.e., the indicator decreased in the entire EU, including Malta and Luxembourg, where significant increases in total employment at 90% and 66%, respectively, occurred, which were the highest among all the Member States. In Malta and Luxembourg, the increases in total employment exceeded the increases in agricultural employment, with the resulting decreases in agricultural employment as a share of total employment at 40% and 35%, respectively. The most significant decreases (positive trend), however, were found for mostly Eastern European Member States (Croatia, Lithuania, Poland, Estonia), as well as Portugal, Finland, and Austria. The performance of Latvia was quite poor.

Figure 2

Percentage changes in the UAA and unadjusted and UAA-adjusted agricultural employment, persons, and agricultural employment as a share of total employment in EU Member States in 2023 compared with 2005



An analysis of agricultural employment should consider changes in the utilised agricultural area. The trend was positive in most of the Member States, except in Luxembourg, Malta, and Sweden. In Luxembourg, the UAA increased by 3%, while agricultural employment increased by 7.5%, thereby exceeding the increase in the UAA; therefore, the trend was negative, indicating an increase in labour input per ha of agricultural land. In Malta, the UAA decreased 13.4%, whereas agricultural employment increased by 14.2%, while in Sweden, the UAA decreased by 6.7%, with agricultural employment remaining unchanged, thereby also indicating a negative trend – an increase in labour input per ha of agricultural land in the analysis period. The best performers were mostly Eastern European Member States (Croatia, Lithuania, Estonia, Bulgaria, Poland, Romania), as well as Portugal and Finland.

An analysis of agricultural employment as a share of total employment adjusted for the UAA revealed a positive trend in all Member States. The best performers were mostly Eastern European Member States (Croatia, Lithuania, Estonia, Poland, Bulgaria), as well as some Western European Member States (Portugal, Finland, Austria). Latvia lagged behind the most among Eastern European Member States.

Overall, one can conclude that there was a trend towards convergence in agricultural employment between Eastern and Western European Member States, yet the disparity was still significant for some Eastern European Member States, including Latvia.

Next, the research examined changes in agricultural labour productivity, measured as agricultural real factor income per annual work unit, and performed a correlation analysis to identify a correlation between changes in agricultural labour productivity and changes in agricultural employment, measured both in persons and AWU. The results are presented in Table 1.

As shown in Table 1, a disparity in agricultural labour productivity between Member States was more than 10-fold, with Belgium being the best performer and Romania being the poorest performer. Lower agricultural labour productivity was characteristic of Eastern European Member States. However, the fastest increase in productivity was also characteristic of Eastern European Member States, especially Slovakia, Poland, Bulgaria, and Hungary. Latvia demonstrated moderately fast progress with a 75% increase, being far behind the leader, Slovakia, with a 257% increase.

The research established that there was a weak negative correlation (correlation coefficient of -0.31) between changes in agricultural labour productivity and changes in agricultural employment measured in persons. In contrast, a strong negative correlation (correlation coefficient of -0.63) was found between changes in agricultural labour productivity and agricultural employment measured in AWU.

The significant difference in the correlation coefficients could mean that AWU is a more accurate measure of labour input than the number of persons employed in the agricultural industry, many of whom are seasonal and part-time employees, thereby making it more difficult to account for. This conclusion is indirectly supported by the finding made by Gollin et al. (2013) that even if considering differences in hours worked and human capital per worker, there is still a puzzlingly large gap in labour productivity between agriculture and the non-agricultural industries.

Table 1

Agricultural real factor income per annual work unit (AWU), EUR, and agricultural employment, persons, and total AWU, and correlations between them in EU Member States in 2005 and 2023

Member State	Agricultural real factor income per AWU			Agricultural employment, thou. persons			Agricultural employment, thou. AWU		
	2005	2023	2023/ 2025, %	2005	2023	2023/ 2025, %	2005	2023	2023/ 2025, %
Romania	2,937.95	4,252.89	44.8	3,010.80	1,760.20	-41.5	2,596.00	1,111.00	-57.2
Slovenia	5,010.73	5,509.15	9.9	84.97	63.16	-25.7	90.04	71.21	-20.9
Lithuania	3,923.86	5,558.95	41.7	176.48	63.64	-63.9	173.60	115.60	-33.4
Latvia	3,664.30	6,425.56	75.4	70.80	58.29	-17.7	138.20	55.80	-59.6
Croatia	4,161.90	7,525.20	80.8	188.79	62.84	-66.7	228.00	172.29	-24.4
Estonia	9,887.61	8,464.53	-14.4	22.71	12.08	-46.8	37.82	16.55	-56.2
Malta	19,082.64	8,587.74	-55.0	2.33	2.66	14.2	4.06	6.34	56.2
Poland	2,922.11	8,647.22	195.9	2,371.20	1,373.10	-42.1	2,283.60	1,366.60	-40.2
Bulgaria	3,594.54	10,008.13	178.4	723.30	492.46	-31.9	626.40	161.40	-74.2
Hungary	4,477.75	10,934.50	144.2	191.74	141.81	-26.0	522.25	274.16	-47.5
Portugal	9,068.20	15,581.92	71.8	569.82	272.03	-52.3	370.76	220.61	-40.5
Czechia	10,435.65	16,072.70	54.0	147.05	130.98	-10.9	139.24	95.18	-31.6
Ireland	21,433.63	19,474.09	-9.1	107.95	101.49	-6.0	155.70	167.25	7.4
Cyprus	13,992.94	19,743.23	41.1	17.26	14.87	-13.8	28.70	18.73	-34.7
Austria	18,622.32	20,171.52	8.3	187.23	119.00	-36.4	146.56	118.62	-19.1
Slovakia	5,737.65	20,487.55	257.1	65.78	43.91	-33.2	98.80	35.50	-64.1
Greece	13,023.18	22,367.80	71.8	528.00	487.80	-7.6	606.60	321.36	-47.0
Finland	23,884.83	25,934.72	8.6	98.80	58.30	-41.0	96.20	58.08	-39.6
Luxembourg	32,887.32	27,438.98	-16.6	3.73	4.01	7.5	3.99	3.49	-12.5
Italy	18,031.60	28,937.13	60.5	931.40	885.20	-5.0	1,240.30	912.10	-26.5
Sweden	21,765.70	30,866.73	41.8	76.00	76.00	0.0	75.55	55.58	-26.4
Spain	25,284.04	34,532.75	36.6	858.90	723.70	-15.7	1,017.23	817.24	-19.7
France	25,266.24	37,521.95	48.5	803.50	659.60	-17.9	907.80	703.85	-22.5
Germany	21,791.24	41,896.79	92.3	632.00	521.00	-17.6	582.60	463.74	-20.4
Denmark	35,482.77	53,202.08	49.9	69.54	59.73	-14.1	62.90	42.48	-32.5
Netherlands	40,034.27	53,691.61	34.1	213.00	190.00	-10.8	165.79	157.41	-5.1
Belgium	32,491.98	56,049.90	72.5	71.50	56.00	-21.7	70.02	49.80	-28.9
Correlation coefficient						-0.31			-0.63

Conclusions

1. A positive change, i.e., a decrease in agricultural employment as a share of total employment, occurred in all EU Member States in the period 2005-2023 due to technological progress (shift from labour- to capital-intensive farming) and the expansion of other industries needing labour, with the best performers being those from Eastern Europe.

2. In absolute terms, agricultural employment increased only in Malta and Luxembourg, 14.2% and 7.5%, respectively, possibly due to changes in the structure of agricultural output (shift to labour intensity) and the availability of cheaper labour from Eastern Europe.

3. There was a converging trend in agricultural employment between Eastern and Western European Member States, yet the gap was still significant for some Eastern European Member States, including Latvia. There was still more than a 10-fold disparity in agricultural labour productivity across the EU; however, the fastest increase in productivity was characteristic of Eastern European Member States.

4. The research found a weak negative correlation with the correlation coefficient of -0.31 between changes in agricultural labour productivity and changes in agricultural employment measured in persons, whereas there was a strong negative correlation (-0.63) between changes in agricultural labour productivity and agricultural employment measured in AWU, which is a more accurate indicator thereof.

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LEGAL FRAMEWORK FOR REGULATING FAIR AND RESPONSIBLE MARKETING COMMUNICATION IN LATVIA'S AGRICULTURAL PRODUCT MARKET

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Abstract
With increasing sustainability requirements, digitalization, and intensifying competition in agricultural markets, marketing communication plays an important role in shaping consumer perceptions and competitive positioning. Despite this, misleading, exaggerated, or non-transparent marketing communication practices, especially ones involving sustainability and environmentally friendly claims, can distort fair competitiveness and undermine consumer trust. For this reason, the legal regulation of marketing communication becomes an important instrument for ensuring fair competition on the agricultural product sector. The current study examines the role of the legal framework in regulating marketing communication to ensure fair competitiveness of agricultural products. This study examines key legal principles and regulatory tools governing marketing communication, with particular focus on the truthfulness, transparency, and consumer protection. By using a comprehensive legal analysis of legal documents, policy framework, and academic literature sources, the research explores how legal regulation affects marketing communication practices and competitiveness on the agricultural product sector. The research findings indicate that although the existing legal framework protects consumers against misleading claims, reduces the risk of greenwashing, promotes responsible and fair marketing communication practices, there are several challenges related to complexity of regulation, enforcement gaps, and the need to harmonize with sustainability and digitalization goals. This study contributes to the discussion on smart and responsible marketing communication by emphasizing the role and current deficiencies of legal regulation in fostering sustainable and fair competitiveness of agricultural products.
Keywords: marketing communication, agricultural products, fair competition, consumer protection, greenwashing.

Introduction

In recent years, the role of marketing communication has become increasingly important in agricultural products market, where producers compete not only on price and quality, but also on brand image, sustainability narratives, and digital visibility. Consumer decisions are influenced by sustainability narratives that emphasize the ethical and environmental practices of producers (Correia et at., 2023).

By focusing on sustainable practices, enterprises can make themselves visible and promote brand loyalty among eco-conscious consumers. It shapes consumers' perceptions of product quality, safety, and environmental impact, and affects how effectively various companies can position themselves in increasingly competitive regional and international markets (Kothari et at., 2025; Daou et al., 2025). At the same time, the European Union's 'Green Deal' initiative, increasing sustainability requirements and the rapid digitalization of marketing channels are adding pressure on agricultural producers (Grinberga-Zalite et al., 2025) to communicate their 'green' and 'responsible' practices in a confident and convincing manner (Khan et al., 2026).

Nevertheless, the increasing use of sustainability, ethics, and other value-based claims in the marketing communication of agricultural products has led to a growing risk of misleading, exaggerated, or unclear communication practices – often known as 'greenwashing' (Arayess & de Boer, 2022). The use of such methods can lead to unfair competition by giving an unlawful advantage to market participants who base their claims on unclear or unverifiable environmental claims, while destroying consumer trust in truly sustainable producers and the agricultural sector as a whole.

This contradiction is particularly topical in the Latvian agricultural products market, where small and medium-sized producers have to comply with both EU-level and national regulations while competing with larger, better-resourced market participants (Grinberga-Zalite et al., 2025).

In this context, the legal framework governing marketing communications plays a key role in balancing the freedom of enterprise, consumer protection, and fair competition. EU legislation, as well as national laws, include a set of principles and instruments related to the truthfulness, clarity, and reliability of commercial claims, including information on environmental issues and sustainability (Micklitz, 2018; Howells et al., 2018).

However, in reality, this legal framework is often complicated and fragmented, resources for enforcement remain limited, and the integration of new sustainability and digitalization goals into existing marketing and consumer protection rules is still in progress. A question that arises for Latvia is how effectively the current legal framework supports smart, fair, and responsible marketing communication in the agricultural sector, and where gaps or inconsistencies are most evident (Furmanova & Grīnberga-Zālīte, 2025). This study explores the role of legal framework in regulating fair and responsible marketing communication to ensure fair competitiveness of agricultural products.

Materials and Methods

The aim of this study is to analyze the legal framework governing fair and responsible marketing

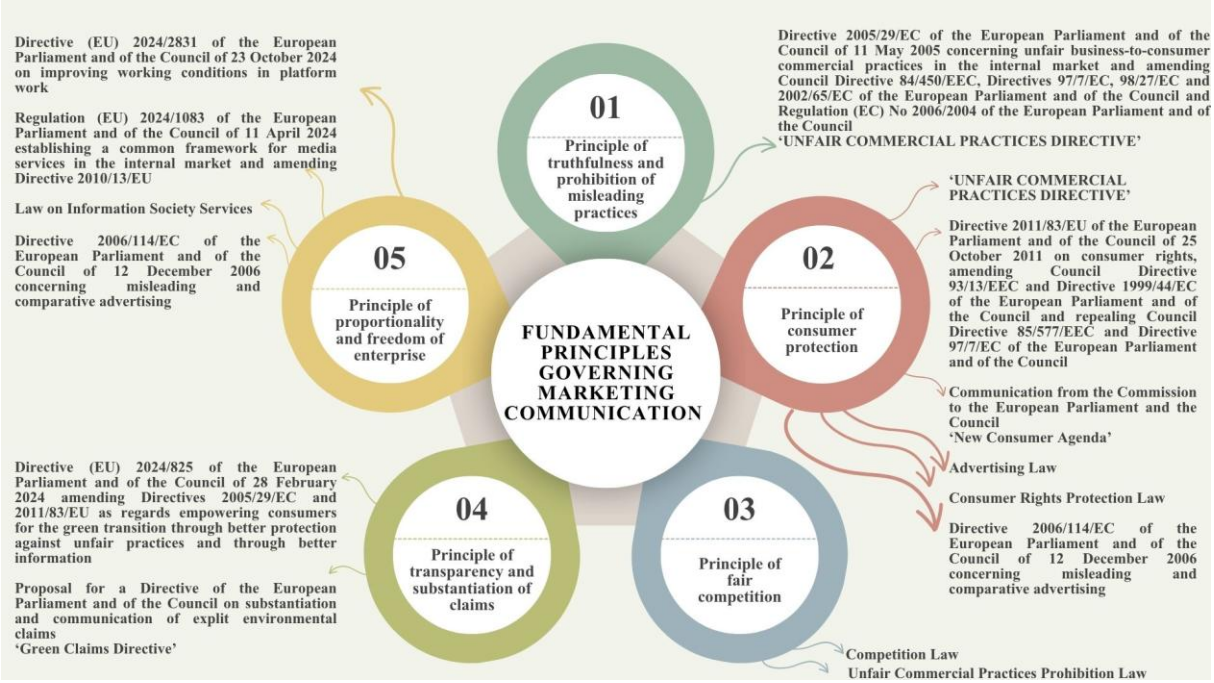
communication in the Latvian agricultural products market, with a focus on sustainability-related and eco-friendly claims. The article first explains the general legal principles and key regulatory instruments governing marketing communications and consumer protection in the agricultural sector. A discussion of the EU-level framework relevant for green claims and fair competition follows, followed by an analysis of Latvia's national regulation and its implementation. Through a comprehensive legal analysis that includes legal documents, policy guidelines, and academic literature, this study examines how legal framework influences marketing communication practices and competitiveness in the agricultural products sector. Finally, the study identifies the main challenges and gaps – such as the complexity of the regulations, enforcement gaps, and the need to better align legal norms with sustainability and digitalization goals – and develops proposals to improve the coherence and effectiveness of the legal framework.

Results and Discussion

Generally legal framework and regulations are based on several fundamental principles deriving from consumer protection law, competition law, and commercial law (OpenAI, 2026).

Figure 1

Fundamental principles governing marketing communication



As shown in Figure 1 created by the authors, fundamental principles that govern marketing communication are based on a certain set of legal framework. In the EU, including Latvia, the legal regulation of marketing communication is based on these principles: derived competition law, commercial law, consumer rights protection law. Directive 2005/29/EC which is called Unfair Commercial Practices Directive determines that commercial practices are unfair if they are against professional diligence and distort consumer behavior (European Parliament and…, 2005; European Commission, 2020). The Directive forbids misleading actions, misleading omissions and aggressive marketing that may deceive an average consumer who is reasonably well-educated and reasonably aware. These regulations apply to advertising, product labeling, environmental claims, and digital marketing. The purpose of consumer protection law is to protect consumers from unfair trade practices and deception (Dickinson, 2026). There is a high level of protection for consumers in commercial communications under EU legislation. In recent years, consumer law has evolved from being a primarily local, vulnerable buyer-focused discipline to one that is shaped by global markets, e-commerce, and international standards. In spite of the fact that consumers' problems are broadly similar around the world, national regulations still need to adhere to local legal, social and cultural traditions, resulting in a mix of globalism and localism (Howells et al., 2018). Directive 2011/83/EU which is called Consumer Rights Directive and Consumer Rights Protection Law provide protection of consumer rights to clear information, protection against misleading advertising and communication, protection of consumer rights to fair comparisons as well as protection of vulnerable consumers (European Parliament and…, 2011; Consumer Rights Protection…, 1999). In turn, Advertising law as well as Directive 2006/114/EC determine that advertising must be lawful, truthful, and objective, and must be created in accordance with fair advertising and

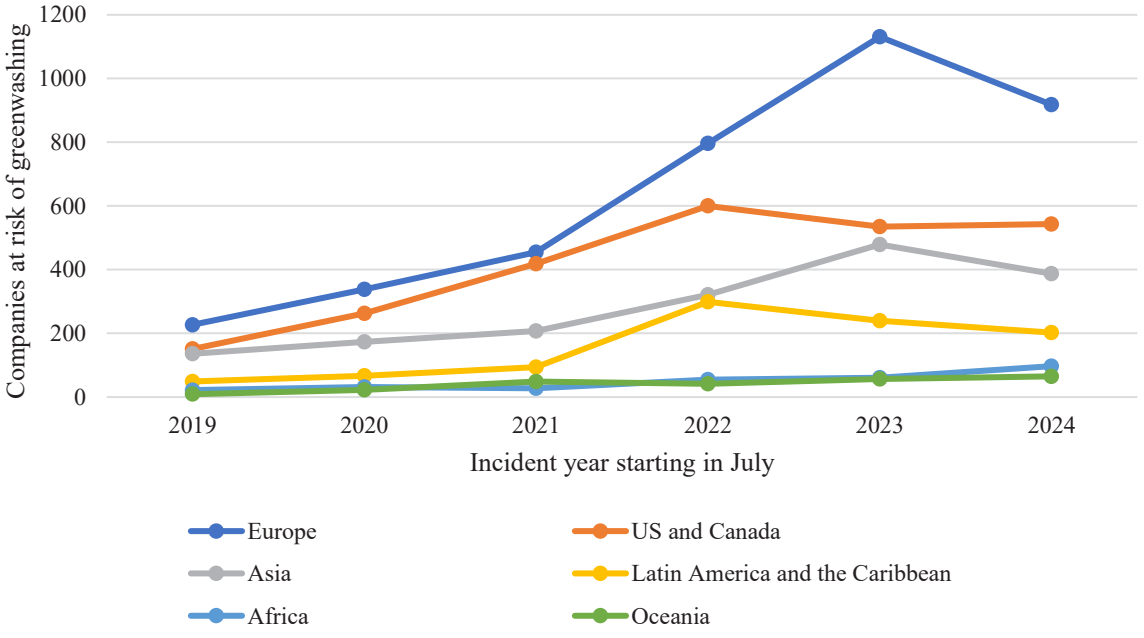
marketing communication practices. Advertising must not reduce consumer trust in advertisements and must meet the principles of fair competition. Comparative advertisements are permitted, but only if they are objective, truthful and are not misleading (Advertising Law, 1999). Based on Competition Law, Unfair Commercial Practices Prohibition Law, and EU regulations shown in Figure 1, it is clear that unfair competition is likely to arise if false claims about environmental impact are made, claims about the origin of the product are misleading, quality labels are unfairly used, and advertising that makes comparisons is misleading (Competition Law, 2001; Unfair Commercial Practices…, 2007). As a result of unfair marketing communication, it affects not only B2C (business to customers) but also B2B (business to business) relations (Rudohradská, 2025). In the agricultural sector, the Directive 2006/114/EC protects consumers and enterprises against misleading advertisements in B2B relations, while defining the conditions for lawful comparative advertising across all EU Member States (European Parliament and…, 2006). Also, Regulation (EU) 2018/848 provides EU rules on organic production, certification, labeling, and import controls, setting high standards for environmental protection, livestock welfare, and consumer trust (European Parliament and…, 2018).

The principle of transparency and substantiation of claims stands for marketing communication that is based on evidence, is verifiable, scientifically substantiated, and clearly understandable (European Parliament and…, 2024a; European Commission, 2023). These regulations specify that environmental claims must be proven by scientific evidence. Previously discussed authors ideas and legislation indicate that the regulation of 'green' and environmental claims is necessary to avoid 'greenwashing' and aggressive advertisements, and guarantee fair competition and marketing communication. Based on principle of proportionality and freedom of enterprise, it is clear that core legislation must balance between freedom of enterprise, protection of consumer rights, fair marketing communication and competition, and sustainability goals (European Parliament and…, 2024b; European Parliament and…, 2024c; Unfair Commercial Practices…, 2007). EU legislation acknowledges that commercial communications are part of economic freedom, but they may be regulated in order to protect consumer rights (European Commission, 2020).

Therefore, the authors reviewed the available data on recorded incidents of misleading communication and greenwashing (Figure 2).

Figure 2

Companies at risk of greenwashing



As shown in Figure 2, the graph reflects the count of companies with at least one ESG risk incident linked to both environmental footprint and misleading communication in a given year (A turning tide…, 2024). Compared to 2023, the number of serious cases related to greenwashing increased by 30% compared to the previous year. These data define serious cases by evaluating three aspects: the consequences of the risk incident, the scope of its impact, and the measure to which the incident was intentional and systematic. Greenwashing cases with a high impact rating are typically characterized by purposeful and systematic actions to hide ESG violations that result in significant consequences for the environment, such as major pollution, and/or for the company, such as financial penalties (A turning tide…, 2024).

Conclusions

1. This study examined the legal framework governing fair and responsible marketing communication in Latvian agricultural products, focusing in particular on claims regarding sustainability and environmental considerations. According to the results, existing legal framework at the European Union and Latvian national level outline a comprehensive system of principles for regulating marketing communication, including truthfulness, transparency, consumer rights protection, fair communication and competition, and proportionality.
2. Several legal instruments limit misleading advertising, unfair commercial practices, and unsubstantiated environmental claims under the current regulatory system, according to the analysis. In the agricultural products market, these regulations prevent greenwashing and support fair competition.
3. At the same time, the study indicates that the legal framework governing marketing communication in the agricultural product market is complex and fragmented, since it comprises multiple EU directives, regulations, and national laws that need to be applied simultaneously. Small and medium-sized agricultural producers, especially, face difficulties because they lack the necessary legal knowledge and resources to meet all legal framework requirements fully.
4. As sustainable, environmental, and ethical claims become increasingly common in marketing communication, they create additional risks of greenwashing, which can deform fair communication and competition and ruin consumer trust in agricultural products. As sustainability demands grow, marketing channels are digitalized, and brand image becomes increasingly important in agricultural product market, this problem becomes even more crucial.
5. This study shows that the current legal framework is still adapting to new challenges related to sustainability requirements, digital marketing, and the European Green Deal objectives. As a result, there are still some misalignments between existing consumer right protection regulation, competition law, and the new requirements related to the provisioning of information on environmental issues and sustainability.
6. In the Latvian agricultural products market, the need to comply with both EU-level and Latvian national- level regulations is creating an additional regulatory workload for producers, which may have a negative impact on the competitiveness of small and medium-sized enterprises compared to larger market participants with greater administrative and financial resources.
7. To enhance the effectiveness of the regulatory framework, it is recommendable that legislators continue to bring national and EU legislation into alignment, simplify the application of rules regarding sustainability claims, and strengthen supervision mechanisms to ensure more effective fulfilment of the requirements for fair marketing communication.
8. Further research is needed to examine how the legal framework is being applied in practice, identify specific cases of misleading marketing communication in the agricultural product sector, and consider how legal framework can better support smart, responsible, and fair marketing communication without causing a disproportionate administrative workload for producers.

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THE THEORETICAL ASPECTS OF AGRICULTURAL LOGISTICS

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Abstract
Agricultural logistics plays an important role in providing the efficient movement, storage, and handling of agricultural products from production places to markets. Due to the specific characteristics of agricultural production – seasonality, perishability, spatial dispersion of production sites, and sensitivity and environmental conditions – logistics activities in agriculture differ substantially from those in other logistics sectors. Despite its practical importance, agricultural logistics remains conceptually fragmented in the academic literature and is frequently addressed only as a component of broader agricultural or agri-food supply chain networks, which limits theoretical clarity and knowledge development. The aim of this paper is the classification of key theoretical aspects and challenges of agricultural logistics in order to provide more structured understanding of this field. The study is based on a content analysis of academic literature, articles and studies in the fields of logistics, supply chain management, and agricultural and agri-food systems. The analysis focuses on finding and clarifying aspects and scope, positioning agricultural logistics within agricultural supply chains, and identifying characteristics and challenges discussed in existing studies. As a result, the paper classifies core theoretical aspects on agricultural logistics and proposes a typology of key challenges encompassing infrastructure – related, operational, coordination and organisational, market and structural, as well as external and environmental challenges. By structuring dispersed insights from literature, the studies contribute a clearer theoretical understanding of agricultural logistics and provides a conceptual foundation for future empirical research and more targeted analytical approaches in this field.
Keywords: agricultural logistics, theoretical aspects, logistics challenges, classification, agricultural systems.

Introduction

Agricultural logistics provides the optimized movement of agricultural products and goods from farms to final markets. Agricultural systems are integrated into world markets, consequently logistics performance increasingly determines cost efficiency, quality preservation, and competitiveness and market accessibility (Yadav et al., 2022). Even the small inefficiencies in the logistics systems can lead to significant losses across the agri-food supply chain. Based on the Food and Agriculture Organization, about one third of all food produced globally is lost or wasted in the supply chain, often due to inadequate storage, transportation, and distribution processes.

These losses are especially significant for perishable agricultural products, where time-sensitive logistics and cold chain infrastructure are important for preserving product quality. Perishability significantly influences network design and distribution strategies (Bolivar et al., 2025; Esteso et al., 2021).

In the context of sustainability policies such as the European Green Deal and the Farm to Fork strategy, the importance of improving agricultural logistics has increased, which promote more efficient and environmentally sustainable food systems. Optimization of the logistics operations can accelerate reduction of food losses, improving resource efficiency and lowering the environmental footprint of agri-food supply chains.

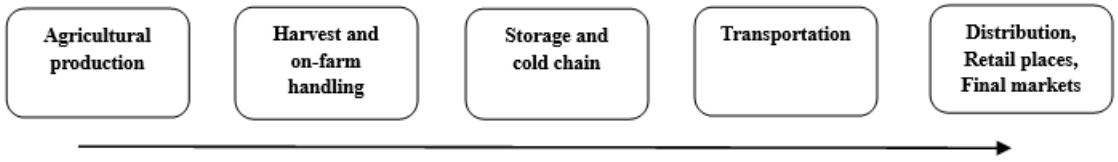
Cold chain performance and infrastructure quality further affect product losses and supply reliability (Han et al., 2025).

Despite growing attention, agricultural logistics is frequently subsumed under broader supply chain management discussions (Kumar & Agrawal, 2023). This integration is analytically useful but often obscures logistics-specific operational challenges such as transport optimization, storage capacity constraints, and first-mile inefficiencies (Gámez-Albán et al., 2024). The aim of this study is to identify the key logistics challenges affecting agricultural production and distribution systems based on recent literature.

Before analysing the main aspects of the agricultural logistics, it is important to understand the overall structure and flow direction of agricultural logistics system, which is illustrated in Figure 1.

The process mostly includes five sequential stages starting from producing the agricultural production and ending with distribution to retail places and final markets.

Figure 1
Structure of the agricultural logistics system



Source: created by the authors'.

Agricultural logistics includes several interconnected stages which ensure the efficient movement of products from farms to handling, manufacturing and finally to market. The logistics process begins with agricultural production and continues through harvesting, storage, transportation, and distribution. Each stage requires very specific coordination, conditions and logistics operations in order to preserve high product quality and minimize losses. Efficient integration of these stages is essential for improving the whole supply chain performance and ensuring the reliability of agri-food distribution systems.

Materials and Methods

In the authors' opinion, agricultural logistics should be analysed as a distinct research field not only as a part or component of agricultural supply chain management. For deeper analysis it is necessary to explore and analyse all possible aspects, which affect or can be affected to the agricultural logistics. The research object of this study is agricultural logistics, while the research subject is the theoretical aspects influencing agricultural logistics systems. The main aim of the article is to classify and analyse the key theoretical aspects and challenges of agricultural logistics. The research question guiding this study is - What are key aspects of agricultural logistics? To address this question, the authors' defined the following research tasks:

1.To conduct a theoretical literature review on agricultural logistics;

2.To identify and classify the main dimensions and characteristics of agricultural logistics

3.To summarize the major logistics challenges discussed in previous studies.

A summative content analysis was used to classify and define these aspects.

Content analysis is commonly applied as a qualitative research method. Instead of representing a single, uniform technique, it is typically used in three main forms – conventional, directed, and summative approaches. These approaches differ primarily in how codes are developed, where they originate from, and how research reliability is ensured. In particular, summative content analysis focuses on identifying and comparing specific words or content elements, which is then followed by an interpretation of their contextual meaning (Hsieh & Shannon, 2005).

The literature review was conducted using scientific databases Scopus, Web of Science, and ScienceDirect. The literature search was performed between January and March 2026. The following keywords and keyword combinations were used: 'agricultural logistics', 'agri-food logistics', 'perishable product logistics', 'agricultural product transportation', and 'logistics challenges in agriculture'.

The literature selection process was based on several criteria. Only peer-reviewed scientific journal articles published in English between 2020 and 2026 were included in the analysis. An initial search identified 34 scientific papers, but after screening, 16 studies were selected for detailed analysis. Priority was given to studies focusing on agricultural logistics systems, agri-food supply chains, logistics infrastructure and transportation, perishability and coordination. Publications unrelated to criteria or focused exclusively on industrial logistics were excluded.

After the initial database search, the identified studies were screened according to relevance, title, abstract, and thematic suitability. The selected studies were analysed and grouped into thematic categories. The analysis process included:

1.Identification of recurring logistics dimensions,

2.Comparison of agricultural and industrial logistics characteristics,

3.Classification of major logistics challenges,

4.Identification of research gaps in existing studies.

The collected literature was interpreted through comparative thematic analysis in order to identify the main theoretical approaches and recurring problem areas within agricultural logistics research.

Results and Discussion

Foundations of Agricultural Logistics

Logistics can be described as a set of coordinated activities that provide the planning, implementation, and controlling the efficient, cost-effective flow and storage of goods, services, and information from the place of origin to the final market. Logistics is a component of supply chain management (SCM) that specifically focuses on the movement and storage of goods. While SCM covers the entire network (including suppliers, manufacturing, and strategy), logistics zooms in on the efficient transportation and warehousing of those items or products. It is important to understand differences between agricultural and industrial logistics. The comparison of both types of logistics is shown in Table 1. The biological production cycles, seasonal variability, and the production perishability shape agricultural logistics, that also affect on high level uncertainty and time sensitivity.

Farms and producers often are located in rural or remote areas that increases transportation distances and have limited access to efficient transport infrastructure. This shows the contrast with the industrial logistics, where manufacturing and producing are more centralized and integrated into well-developed logistics networks. It should be mentioned that agricultural logistics systems face constraints related to coordination among multiple small-scale actors.

These aspects underline the importance of analysing agricultural logistics as a distinct field and explain why logistics models developed for industrial application may not be be fully applicable to agricultural systems.

Table 1
Comparison of agricultural and industrial logistics

Dimension	Agricultural logistics	Industrial logistics
Production process	Many biological processes dependent on natural conditions	Controlled manufacturing processes
Dimension	Agricultural logistics	Industrial logistics
Production cycle	Seasonal and irregular	Continuous or predictable
Product characteristics	Perishable, short shelf life	Durable products
Quality variability	High variability due to weather and biological factors	Standardized quality
Storage requirements	Often requires refrigeration and controlled environments	Standard warehouses sufficient
Transport urgency	Time-sensitive due to perishability	Less time-critical
Supply uncertainty	High (weather, pests, climate)	Relatively stable production
Price stability	High volatile	Generally stable
Logistics infrastructure	Often located in rural areas with weaker infrastructure	Lower product spoilage risk
Traceability requirements	Increasingly important for food safety	Important, but less critical

Source: created by the authors' – based on reviewed literature.

To analyse main specific aspects of the agricultural logistics, the key dimensions identified in the literature are shown in Table 2. Agricultural logistics refers to the planning and control of physical and informational flows within agricultural production and distribution systems. Network design literature highlights multi-objective optimization considering cost, sustainability, and responsiveness (Yadav et al., 2021). Recent reviews emphasize the strategic integration of logistics decisions within agri-food systems (Yadav et al., 2022).

Table 2
Key approaches to agricultural logistics

Key agricultural logistics dimension	Theoretical focus	Implication	Author (s)
Integration	Supply chain review	Need for coordination	Yadav et al. (2022)
Perishability	Network design modelling	Decentralized storage	Bolivar et al. (2025)
Local distribution	Short food chains	Coordination complexity	Paciarotti & Torregiani (2021)
Temperature control	Cold chain review	Infrastructure dependency	Mustafa et al. (2024)

Source: created by the authors'.

As shown in Table 2, previous studies highlight main dimensions of agricultural logistics, including integration in the supply chains, perishability management, local distribution structures, and temperature-controlled logistics. These dimensions emphasize the need for coordination across all activities within agri-food systems – production, storage, and distribution.

Perishability is a defining feature shaping logistics configuration. Modelling studies demonstrate that shorter shelf life necessitates decentralized storage and faster transport cycles (Esteso et al., 2021; Bolivar et al., 2025). Short food supply chains introduce additional logistical coordination challenges (Paciarotti & Torregiani, 2021).

Main Characteristics of Agriculture Logistics Systems

Agricultural logistics systems are characterized by several structural features that differentiate them from other logistics sectors. These characteristics and their implications are shown in Table 3.

Table 3
Structural characteristics of agriculture logistics systems

Characteristic	Description	Logistics impact	Author (s)
Seasonality	Concentrated harvest periods	Capacity imbalance	Garima et al. (2026)
Perishability	Limited shelf life	Fast transport required	Esteso et al. (2021)
Spatial dispersion	Rural production	High transport cost	Gámez-Albán et al. (2024); Nakoma-Ngoma et al. (2025)
Climate sensitivity	Weather variability	Risk exposure	Sahar et al. (2025)

Source: created by the authors'

The seasonality creates temporal concentration of logistics demand, leading to capacity imbalances. Farm-level harvest constraints and spatial dispersion further complicate coordination (Garima et al., 2026).
Table 3 demonstrate that agricultural logistics cannot be fully explained using usual logistics models and flow movements. These structural characteristics introduce persistent variability, uncertainty, and temporal concentration of agricultural product flows.
Table 3 illustrates how various characteristics of agricultural production directly influence logistics planning. Seasonality and perishability create strong time constraints, while spatial dispersion increases the transportation complexity, routes and costs. Agricultural logistics depends on the weather variability where the risk exposure has significant logistics impact. Due to wide spatial dispersion and many small-scale producers, rural production increases total transport costs.

Typology of the Key Challenges

The typology of the main agricultural logistics challenges was made based on the analysed research papers and is illustrated in Table 4. The literature explains seven major challenge categories: infrastructure-related, operational, coordination, market-structural, environmental, spatial dispersion and climate challenges. As shown in Table 4, these challenges highlight the multidimensional and complex nature of logistics constraints within agricultural systems.
Infrastructure-related challenges include insufficient cold chain facilities and weak rural transport networks (Han et al., 2025). Operational challenges stem from perishability and seasonal output variability (Esteso et al., 2021). Coordination challenges arise due to fragmented production structures and weak integration (Qiu et al., 2020).
Market and structural challenges relate to volatility and demand uncertainty (Garima et al., 2023). Environmental and risk-related challenges include climate variability and systemic disruptions (Sahar et al., 2025; Yongjie et al., 2025).

Table 4

Typology of agricultural logistics challenges

Category	Core issues	Mechanism	Author (s)
Infrastructure	Weak cold chain	Physical bottlenecks	Han et al. (2025); Shi et al. (2024)
Operational	Seasonality	Capacity mismatch	Esteso et al. (2021)
Coordination	Fragmented farms	Information asymmetry	Qiu et al. (2020); Yongjie et al. (2025)
Market	Demand volatility	Price risk	Garima et al. (2026)
Spatial dispersion	Rural production	High transport cost	Gámez-Albán et al. (2024)
Climate sensitivity	Weather variability	Risk exposure	Sahar et al. (2025)

Source: created by the authors'.

The analysis confirms that agricultural challenges are interconnected. The agricultural logistics challenges are multidimensional and come from natural characteristics of the agricultural production systems and external environmental conditions. Weak transport networks, storage capacity limitations, and the lack of cold chain facilities creates fundamental constraints for the effective movement and preservation of agriculture products. The typology enhances theoretical clarity by structuring fragmented insights.
Poor information exchange and insufficient decision - making can be caused by fragmented structure of coordination and organizational processes. The proposed typology indicates that challenges come not as isolated inefficiencies but as outcomes shaped by interactions among many conditions, mechanisms and external uncertainty. Further, there is a need for flexibility oriented models, resilience based planning approaches and adaptive coordination structures.
In addition, in identifying and analysing existing challenges, the literature also shows few research gaps in recent agricultural logistics studies. These gaps are shown in Table 5. The network design optimization must integrate perishability, risk, and sustainability criteria (Yadav et al., 2021). Digitalization offers performance improvements but introduces new organizational complexities (Kumar & Agrawal, 2023).

Table 5

Research gaps in agricultural logistics literature

Research area	Dominant focus	Research gap
Network design	Cost optimization	Limited resilience integration
Cold chain	Technology	Governance gaps
Risk management	Disruption modelling	Farm-level integration lacking
Digitalization	IoT tracking	Organizational readiness

Source: created by the authors'.

As shown in Table 5, although research in the agricultural logistics has expanded significantly in recent years, important gaps remain in areas such as resilience-oriented network design, governance of cold chain systems, and the organizational readiness for digital technologies.

The findings of this study highlight that agricultural logistics systems differ significantly from industrial logistics due to the specific characteristics of agricultural production processes and material flow. Factors such as biological production cycles, seasonal output fluctuations, spatial dispersion of farms, and high product perishability create structural complexities that influence logistics planning and management. These characteristics increase the importance of efficient transportation systems, appropriate storage infrastructure, and coordinated distribution mechanisms.

The typology of logistics challenges identified in this study – covering infrastructure, operational, market, and environmental factors – provides a view and perspective on the main barriers affecting agricultural logistics performance. This classification contributes to a clearer understanding of how different categories of challenges interact and influence fundamental supply chain outcomes. For example, infrastructure limitations may exacerbate operational inefficiencies, while market volatility can increase the complexity of logistics planning for perishable products.

From a practical perspective, the results suggest that improving agricultural logistics requires an integrated approach that combines infrastructure development, technological innovation, and improved coordination among supply chain actors. Investments in cold chain logistics, digital monitoring technologies, and optimized distribution networks can significantly reduce post-harvest losses and improve supply chain responsiveness. Additionally, stronger collaboration between farmers, logistics providers, and policy makers is necessary to address systemic inefficiencies agricultural logistics systems.

The findings also demonstrates that the effectiveness of agricultural logistics systems increasingly depends on the integration of digital technologies and coordinated decision-making mechanisms. Technologies such as IoT-based monitoring systems, GPS-supported transportation planning, and real-time cold chain tracking can improve logistics transparency and reduce operational inefficiencies. However, the implementation of such technologies remains uneven, particularly among small-scale producers operating in rural regions with limited financial and technological capacity. Therefore, future logistics development strategies should combine infrastructure investments with organisational support mechanisms, training, and policy-based coordination measures.

Conclusions

1.This study confirms that agricultural logistics differs substantially from industrial logistics due to the specific characteristics of agricultural production systems.

2. The analysis of scientific literature allowed the identification and classification of the main theoretical dimensions of agricultural logistics, including perishability management, local distribution, temperature – controlled logistics, and coordination.

3.The proposed typology of agricultural logistics challenges demonstrates that logistics constraints are multidimensional and interconnected. The main challenge categories include infrastructure limitations, operational inefficiencies, fragmented coordination, market volatility, spatial dispersion, and climate-related risks.

4.From a practical perspective, the study indicates that improving agricultural logistics requires integrated investments in transport infrastructure, cold chain systems, digital monitoring technologies, and coordinated distribution networks.

5.The study also highlights several important research gaps, particularly regarding resilience - oriented logistics planning, governance of cold chain systems, and organisational readiness for digitalisation in agricultural logistics systems.

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HIERARCHICAL STRUCTURING OF SUSTAINABILITY-ORIENTED ECONOMIC CONCEPTS

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Abstract
The rapid expansion of sustainability-oriented economic concepts has led to growing conceptual ambiguity regarding their scope, analytical level, and functional role. Terms such as the green, blue, circular, bio-, and social economy are often used interchangeably, while approaches like the human-centred, well-being, low-carbon, regenerative, and degrowth economy are frequently treated as equivalent models despite serving distinct purposes. This fragmentation complicates theory development, limits comparability across studies, and hinders the operationalisation of sustainability frameworks in research and policy. This study clarifies the hierarchical and functional relationships among these concepts through a PRISMA-based systematic literature review combined with qualitative conceptual content analysis. Peer-reviewed articles from Scopus and Web of Science were screened using PRISMA guidelines. The final sample was analysed using structured coding based on sustainability dimensions and functional roles. Each concept was evaluated in terms of its primary sustainability dimension(s), analytical level, scope, and relationships to other concepts. This two-layer coding enables differentiation between overarching frameworks, human-dimension approaches, and specific instruments or critical perspectives. Findings reveal systematic conceptual overlap, particularly where concepts addressing different sustainability dimensions are positioned at the same analytical level. Broad frameworks are often conflated with narrower instruments targeting specific environmental or social issues. The study proposes a hierarchical structure distinguishing: (1) overarching sustainability transformation frameworks, (2) approaches strengthening social and human dimensions, and (3) instrumental or critical approaches addressing specific challenges. This meta-level framework enhances conceptual clarity, supports interdisciplinary dialogue, and provides guidance for sustainability research and policy.
Keywords: sustainability-oriented economies, conceptual hierarchy, qualitative content analysis, PRISMA, well-being economy.

Introduction

In recent decades, sustainability has become a central guiding principle in economic thinking, shaping both academic debates and policy agendas worldwide. This shift has led to the emergence of numerous concepts intended to capture different pathways towards more sustainable economic systems. Rather than representing a single coherent framework, the field is characterised by a diverse and evolving set of approaches that emphasise different priorities, values, and mechanisms of change.

While this diversity reflects the multidimensional nature of sustainability, it also creates challenges in terms of conceptual coherence. Different approaches often originate from distinct disciplinary traditions and address specific aspects of sustainability, such as environmental protection, social well-being, or economic restructuring. As a result, the boundaries between concepts are frequently blurred, and their roles within the broader sustainability discourse remain insufficiently defined. This lack of conceptual structuring makes it difficult to assess how individual approaches relate to one another and to what extent they contribute to systemic sustainability transformations.

From a research perspective, the absence of a clear conceptual structure limits the ability to synthesise findings across studies and to develop cumulative knowledge. In policy and practice, it may lead to fragmented or inconsistent strategies, where different sustainability initiatives are implemented without a shared understanding of their underlying assumptions or intended outcomes. Addressing these issues requires moving beyond isolated concept descriptions towards a more integrative analytical perspective.

Although previous studies have explored individual sustainability-oriented economic approaches or compared selected concepts, there is still a lack of comprehensive frameworks that systematically organise these concepts according to common analytical criteria. Limited attention has been paid to distinguishing their functional roles and positioning them within a broader hierarchical structure.

This study seeks to contribute to this area by developing a structured perspective on sustainability-oriented economic concepts. The aim of the research is to analyse and systematise these concepts in order to better understand their roles and relationships within the sustainability discourse. Specifically, the study addresses the following research questions:

1. How can sustainability-oriented economic concepts be organised within a coherent analytical framework?
2. What functional roles do different concepts perform in the context of sustainability transformations?
3. How can relationships between these concepts be interpreted in a hierarchical perspective?

By providing a more structured understanding of sustainability-oriented economic thinking, this research aims to support clearer communication across disciplines and contribute to more consistent application of sustainability concepts in both academic and policy contexts.

Materials and Methods

This study adopts a systematic literature review combined with qualitative conceptual content analysis to investigate sustainability-oriented economic

concepts and their interrelationships. Such a methodological approach is particularly suitable for synthesising fragmented and interdisciplinary knowledge while identifying conceptual structures and relationships across diverse economic paradigms (Ochoa et al., 2025; Kirchherr et al., 2023; Suchek et al., 2021). The research design follows established systematic review methodologies to ensure transparency, consistency, and analytical rigour (Mengist et al., 2019).

Data collection, search strategy and PRISMA study selection

The literature review was conducted in accordance with the PRISMA 2020 (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure a systematic, transparent, and replicable study selection process (Page et al., 2021a). Data collection was performed using two widely recognised scientific databases — Scopus and Web of Science — which are commonly recommended in systematic literature reviews to ensure comprehensive coverage of peer-reviewed studies and to minimise selection bias (Page et al., 2021a). These databases are particularly suitable for interdisciplinary sustainability research due to their extensive indexing of high-quality academic publications (Ochoa et al., 2025).

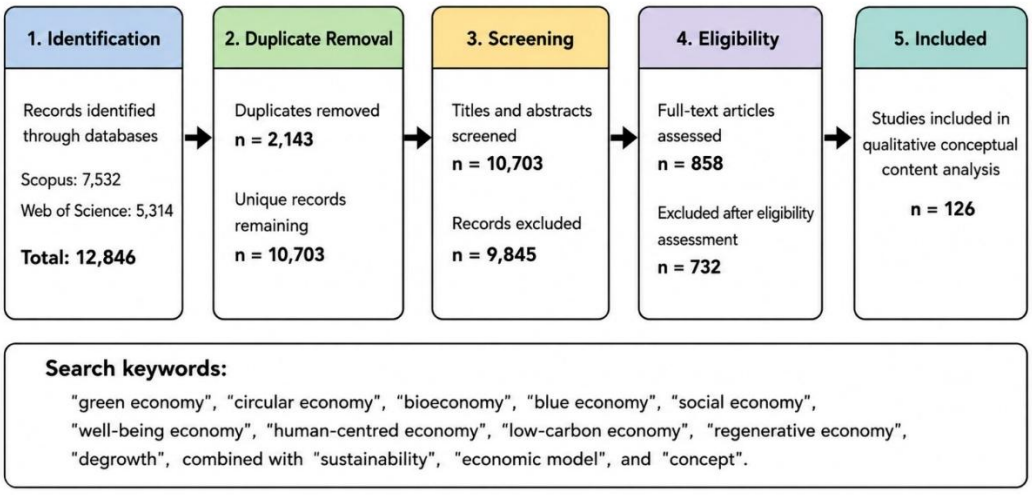
A structured search strategy was developed to identify a broad spectrum of sustainability-oriented economic concepts discussed within the scientific literature. The search query included terms such as 'green economy', 'circular economy', 'bioeconomy', 'blue economy', 'social economy', 'well-being economy', 'human-centred economy', 'low-carbon economy', 'regenerative economy', and 'degrowth'. These terms were combined using Boolean operators (OR, AND) and supplemented with broader keywords including 'sustainability', 'economic model', and 'concept'. The use of structured search strings and Boolean logic is essential for ensuring systematic and comprehensive literature retrieval, particularly in environmental and sustainability research (Mengist et al., 2019). The selection of sustainability-oriented economic concepts was supported by previous studies emphasising their relevance and diversity within the broader academic discourse on sustainable development (Kirchherr et al., 2023; Suchek et al., 2021).

The initial database search identified 12,846 records, including 7,532 publications from Scopus and 5,314 publications from Web of Science. After merging the datasets and removing duplicate records (n = 2,143), 10,703 unique articles remained for further screening. Duplicate removal and dataset refinement are important stages in systematic review methodology to ensure data accuracy and avoid redundancy within the analysis process (Pati & Lorusso, 2017).

The screening procedure followed the PRISMA methodology, which consists of five main stages: identification, screening, eligibility, and inclusion (Page et al., 2021a).

Figure 1

PRISMA literature flow diagram of the study selection process



During the screening stage, titles and abstracts were reviewed to assess their relevance to sustainability-oriented economic concepts. Studies lacking conceptual relevance or alignment with the research objective were excluded (n = 9,845). This stage follows established recommendations for systematic literature review screening procedures (Pati & Lorusso, 2017).

The remaining 858 full-text articles were assessed for eligibility using predefined inclusion and exclusion criteria. The inclusion criteria comprised peer-reviewed journal articles published in English that explicitly addressed one or more sustainability-oriented economic concepts and provided conceptual definitions, theoretical frameworks, or analytical discussions relevant to the research objective. The exclusion criteria included conference abstracts, editorials, book reviews, other non-peer-reviewed publications, studies lacking a clear conceptual focus, and articles for which full-text access was unavailable.

The application of predefined criteria contributes to methodological transparency and reduces selection bias in systematic literature reviews (Mengist et al., 2019; Pati & Lorusso, 2017).

Following the eligibility assessment, a final sample of 126 studies was selected for qualitative conceptual content analysis. The complete study selection process is illustrated in Figure 1 through the PRISMA literature flow diagram, which presents the identification, screening, eligibility, and inclusion stages of the review process. The documentation of included and excluded records at each stage aligns with PRISMA 2020 recommendations for transparent and reproducible reporting in systematic reviews (Page et al., 2021a, 2021b).

Qualitative Conceptual Content Analysis

Following the selection process, qualitative conceptual content analysis was conducted to examine the relationships and classifications of sustainability-oriented economic concepts. This analytical approach enables the systematic interpretation of textual data and the identification of themes, patterns, and conceptual linkages across studies.

The analysis focused on identifying how different economic models—such as green economy, circular economy, and degrowth—are defined, operationalised, and interconnected within the literature. This is consistent with prior studies that have explored the evolution and diversity of sustainability-related economic concepts through qualitative and conceptual analysis (Kirchherr et al., 2023).

Furthermore, the study aimed to identify overarching frameworks and classification patterns among these concepts, contributing to a more integrated understanding of sustainability-oriented economic paradigms. This aligns with previous research examining the interrelationships between innovation, sustainability transitions, and circular economy frameworks.

Analysis Approach

A qualitative content analysis was applied in this study to systematically interpret and structure the conceptual content of the selected academic publications. This approach enables a rigorous and transparent examination of how sustainability-oriented economic concepts are defined, interpreted, and positioned within the academic literature (Byrne, 2021; Braun & Clarke, 2020). It is particularly suitable for identifying patterns, relationships, and conceptual distinctions across diverse and interdisciplinary sources.

The analytical process was based on a two-level coding approach designed to ensure both thematic and functional differentiation of the analysed concepts (Humble & Mozelius, 2022). This structured approach allows for a more comprehensive understanding of the role and positioning of sustainability-oriented economic models within the broader sustainability discourse.

At the first level, coding was conducted according to sustainability dimensions, identifying the relationship of each concept to environmental, social, economic, governance, and human dimensions. This multi-dimensional perspective is consistent with contemporary sustainability research, which emphasises the interconnected and systemic nature of sustainability challenges (Dar et al., 2025). The purpose of this stage was to capture the primary focus and orientation of each concept within the sustainability framework.

At the second level, coding was performed based on the functional roles of the concepts, analysing their significance and positioning within sustainability discourse. At this stage, concepts were classified into categories such as overarching frameworks or paradigms, approaches strengthening specific sustainability dimensions, and instrumental or critical approaches. This type of functional classification supports the development of integrative conceptual frameworks and enables the identification of relationships between different economic models (Schork et al., 2025).

The coding process was conducted iteratively, with categories continuously reviewed and refined to ensure consistency, accuracy, and analytical depth (Byrne, 2021). This iterative refinement allowed for the identification of emerging patterns, overlaps, and distinctions among the analysed concepts.

Overall, the applied analytical approach provides a systematic and robust foundation for identifying common patterns, differences, and relationships among sustainability-oriented economic concepts, contributing to the development of a coherent conceptual structure within the field.

Results and Discussion

Conceptual Overlap in Sustainability Literature

The academic literature reveals substantial conceptual overlap among sustainability-oriented economic paradigms, despite their distinct theoretical foundations and operational emphases. For example, an extensive analysis of circular economy definitions demonstrates significant diversity and ambiguity in how the concept is interpreted and applied across studies (Kirchherr et al., 2023). Similarly, frameworks such as green economy, circular economy, and bioeconomy share a common objective of reconciling economic development with environmental and social sustainability yet differ in their underlying assumptions and scope (D'Amato et al., 2017).

This overlap contributes to conceptual ambiguity, as these terms are often used interchangeably in both academic and policy discourse (Passalía & Peinado, 2025). Additional concepts—including 'well-being economy', 'regenerative economy', 'doughnut economics', and 'degrowth'—further diversify the sustainability landscape and reinforce its heterogeneous nature (Friant et al., 2020).

Across the literature, these concepts converge around shared priorities such as 'resource efficiency', 'environmental protection', 'social equity', and 'long-term sustainability', while diverging in their emphasis

on economic growth, technological innovation, and systemic transformation (D'Amato & Korhonen, 2021; Milios, 2017). The degree of overlap is also influenced by sectoral and regional contexts, as well as governance structures (Zeng, 2025).

Classification Based on Sustainability Dimensions

The analysis indicates that sustainability-oriented economic concepts can be classified according to multiple sustainability dimensions, extending beyond the traditional environmental–social–economic framework. Contemporary research highlights five key dimensions: environmental, social, economic, governance, and human (Dar et al., 2025).

The environmental dimension is the most consistently represented across all concepts, encompassing 'resource efficiency', 'emissions reduction', and 'ecological preservation' (Foroozanfar et al., 2022). However, the mechanisms differ: circular economy focuses on resource loops, green economy on decoupling growth from environmental impact, and bioeconomy on renewable biological resources (D'Amato & Korhonen, 2021).

The social dimension varies significantly. Concepts such as 'social economy' and 'regenerative economy' explicitly prioritise equity and community well-being, while others address these aspects more indirectly (Rostamnezhad & Thaheem, 2022; Čegar et al., 2024). Economic dimensions are reflected in different ways, including sustainable growth, innovation, and long-term value creation (Karakaya & Balcıoğlu, 2026). Meanwhile, governance and human dimensions—covering institutional structures, participation, well-being, and quality of life—are increasingly recognised as essential for successful sustainability transitions (Belkhiri et al., 2026; Comes & Oneț, 2025).

Table 1

Classification matrix for sustainability-oriented economic concepts

Concept	Environ-mental	Social	Economic	Governance	Human
Green economy	●	●	●	○	○
Circular economy	●	●	●	○	○
Bioeconomy	●	○	○	○	
Social economy		●	○	○	○
Regenerative economy	○	○	○	○	
Well-being economy	●	●	○	○	●
Degrowth	●		○		●

Legend: ● — primary emphasis; ○ — secondary emphasis.

A classification matrix (Table 1) can be developed to map these concepts across the five dimensions, enabling systematic comparison and highlighting their primary and secondary emphases (Kaya & Uyar, 2026).

Functional Differentiation of Concepts

The findings demonstrate that sustainability-oriented economic concepts perform distinct functional roles within sustainability discourse (Sánchez-Planelles et al., 2020).

At the highest level, overarching frameworks such as sustainable development and just transition provide normative direction and define long-term goals (Ratnu, 2025). These serve as guiding paradigms for sustainability transformation.

At an intermediate level, systemic approaches such as circular economy, green economy, and bioeconomy translate these principles into structured economic models (D'Amato & Korhonen, 2021). These frameworks establish linkages between economic activity and sustainability outcomes.

At the operational level, instrumental concepts—including sustainable supply chains, regenerative design, and green procurement—offer practical tools and implementation mechanisms (Zeng, 2025; Franconi et al., 2022).

In addition, critical approaches such as degrowth and doughnut economics challenge dominant economic assumptions and propose alternative development pathways (Passalía & Peinado, 2025; Friant et al., 2020). These concepts play a transformative role by questioning existing paradigms and introducing new perspectives.

Proposed Conceptual Hierarchy

Based on the analysis, a hierarchical structure of sustainability-oriented economic concepts is proposed as the main contribution of this study. This structure organises concepts into three analytical levels:

Level 1: Overarching frameworks

These include broad sustainability paradigms such as sustainable development and justice-oriented frameworks, which define the fundamental values and objectives of sustainability (Moallemi et al., 2019; Moro-Visconti, 2025).

Level 2: Human and social enhancers / systemic frameworks

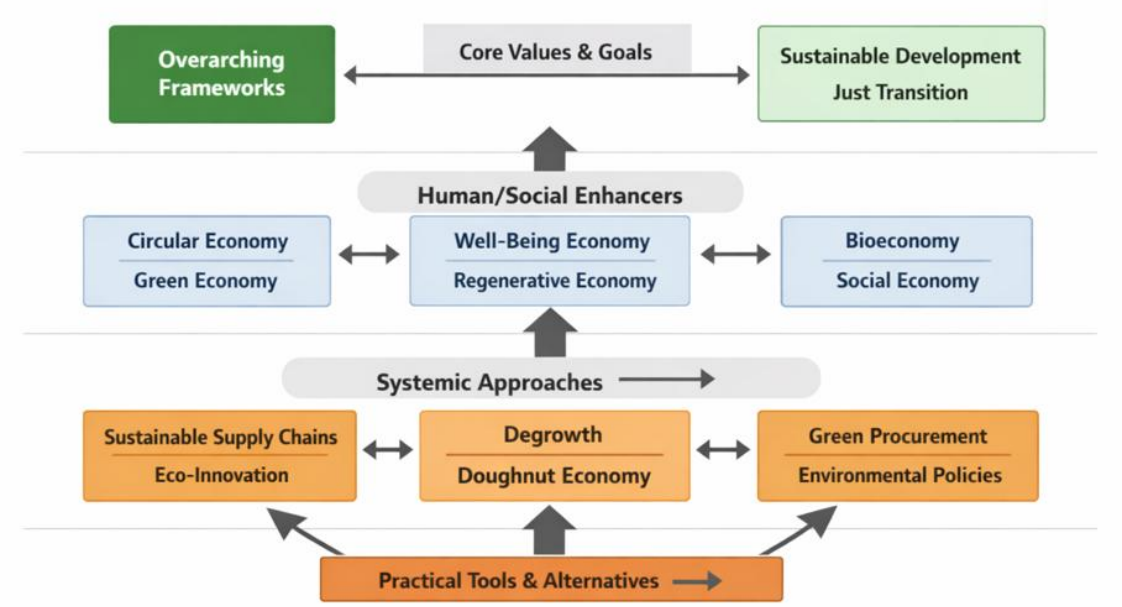
This level includes concepts such as circular economy, green economy, bioeconomy, regenerative economy, and well-being economy, which operationalise sustainability principles at a systemic level (D'Amato & Korhonen, 2021; Karakaya & Balcıoğlu, 2026; Sezer, 2025).

Level 3: Instruments and critical approaches

This level encompasses both practical tools (e.g., life-cycle assessment, circular business models, sustainable procurement) and critical frameworks such as degrowth and doughnut economics (Moreno et al., 2016; Franconi et al., 2022; Friant et al., 2020).

This hierarchical structure highlights both vertical relationships (from principles to implementation) and horizontal relationships (between alternative approaches at the same level) (Kaya & Uyar, 2026; D'Amato et al., 2017).

Figure 2
The proposed hierarchy and interactions among different levels of sustainability-oriented economic concepts



As shown in Figure 2, the conceptual diagram visualises the proposed hierarchy and highlights the interactions among different levels of sustainability-oriented economic concepts.

Implications

Theoretical Implications

Clarifying the relationships among sustainability-oriented economic concepts contributes to advancing sustainability theory by reducing conceptual ambiguity and enabling more precise analytical distinctions (Kirchherr et al., 2023; Sánchez-Planelles et al., 2020). The findings suggest that these concepts should not be viewed as competing alternatives but rather as complementary components within a broader sustainability transformation framework (D'Amato & Korhonen, 2021; Rabbi, 2025).

Furthermore, the hierarchical model provides a foundation for integrating research across multiple analytical levels, supporting cumulative knowledge development (Deirmentzoglou et al., 2026; Ghinizzini et al., 2025; Pelzeter et al., 2025).

Practical Implications

From a policy perspective, conceptual clarity enables more targeted and coherent policy design, allowing policymakers to combine elements from different frameworks depending on specific objectives (Milios, 2017; Judijanto, 2026; Mondal et al., 2025).

For organisations, the hierarchical structure provides guidance for implementation, helping to align operational practices with broader strategic and systemic frameworks (Barbosa et al., 2025; Karakaya & Balcıoğlu, 2026).

At the governance level, clearer conceptual understanding facilitates stakeholder dialogue and supports more effective collaboration across different sustainability priorities (Deirmentzoglou et al., 2026; Ratnu, 2025).

Finally, for future research, the findings highlight underexplored areas—particularly social and governance dimensions—and emphasise the need to investigate interactions among different sustainability concepts (Rostamnezhad & Thaheem, 2022; Nogueira et al., 2023.

Conclusions

1. Sustainability-oriented economic concepts are often conflated, despite differing in theory, mechanisms, and focus. This leads to ambiguous policies, inconsistent implementation, and reduced analytical clarity.
2. Overlapping terminology obscures key distinctions (e.g., resource cycling, decoupling, renewable resources, well-being focus).
3. A multidimensional framework (environmental, social, economic, governance, human) improves clarity.
4. Concepts vary in emphasis across dimensions:
   - some prioritize environmental management,
   - others focus on well-being or governance,
   - some integrate multiple dimensions,
   - enables identification of complementarities, gaps, and trade-offs.
   - concepts are complementary, not mutually exclusive.
5. A four-level hierarchy structures concepts:
   - Normative-foundational (principles, goals);
   - Systemic-strategic (economic transformation pathways);
   - Sectoral-functional (domain-specific applications);
   - Operational-instrumental (practical tools and actions).
6. Effective transformation requires coordination across levels.

7. Theoretical implications:
   - Moves beyond ‘one best model’ debates,
   - Supports integration of diverse frameworks,
   - Improves analysis of synergies and trade-offs,
   - Enables cumulative knowledge building.
8. Practical implications:
   - Supports tailored policy design using multiple frameworks,
   - Helps organisations with implementation, sequencing, and integration,
   - Enhances stakeholder alignment and governance processes.
9. Key barriers to implementation:
   - governance fragmentation;
   - weak institutional coordination;
   - inconsistent regulation;
   - limited alignment across sectors.
10. Challenges are greater in emerging economies and SMEs.
11. Social and human dimensions remain underdeveloped.
   - equity, labour, inclusion, well-being need stronger integration
12. Future research needs:
   - role of contextual factors (institutions, culture, geography);
   - links between sustainability and politics, innovation, and social change.

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BIOMETHANE PRODUCTION FROM AGRICULTURAL BY-PRODUCTS IN RURAL AREAS OF LATVIA

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Abstract
The challenge of European energy security is driven by the energy transition from fossil fuels to renewable energy sources (RES). Among the latter, biomethane represents a valuable source within the framework of the rural development and circular bioeconomy, by promoting the valorisation of agricultural by-products. Within the portfolio of RES, the expansion of biomethane has assumed a growing strategic relevance in the European energy policy framework, particularly as a response to the geopolitical disruptions caused by the Russia–Ukraine war and in alignment with the energy diversification and security objectives outlined in the 2022 REPowerEU plan. Within this framework, Latvia with an investment of EUR 21.5 million aims to foster biomethane production and expand its transport infrastructure, positioning itself as a leading player in the Baltic region. Rural areas, leveraging their agricultural production capacity, can play an active role in biomethane expansion, generating economic and environmental benefits while promoting a new business growth model for these territories. The present study provides an evaluation of the potential biomethane production from agricultural feedstocks, by interpreting data from the Central Bureau of Statistic. The study shows a theoretical agri-biomethane potential of about 93.51 Mm^3 CH_4 $year^{-1}$, derived from livestock manure, with notable regional differences favouring agriculturally intensive areas. These findings highlight the key role of rural regions in supporting renewable gas production and suggest the need for targeted policies to foster biomethane development, circular bioeconomy, and energy security.
Keywords: agri-biomethane, rural area, Latvia, energy transition, circular economy.

Introduction

The European Union (EU) has embarked on an ambitious path to achieve climate neutrality by 2050. With the Green Deal policy (2019), this strategy aims at a deep decarbonization of all economic sectors, placing the integration of different renewable energy sources (RES) at the heart of the green transition (EU Commission, 2019; EU Commission, 2020). In this context, biomethane ($BioCH_4$), obtained from the upgrading of biogas derived from anaerobic digestion technology - which breaks down organic matter by microbial action - has emerged as a unique strategic solution. It offers a path not only for decarbonization and energy security, but also for deeply involving agricultural areas in its production (Ardolino et al., 2021). In compliance with this, a decisive boost has come from the geopolitical energy crisis of the Russia - Ukraine war, which has accelerated the energy transition processes and the consequent search for Europe's energy independence. In response to these events, the European Commission launched the REPowerEU plan in 2022 (EU Commission, 2022). This program sets an ambitious goal of producing 35 billion m^3 (bcm) of biomethane per year by 2030. Currently, the most updated data indicates that there are a total of 1678 biogas and biomethane producing facilities in Europe (EBA, 2025). Agricultural residues account for more than half of the feedstock used for their operation, covering 25 countries, and recording a significant increment in number of plants from the starting of REPowerEU program in 2022, where the number of plants stopped at 1322 (EBA, 2022). At least 86% of the biomethane plants currently operating in Europe are connected to the gas grid. To date, the total production of biogas and biomethane in Europe in 2025 was about 22 billion m^3 (bcm), (EBA, 2025). According to the revised National Energy and Climate Plan (2021-2030), Latvia's biomethane production potential would allow for the replacement of all domestic natural gas, but biomethane production must increase significantly (Government of Latvia, 2020). To support these goals, new funding schemes have been approved by the government, an investment of EUR 21.5 million, aims to foster biomethane production and expand its transport infrastructure (Cabinet of Ministers of Latvia, 2025). Currently, according to the Latvia Biogas Association, there are 12 Biomethane plants in Latvia, five of them use only agriculture by- products. In this scenario this research focuses on agri-biomethane, a RES produced exclusively from agricultural by-products and zootechnical residues, this latter source plays a key role in the green transition while supporting the circular economy, and rural area development in line with REPowerEU objectives (Labianca et al., 2024) and Common Agricultural Policy (CAP). Agri-biomethane also offers key advantages, including the use of local feedstocks, compatibility with existing infrastructure, also the production of digestate as a natural alternative to synthetic fertilizers. Additionally, anaerobic digestion plants for biomethane production are widely accepted within the communities where they are installed and developed (Iannantuono et al., 2025). In this context, Baltic area (NUTS3), especially Latvia (NUTS1) has large unexpressed potential in terms of biomethane production (Millers and Pilvere, 2023). Latvia is a country with a strong rural component and agricultural tradition; in 2024, the rural population accounted for approximately 31.2% of the total population (World Bank, 2026). According to Rural Pact Community Platform, 98% of Latvia territory is covered by rural areas (European

Commission, 2025). Latvian rural development policies are funded through two main pillars: the CAP Strategic Plans (European Commission, 2023) and the European Agricultural Fund for Rural Development (EAFRD) (European Parliament, 2021). These initiatives aim to support rural development by promoting agricultural competitiveness, sustainable resource management, climate action, and balanced territorial growth, complemented by national and regional funding sources. The successful development of agri-biomethane requires well-structured strategic planning that considers the specific territorial features of rural areas and actively involves local farmers and economic stakeholders, ensuring shared acceptance and support for such investments and innovative initiatives (Labianca et al., 2024). In summary, the integration between the Green Deal directives and rural support provides Latvia with a favourable regulatory and financial framework to transform agricultural by-products into an engine of sustainable economic growth of rural area (Millers et al., 2023). A review of the existing literature indicates that only a limited number of studies have examined the role of biomethane in supporting rural area development in Latvia, but no study has focused on agri-biomethane and rural area development connection. However, these contributions present relevant limitations, as they do not adequately consider the different feedstock typologies for biomethane production. Considering these gaps, this paper aims to provide an evaluation of the potential agri-biomethane production from agricultural and zootechnical feedstocks to understand the possibilities of local farmers from the rural area to supporting green transition and circular economy. To do this, the authors relied on an existing case study by analysing the feedstocks used in a biomethane plants located in Latvia. Based on the feedstock composition, the crops most suitable for agri-biomethane production in agricultural systems were identified. However, since the available data referred only to energy crops, the authors decided to focus on manure and sewage, as energy crops conflict with land use for food production (Vera et al., 2022). The collected data were then organised on a regional basis to obtain a more representative overview of the areas of interest (Bumbiere et al., 2021; Naglis-Liepa & Pelse, 2014; Scarlat et al., 2010). The different regions of Latvia were analysed and classified according to the definition of statistical region supplied by the Ministry. After that rural areas were identified, and agricultural biomass availability for supplying agri-biomethane plants was assessed for each region. These data, together with the current state incentives for the construction of biomethane plant and upgrading from biogas, were also evaluated. This model is intended to serve as one of the tools fostering more appropriate energy planning for policymakers in accordance with the most recent policy program 'REPowerEU' and CAP, defining specific planning strategies in that framework, aimed at increasing agri-biomethane production, especially in rural areas.

Literature review

To evaluate the current state of the art of scientific literature about biomethane as tool in supporting the development of rural areas, a non-systematic literature review was conducted through the research platform SCOPUS. The authors evaluated such works as scientific articles and conference proceedings that included keywords 'Latvia' 'Biomethane' 'Rural Area'. Previous studies have explored various links between biomethane and rural development, they have not specifically examined the relationship and potential this RES holds for Latvian territory. Consequently, this study serves to bridge the critical gap in the current literature. The main scientific contributions may be classified in three clusters: the first refers to the potential role of biomethane in the Baltic area, especially the analysis of economic and normative aspects was conducted (Ansone et al., 2024; Bumbiere et al., 2021; Gancone et al., 2020; Repele et al., 2017; Zemite et al., 2022.). The second cluster focuses on technologies to improve the existing distribution network and on the purification of biomethane (Jansons et al., 2024; Mežulis et al., 2022; Zemite et al., 2025). Alongside this, a separate body of work investigates biomethane as an alternative to fossil fuels in the transport sector (Argalis & Vegere, 2021; Barisa et al., 2020; Savickis et al., 2020, 2021). Regarding the broader research context, Ansone et al. (2024) provided the initial investigation into biomethane production potential within the Baltic region, focusing primarily on bio-CNG development and the necessity for coordinated support policies. The policy theme aligns with the work of Zemite et al. (2022), who analyzed incentive mechanisms designed to support reforms and encourage the conversion of existing biogas plants to biomethane production. The work of Bumbiere et al. (2021) is also focused on the evolution of the Latvian biogas sector towards business models based on upgrading to biomethane, where EU climate policies are integrated to support the energy transition. Among these Gancone et al. (2020) argue that transitioning to biomethane is more efficient and sustainable than relying on electricity production alone, while offering significant advantages for national security. An initial analysis of the regulatory framework and economic barriers to the development of the Latvian biomethane market has been done by Repele et al. (2017), emphasizing the need for stronger financial support mechanisms, improved incentive schemes, and clearer regulatory frameworks to overcome existing economic barriers and foster market development. Additionally, several positive studies have highlighted the role of biomethane in the Baltic States and in Latvia; however, none has focused exclusively on agri-biomethane produced solely from agricultural by-products as a driver for rural development in Latvia. Therefore, this work aims to address this gap in the current literature.

Materials and Methods

Agricultural systems generate considerable quantities of organic residues and by-products originating from both crop cultivation and livestock farming. These materials mainly consist of fractions of the original biomass removed during harvesting operations or produced during animal husbandry activities. Among the available resources, livestock manure and crop residues represent the most relevant biomass streams that can be effectively valorised through anaerobic digestion for renewable energy production. Due to their widespread availability within agricultural landscapes, these substrates constitute a reliable and locally accessible feedstock for agri-biomethane generation (Vismara et al., 2009). Based on these premises, this study estimates agricultural -biomethane production potential by evaluating the regional availability of organic substrates across Latvia, where rural territory accounts for 98% of the land area (Labianca et al., 2024). To analyse these substrates, data on existing biogas plants converted to biomethane production was obtained directly from the Latvia Biogas Association. These facilities are considered representative of the national context, as verified by existing literature on domestic biogas production. Information on the feedstock composition was collected through an interview with the plant operator, allowing the identification of the feedstock mixtures currently used for agri-biomethane production. These feedstock combinations are consistent with previous studies assessing the availability of raw materials in Latvia and identifying the most suitable crops for biomethane production (Naglis-Liepa & Pelse, 2014; Priekulis et al., 2021; Vismara et al., 2009). The current optimum feedstock used for Latvia is composed of a mixture consisting of 78% manure and slurry (from cattle or pig) and 22% maize silage. Both feedstocks are agricultural products, and no municipal waste is used for biomethane production. This result is in line with the findings of Naglis-Liepa & Pelse (2014) and Wicki et al. (2022). After confirming the feedstocks used in the selected biomethane plant, the regional availability of the main crops used for biomethane production, and the livestock manure resources was assessed. The analysis focused on evaluating the distribution and potential availability of these substrates across the different regions of the study area. To reach this, a quantitative analysis was used, collecting data from the Central Statistical Bureau (CSB) and Rural Support Service (RSS) to establish a theoretical baseline (Central Statistical Bureau of Latvia, 2025; Rural Support Service, 2025) the data for livestock refers to all statistical regions of Latvia: Riga, Vidzeme, Kurzeme, Zemgale, and Latgale. For the crop resource due to lack of data, the estimation could be unrealistic, as they choose to focus on livestock data. This granular level of analysis is critical to identifying high-potential regions for agri-biomethane development production and is useful for clearly showing the comparison of the different areas as they may have potential and critical issues. The collected statistics were divided into two main categories: livestock and poultry. Both datasets were cross-referenced with national metrics to accurately apply species and age distributions at the regional scale. The analysis utilizes the latest updated publications for both sectors, referring data from the end of 2024.

Livestock and poultry data

The study was limited to species, as identified in the analysed case study of Latvia, since they were considered the most suitable substrates for agri-biomethane production. In the first phase of the analysis, national data for Latvia on livestock populations were analysed (CSB, 2025). The investigation focused on the main livestock categories: cattle, pigs and poultry. Each category was further subdivided according to age and productive function, as these factors correspond to different coefficients of livestock manure production (Castelli & Negri, 2011; Food and Agriculture Organization of the United Nations, 2011; Tricase & Lombardi, 2009). Sheep and goat effluents are excluded, as their substantial amounts are easily managed by being spread on soil during extensive or semi-extensive farming. Livestock wastes are classified as manure (collectable with a shovel, bedding waste) and slurry (non-collectable, without bedding). Manure is typically used as fertilizer due to its good agronomic quality, whereas sewage, although richer in nutrients and produced in larger quantities, often represents a disposal challenge because of its liquid form. This work focuses only on the sue of sewage to produce biomethane. The total cattle population amounts to 352.10 thousand heads, and it was divided into the following groups: dairy cows (56.69%) calves (27.32%), and cattle under two years of age (15.99%). In the second phase of the study, the pig population in Latvia was analysed using national livestock statistics (CSB, 2025). Similarly to the cattle analysis, the pig category was subdivided according to age, live weight and production function. The swine population was therefore classified into four main groups: fattening pigs (39.57%), growers (28.83%), piglets (19.20%), and sows (12.40%), the pig population amounts to 300.10 thousand heads. For poultry, the available data included only the total number of birds raised and the number used exclusively for egg production. By difference, the proportion of laying hens was derived; out of a total of 5985.2 thousand birds, 59.49% were classified as laying hens. In Table 1, the division by regions of national animal data is reported.

Consequently, after organising the data at the national and regional level, disaggregated by region and based on coefficients and models available in the literature (Castelli & Negri, 2011; Naglis-Liepa & Pelse, 2014; Tricase & Lombardi, 2009), the biomethane potential was then calculated. First, the average annual manure production from the three species was estimated.

Table 1
Number of animals in head per thousand by region

Species	Riga	Vidzeme	Kurzeme	Zemgale	Latgale
Cattle	7,772	111,584	80,653	61,096	86,989
Pigs	63,572	52,168	63,835	104,305	16,229
Poultry	2,388	0,427	0,800	3,059	0,003

To determine the amount of manure available over the course of a year, reference can be made to the guidelines reported which provides indicative values of effluent production (m³ per tonnes of live weight per year) for different types of manure according to animal category and housing system, divide the percentage of regional head per thousand animal, the formula is subsequently:

$$Manure = (Nspecies, region \times Pcategory) \times Wcategory \times Ccategory \quad (1)$$

where:

- $N_{species,region}$ = total number of animals in the region
- $P_{category}$ = national proportion of each animal category
- $W_{category}$ = average live weight of the category (t)
- $C_{category}$ = sl production coefficient (m³ t⁻¹ live weight year⁻¹)

Results and Discussion

Following the estimation of available biomass from animal manure, the potential agri-biomethane production was calculated at the regional level. The results of this analysis are presented in the following section. First for manure the author uses the conversion coefficients of Naglis-Liepa & Pelse (2014), 2 (Table 3). The coefficients represent the average volume of biogas obtainable per unit of manure (m³ of biogas per m³ of manure), assuming a density of 1 t ≈ 1 m³, as commonly adopted in the literature (Castelli & Negri, 2011; Naglis-Liepa & Pelse, 2014; Vismara et al., 2009). Based on these coefficients, specific biogas yields were assigned to each livestock category: 25.0 m³ m⁻³ for cattle manure, 30.0 m³ m⁻³ for swine manure, and 60.0 m³ m⁻³ for poultry manure.

Table 2
Conversion index

Type of manure (1 ton or 1 m³*)	Average biogas (m³)
Cattle	25.0
Pigs	30.0
Poultry	60.0

The regional biogas potential was calculated by multiplying the estimated manure production for each livestock category by the corresponding coefficient.

In conclusion, the biomethane potential was determined by converting the calculated biogas yield, applying an average methane concentration of 55% based on reported biogas composition. Accordingly, biomethane production was quantified by multiplying the total biogas volume by the methane fraction, following conventional values referenced in the literature set for Latvia (Alberici et al., 2022; Adnan et al., 2019; European Biogas Association, 2025; International Energy Agency, 2020). The result is shown in Table 3.

Table 3
Potential production of biomethane per region

Region	Biomethane potential (Mm³ CH_4/year) from manure
Riga	7.68
Vidzeme	25.64
Kurzeme	21.09
Zemgale	21.49
Latgale	17.61

The regional distribution of biomethane potential derived from manure is reported in Table 3. Overall, the potential amounts to approximately 93.51 Mm³ CH_4 year⁻¹ at the national level. At the regional level, Vidzeme shows the highest biomethane potential, with 25.64 Mm³ CH_4 year⁻¹, corresponding to approximately 27.3% of the national total.

This result reflects the relatively high livestock activity in the region, which increases the availability of manure suitable for anaerobic digestion. Similarly, Zemgale and Kurzeme also exhibit significant potentials, with 21.49 Mm³ CH_4 year⁻¹ (23.3%) and 21.09 Mm³ CH_4 year⁻¹ (23.0%), respectively.

Together, these two regions account for nearly 46% of the national biomethane potential, highlighting the importance of the central and western agricultural areas of the country for the development of biomethane production.

A slightly lower potential is observed in Latgale, where the estimated biomethane production reaches 17.61 Mm³ CH_4 year⁻¹, corresponding to approximately 19.1% of the national total. Although this value is lower than those observed in the previously mentioned regions, Latgale still represents a relevant source of biomass for biomethane generation due to the availability livestock residues.

In contrast, the Riga region presents the lowest biomethane potential, with an estimated value of 7.68 Mm³ CH_4 year⁻¹, representing only 7.3% of the national total. This result can be explained by the limited agricultural and livestock activities in the region compared with other parts of the country, which reduces the availability of organic substrates suitable for biogas production.

From a national perspective, the results highlight that livestock manure represents the dominant feedstock for biomethane production. The regional distribution further suggests that the development of agri-biomethane production facilities should primarily focus on regions with higher agricultural and livestock densities, particularly Vidzeme, Zemgale, and

Kurzeme, where the majority of the national biomethane potential is concentrated.

Conclusions

1. This study evaluated the potential production of agri-biomethane in Latvia based on the availability of agricultural by-products and livestock manure across the main statistical regions of the country. By analysing the regional distribution of biomass resources, the research provides an overview of the theoretical capacity of Latvian rural areas to contribute to renewable gas production through the valorisation of locally available agricultural residues.
2. The results indicate that Latvia has a total theoretical agri-biomethane production potential of approximately 93.51 Mm^3 CH_4 $year^{-1}$. The analysis shows that the largest share of production potential comes from livestock manure, confirming the key role of livestock residues as the most reliable and abundant feedstock for anaerobic digestion processes in the Latvian agricultural context.
3. The regional analysis highlights significant spatial differences in the availability of biomass resources suitable for biomethane production. Vidzeme, Zemgale, and Kurzeme show the highest production potential due to their strong agricultural and livestock activities, which generate large quantities of organic residues. Conversely, the Riga region presents the lowest potential because of its relatively limited agricultural production and livestock presence.
4. These findings confirm that rural areas can play a central role in the expansion of biomethane production in Latvia. The availability of livestock by-products provides a valuable opportunity to convert organic residues into renewable energy while simultaneously supporting the development of circular bioeconomy practices and improving the sustainability of agricultural systems.
5. From a policy perspective, the results suggest that the development of agri-biomethane should be supported through territorially targeted strategies, prioritising regions characterised by higher livestock density and agricultural production. Supporting investments in biomethane plants in these areas could facilitate the efficient use of locally available biomass resources and strengthen the integration between the energy sector and agricultural activities.
6. Overall, the study demonstrates that agri-biomethane production from zootechnical by-products represents a promising pathway for supporting the energy transition, rural development, and circular bioeconomy in Latvia, while providing useful insights for policymakers in designing strategies aimed at expanding renewable gas production and improving energy security.

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DEFINING THE PRIORITY RESEARCH AREAS IN DIGITAL TECHNOLOGIES, ARTIFICIAL INTELLIGENCE OF UKRAINE BY DELPHI SURVEY

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Abstract
Digital technologies (DT) and artificial intelligence (AI) play a crucial role in the development of science and technology (S&T), future economic reconstruction, the reliability of processes serving the agricultural exports, and implications for the defence industry, which helps to maintain a sovereign state. After 2022, cybersecurity, AI, and robotics significantly increased their influence across all spheres of the Ukrainian technological sector, and their relevance continues to grow. The study aims to define the priority research areas of Ukrainian S&T in the thematic block 'Information and Communication Technologies (ICT), DT, AI, Robotics, and Cybersecurity'. The study was conducted from July to December 2024 in three stages using the Delphi survey. It includes 543 experts proposed by the branches of the National Academy of Sciences (NAS) of Ukraine and sectoral national academies. They identify the most relevant and promising research areas that merit priority support based on experts' scores. The experts evaluate the research directions of Ukrainian S&T defined in 2021 in light of current war conditions, present new expertise on the war's influence and further development. The experts assess the potential of the promising research areas, using the following criteria: relevance, personnel, equipment, contribution, and international cooperation. The percentage (%) of experts who give the highest relevance score (5 points) determines the top relevance criteria. A map of keywords based on a Scopus database filter search is visualised using VOSviewer software to identify gaps between the existing academic output and experts' foresight S&T priority proposals for the near future.
Keywords: artificial intelligence, digital technologies, S&T policy, Delphi survey, VOSviewer map.

Introduction

AI and DT play a significant role in research and innovation, boosting the economy, automating processes, and enhancing decision-making. Ukraine is eager to develop competitive advantages for its economy, increase citizens' well-being, and protect its sovereignty by implementing new technologies. AI is considered one of the most important drivers of increased productivity, coordination and business architecture (Skrypnyk & Shpatakova, 2023). Ukraine has an ambitious goal to rank among the top three countries in the world in AI implementation by 2030 (Ministry of Digital Transformation of Ukraine, 2026). The Ukrainian government defined the implementation of AI in defence, medicine, biotechnology, government services, education, green energy and sustainability, AUVs, space development, and other areas as priority fields under the Digital Innovation Development Strategy until 2030 (WinWin). WinWin plans to achieve 50% growth in startups and make Ukraine the largest European hub for AI developers (Cabinet of Ministers of Ukraine, 2024). The state of DT and AI integration across numerous sectors of economic and innovation activity (Dubniak, 2025), digitalisation, AI, and blockchain in financial services quality (Borodenko & Gaponiuk, 2025), and the development of business digitalisation in Ukraine (Khomutenko et al., 2025) have significantly increased their influence.

Shchyrska et al. (2025) made an essential contribution to the field of study by addressing the regulatory challenges of AI governance. They proposed legislative support to harmonise the approach with that of European countries (Shchyrska et al., 2025). Additionally, author Bolila emphasises the necessity of AI use in the military-tech industry and the priority of defence technologies (Bolila, 2023). There are works dedicated to outlining the weaknesses of Ukrainian digital development in comparison with EU countries on the examples of World Digital Competitiveness Ranking (WDCI) and the Digital Economy and Society Index (DEST) and proposing measures to improve the level of digitalisation of Internet infrastructure, digital government services, cybersecurity by developing an IT investment attraction strategy, harmonising legislation with EU norms (Kiriienko, 2025). Forecasting digital competitiveness and defining the importance of digital integration for Ukrainian society and the state remain unresolved (Halushchak et al., 2023).

Some authors identify the peculiarities, advantages, and drawbacks of AI use in strengthening cybersecurity, improving its legislation at the state and international levels, and preventing human rights violations (Hurzhii, 2023), formulate recommendations for AI utilisation across defence, education, industry, science, healthcare, and social development to enhance recovery and technology leadership in war and post-war conditions (Kovalevskyy, 2023). Some papers suggest identifying S&T priorities using data from the registration cards of scientific projects and dissertations (Bulkin, 2021), present AI integration priorities based on global and NATO experience and propose methodological issues for the design of the Ukrainian AI strategy (Kondratenko & Shevchenko, 2024), others to define priorities in the areas of food security, bioeconomy (Koretskyi et al., 2025), natural science (Kavunenko & Chernohaeva, 2025), industry sector and AI policy integration (Han, 2021), digital education for healthcare

(Potter et al., 2025) by the Delphi method.
At the same time, there are insufficient justifications for defining the exact priorities of S&T in ICT, DT, AI, robotics, and cybersecurity that Ukraine needs to develop over the next 5-10 years to achieve sustainable economic growth, ensure the security of data transmission in cyberspace and accelerate the use of AI applications in civil and defence sectors.
The study aims to determine whether the S&T priorities of Foresight 2021 remain relevant in the context of full-scale war, identify discrepancies and similarities between existing academic output based on the Scopus database and experts' foresight S&T priorities for the near future, provide proposals to increase the utilisation of S&T potential and outline the first of all S&T policy measures for stopping the 'brain drain'.

Materials and Methods
In the study, nine methodological groups worked across the nine thematic areas (Popovych et al., 2024). The general methodological group coordinated the activities of these twenty-five researcher groups. The experts submitted their responses via Google Forms. It was proposed to evaluate the relevance, personnel and equipment support, scientific achievements, and the level of international cooperation regarding the prospective aspects of the research areas. Based on this, new ideas and proposals would be formulated to address open questions and describe problems that are relevant today but were absent in 2021 (Popovych, 2022). The S&T priorities were ranked by the top-relevance criterion, meaning the percentage of the highest relevance score (5 points) was assigned by experts to each specific research area. The survey was conducted in three rounds using the RAND Corporation methodology (Khodyakov et al., 2023). More than five hundred experts, mostly from the NAS of Ukraine and other national sectoral academies, participated in the whole study, and the thematic block 'ICT, DT, AI, Robotics, Cybersecurity' involved 37 experts. After that, we discovered a correspondence between the identified priorities of S&T foresight studies for the next 5-10 years and the tendencies already evident in the publications of Ukrainian researchers, reflecting the most current scientific problems and S&T achievements. The bibliometric dataset was retrieved from the Scopus database using keywords related to artificial intelligence, cybersecurity, robotics, digital technologies, and unmanned systems (Elsevier, 2026). The search was restricted to publications affiliated with Ukraine and published between 2022 and 2026. A total of 10490 publication records were obtained within all subject areas, and 5165 were retrieved within the Computer Science subject area as of 1 March, 2026. RIS file records were downloaded from the Scopus database, and a map of keyword co-occurrences was generated using software VOSviewer for constructing and visualising bibliometric networks, where the weight of the item keyword as a label and the circle size determine the keyword's frequency (Leiden University, 2026). The distance between keywords indicates their relatedness. The closer the keywords are located, the stronger the relatedness. The scientific network shows the interconnections and gaps between academic publication output and the S&T priorities that should be achieved and promoted in the next 5-10 years, according to experts' opinions.

Results and Discussion
Ukrainian post-war recovery considers using AI for active use in planning infrastructure projects, damage assessment, agricultural development, soil, air, and crop monitoring, medical diagnostics, telemedicine, surgery, and digitalisation of education (Kliuchnyk & Livandovska, 2024). The usage of international digitalisation indicators in Ukraine, harmonisation of indicators in digital technologies on the example of European Innovation Scoreboard (Yehorov & Kotlyarevskyy, 2021), challenges of implementing long-term programs to support research and innovation, integration into digital metasystems (Mekh & Boublyk, 2023), integrating AI for yield prediction, robotics in harvesting, crop monitoring drones, smart irrigation systems into the agriculture are essential for Ukrainian digital transformation process (Linde et al., 2024). AI, ICT, and the digitalisation of the economic and defence sectors help increase productivity and ensure that Ukrainian science and business remain competitive.
Given the reality that even advanced economies have limited resources, it is necessary to invest in progressive technologies and promising research areas to secure leadership breakthroughs. Table 1 presents a comparison of the defined S&T priorities of Foresight 2021 and 2024 for the thematic block 'ICT, DT, AI, Robotics and Cybersecurity'. The results describe that research priorities have shifted from classic infrastructure cybersecurity and generic digitalisation toward AI-centric, autonomous, and governance-oriented topics, even though cybersecurity remains the dominant frame. Experts are moving away from narrow application domains such as healthcare and industrial systems toward cross-cutting themes, including adaptive security, artificial general intelligence (AGI), public safety, and the ethical and regulatory aspects of AI.
The 2024 priority list is dominated by AI-related topics: autonomous AI and swarm intelligence, strong AI (AGI) systems, AI for public safety, and several entries on AI regulation and ethics. By contrast, the 2021 list referenced data-driven systems only indirectly, through 'IT in healthcare' and 'Cloud & grid technologies'. This tendency may indicate that AI has moved from a background enabler to a primary object of research. Among the top nine research areas, seven relate to cybersecurity, technology protection, risk identification, and information security, underscoring the central role of risk-management and

data-protection directions in a wartime context.

Cybersecurity remains central but has become more dynamic and systemic. The static focus on 'Critical infrastructure cybersecurity' and 'Industrial systems cybersecurity' in 2021 changed in 2024 to 'Adaptive cybersecurity systems' and the 'Cybersecurity of unmanned and robotic systems', 'Robotic process automation'. The emphasis shifts from protecting fixed infrastructure to securing highly automated, continuously changing socio-technical environments, including large data centres and the transmission and storage of commercial and private information. In the legal and governance domain, 'Legal aspects of human information society' in 2021 evolved into 'AI regulation and law' in 2024, now complemented by 'Ethical and transparent AI'. This evolution underscores the need for not only technical safeguards but also robust regulatory frameworks and explicit normative principles to support rapid AI diffusion. Similarly, 'Quantum cybersecurity' in 2021 has been reframed as 'Quantum computing & information technologies', broadening the focus from a defensive niche to the broader strategic landscape of quantum capabilities. This shift signals interest in both harnessing quantum technologies and understanding their systemic impacts on ICT and security.

Table 1

Wartime shift of Ukraine's S&T priorities in 'ICT, DT, AI, Robotics and Cybersecurity' thematic block based on Foresight 2021, 2024

Foresight 2021	Ranking by top relevance indicator, %			Foresight 2024
Critical infrastructure cybersecurity	83%	1	88%	Adaptive cybersecurity systems
Research-to-innovation breakthrough conversion	82%	2	81%	Swarm intelligence of self-moving objects
IT in healthcare	75%	3	76%	Cybersecurity of unmanned and robotic systems
Industrial systems cybersecurity	71%	4	65%	Cybersecurity of robotic process automation
Quantum cybersecurity	59%	5	53%	Autonomous 'Strong AI' (AGI) systems
Industrial cyber risk & environment	50%	6	47%	AI for public safety
Psychological cybersecurity of the individual	50%	7	35%	Quantum computing & information technologies
Legal aspects of human information security	50%	8	35%	AI regulation and law
Cloud & grid technologies	50%	9	35%	Ethical and transparent AI

Source: authors' calculations based on the results of the experts' survey.

The 2024 priorities closely mirror the capabilities Ukraine has had to develop under wartime conditions − cyber resilience, autonomous and AI systems, and legal-ethical frameworks − rather than the more generic ICT and sectoral applications of 2021. The full-scale war in Ukraine has accelerated and redirected these priorities toward wartime cyber defence, AI-enabled operations, and the governance of high-risk technologies, while de-emphasising peacetime digitalisation. Since 2022, Ukraine has faced continuous Russian cyberattacks targeting government systems, critical infrastructure, banks, and communications networks (State Service of Special Communications and Information Protection of Ukraine, 2024). This experience has reinforced the shift from static 'Critical infrastructure cybersecurity' to 'Adaptive cybersecurity systems' and the security of highly networked operational technologies (mobile, robotic, and RPA systems), which better reflect the need to keep state and military functions operational despite persistent attacks. The war has also turned Ukraine into a testbed for AI in defence, including geospatial intelligence, drone and unmanned systems control, cyber operations, and battlefield decision support. Air-defence applications and AI-enabled early-warning systems, such as electronic personal protection orders (ePPO) and personalised missile-alert services, illustrate how AI is being used directly to protect civilians and urban infrastructure in wartime (ePPO). This explains the emergence of 'AI for public safety' as a distinct 2024 research area and the broader move from sector-specific IT modernisation toward dual-use technologies that support both defence and civilian protection. Wartime deployment of facial-recognition tools (for example, Clearview AI), extensive biometric identification, and AI-generated disinformation have raised acute human-rights and privacy concerns. This underpins the elevation of 'AI regulation and law' and 'Ethical and transparent AI' to the top nine priorities in 2024, evolving from the narrower 'Legal aspects of human information security' focus of 2021 and aligning with updates to Ukraine's cybersecurity and AI strategies.

The military use of advanced sensing, remote-sensing, and cryptographic technologies, combined with global trends, has also made quantum computing and information technologies strategically salient. The shift from 'Quantum cybersecurity' in 2021 to 'Quantum computing & information technologies' in 2024 reflects a broader, war-informed interest in the defensive and enabling roles of cyber operations. Topics such as research-to-innovation transfer,

psychological cybersecurity, and generic industrial cyber risk have fallen out of the top nine by 2024, even though they remain structurally important. This reflects wartime triage: resources and political attention are concentrated on capabilities with immediate impact on survival, cyber defence, and AI-enabled operations, tightening the research agenda around high-intensity security and governance challenges.

Table 2 presents expert assessments of Ukraine's S&T research capacity concerning talent, equipment, contributions, and international cooperation. The data reveal an overall strengthening of research capabilities between 2021 and 2024, despite the severe pressures of the full-scale war.

Table 2

Comparative assessment of experts' average scores given to S&T priorities: Foresight 2021 vs. 2024

S&T priorities for the next 5-10 years	Talent	Equipment	Contribution	International cooperation
	Foresight 2021			
Critical infrastructure cybersecurity	3.50	2.83	3.22	3.33
Research-to-innovation breakthrough conversion	3.11	2.83	3.00	3.11
IT in healthcare	3.69	2.94	3.60	2.94
Industrial systems cybersecurity	3.56	3.06	3.41	3.12
Quantum cybersecurity	3.33	2.82	3.00	2.94
Industrial cyber risk & environment	3.50	3.00	3.35	3.11
Psychological cybersecurity of the individual	2.72	2.61	2.59	2.76
Legal aspects of human information security	3.11	3.00	2.59	2.94
Cloud & grid technologies	3.53	2.75	3.47	3.59
	Foresight 2024			
Adaptive cybersecurity systems	3.88	3.24	3.63	3.31
Swarm intelligence of self-moving objects	3.69	3.19	3.53	3.41
Cybersecurity of unmanned and robotic systems	3.71	3.31	3.24	3.29
Security of robotic process automation	3.65	3.18	3.29	3.29
Autonomous 'Strong AI' (AGI) systems	3.35	3.06	3.13	3.12
AI for public safety	3.12	2.88	3.00	3.12
Quantum computing & information technologies	3.12	2.71	2.76	2.94
AI regulation and law	2.94	3.18	2.53	3.18
Ethical and transparent AI	3.18	3.06	3.00	3.24

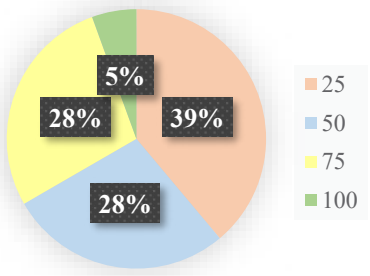
Source: authors' calculations based on the results of the experts' survey.

The 2024 priority areas − which focus on adaptive cybersecurity, autonomous AI and robotics − consistently command higher ratings for talent and research contributions than the 2021 list. This suggests that the research community has deepened its expertise and improved its output in high-priority, war-relevant domains. However, structural challenges persist. Equipment scores remain the weakest link, rarely exceeding 3.25. While the quality of talent is rising, these infrastructure constraints likely limit Ukrainian scientists' ability to work at the absolute global frontier. International cooperation has proven resilient, with scores consistently holding in the mid-three range. This stability demonstrates that, even as national research priorities have pivoted from generic IT and healthcare toward high-intensity security and AI, the underlying network of international partnerships remains intact.

The majority of experts (67%) believe that Ukraine's S&T potential in AI and IT is utilised at only 25% to 50% of its capacity (Figure 1). Such a potential gap is a widespread problem for transition economies, but in Ukraine's case, it is complicated by structural challenges that have lasted since it became an independent state.

Figure 1

The percentage of the country's S&T potential currently being utilised in the area of ICT, DT, AI, robotics and cybersecurity (the percentage of experts' responses)



Source: authors' calculations based on the results of the experts' survey.

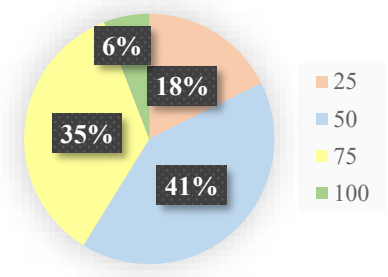
The underutilisation of S&T potential can be explained by the disparity between the supply of S&T and the demand from industry and services. Ukraine possesses a qualified STEM education, a legacy of engineering and materials science schools, and experienced IT personnel, but demand for domestic innovative

products from venture capital, enterprises, and state procurement remains low.

Figure 2 shows that 76% of experts evaluate that Ukrainian S&T potential in the sphere of national security and defence is utilised at 50-75%. The level of utilisation in defence tech is much higher than in the civilian IT sphere and yet hasn't reached the full resource scope. This can be explained by the fact that Ukrainian S&T is more effective in the war economy than in the general one, due to the need to implement breakthrough applied developments that receive quick feedback from the front line. However, general Ukrainian AI research often lacks direct communication with customers due to its outsourced character.

Figure 2

The percentage of the country's S&T potential currently being utilised in the area of national security and defence (the percentage of experts' responses)



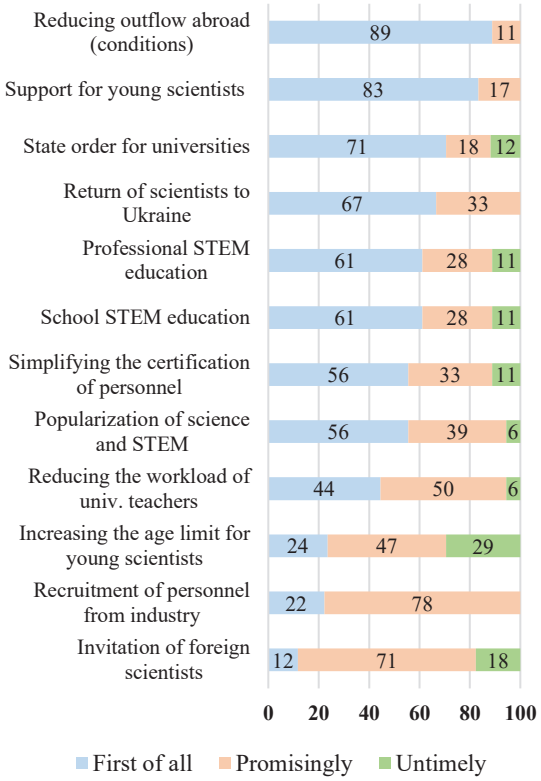
Source: authors' calculations based on the results of the experts' survey.

In the third round, the experts outline the priority measures to restore human S&T resources, focusing on stabilisation rather than external recruitment (Figure 3). Judging from the experts' responses, the first of all measures for stopping the 'brain drain' are 'Reducing outflow abroad' (89%) and 'Support for young scientists' (83%). The secondary tier of priorities involves the state's role in supporting the reproduction of personnel: 'State order for universities' (71%), 'Return of scientists to Ukraine' (67%), 'STEM education' (61%). As promising measures to restore the human resources, experts indicate 'Recruitment from industry' (78% as a promising measure and only 22% as first of all), 'Invitation of foreign scientists' (71% – promising, 12 – first of all)'.

The experts' responses are well-founded because industry salaries are much higher than those in science, and foreign researchers will not want to work in a country that is unsafe due to war. Instead, an alternative solution can be proposed to improve ties and cooperation with the science diaspora, creating joint R&D centres with foreign companies and using cloud-based scientific infrastructure such as AWS and Azure as a temporary measure. An additional recommendation is to integrate military developments into civilian applications, for example, through the dual use of drones in agriculture, demining, and the defence sector, to ensure better returns on resources, their effective use, and long-term economic growth.

Figure 3

Assessment of priority measures to restore human S&T resources (the percentage of experts' responses)



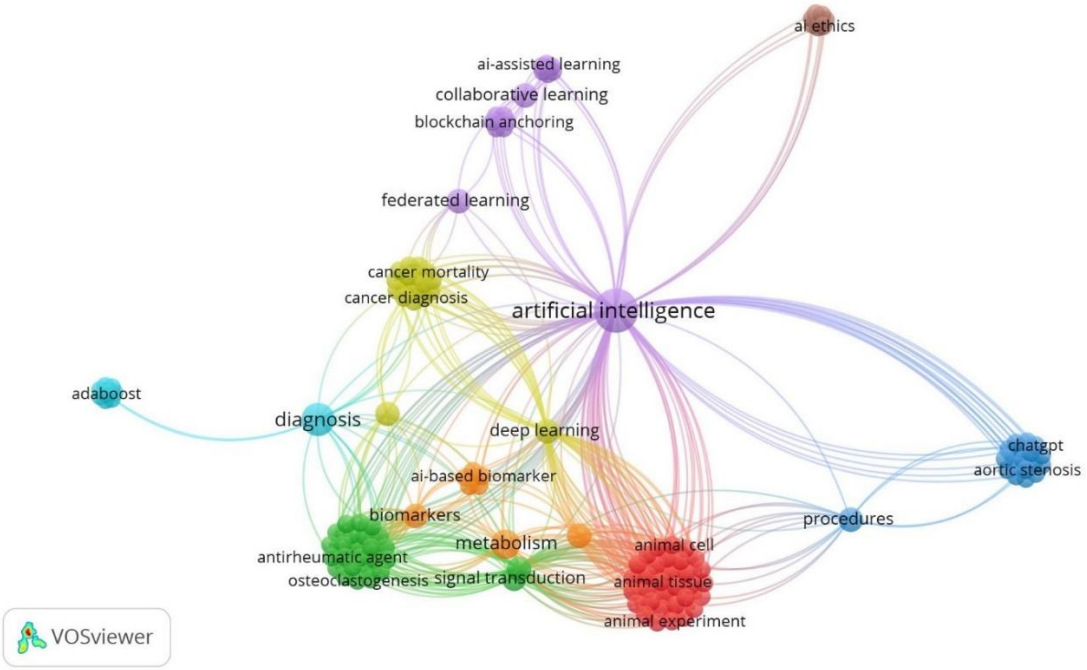
Source: authors' calculations based on the results of the experts' survey.

In order to discover a correspondence between the identified priorities of S&T foresight studies for the next 5-10 years and the publications of Ukrainian researchers, reflecting the most current scientific problems and S&T achievements, we created a keyword map of Ukrainian publications based on the Scopus database using VOSviewer software (Figure 4). The keyword 'artificial intelligence' is the most frequent and prominent item. It maintains its central position and indicates the highest number of links within the network. Taking into consideration that the distance among keywords means the level of their relatedness, we observe that 'deep learning' indicates a strong co-occurrence with AI. The provided network map of keyword co-occurrence reflects the multidisciplinary research activity of Ukrainian S&T, where artificial intelligence is a core catalyst across the learning framework, cancer diagnosis, ethics, and computational support domains. Besides that, there are interdependencies in which 'deep learning' serves 'AI-based biomarker' and 'signal transduction' to discover the properties of neurological and oncology markers. We observe a close interaction between 'AI-based biomarker' and 'deep learning'. Both technologies automate the identification of diseases in genomics,

medical imaging, and help to establish early diagnosis in oncology and neurodegenerative diseases. Next item 'diagnosis' represents the high frequency with 'adaboost' technology, 'cancer diagnosis', to enhance the efficiency of binary classification tasks like medical diagnosis and clinical detection research tasks. Item 'ChatGPT' shows strong relatedness to 'aortic stenosis', enabling the application of LLMs to specialised medical tasks. The general map characterises the rise of 'ChatGPT', 'aortic stenosis', and 'procedures', which are depicted in blue and are situated far from the central place of 'artificial intelligence'. This tendency reflects the compliance with priority №2 of Foresight 2021 'Research-to-innovation breakthrough conversion'. This means Ukrainian researchers are actively integrating new innovative tools, such as ChatGPT and other LLMs, into their clinical workflow. The other systemic keyword 'AI ethics' reflects the interactions aligned with human values, reducing risks and harmful impacts on society while using AI. The scientific network represents the brown cluster 'AI Ethics' that is an emerging branch that mirrors the priority №9 of Foresight 2024, 'Ethical and transparent AI'. Figure 4 describes that AI in healthcare is the largest branch of the scientific network. It shows a strong interdependence between AI and medical diagnostics, such as 'diagnosis' and 'cancer diagnosis'. 'AI-based biomarker' clusters depicted by yellow and light-blue colours. Though we see a compliance between the AI in healthcare research direction and priority №3 in Foresight 2021 'IT in Healthcare' (75% of top relevance).

Figure 4

Network visualisation map of Ukraine's keyword co-occurrence clustering from the database Scopus within all subject areas, 2022-2026



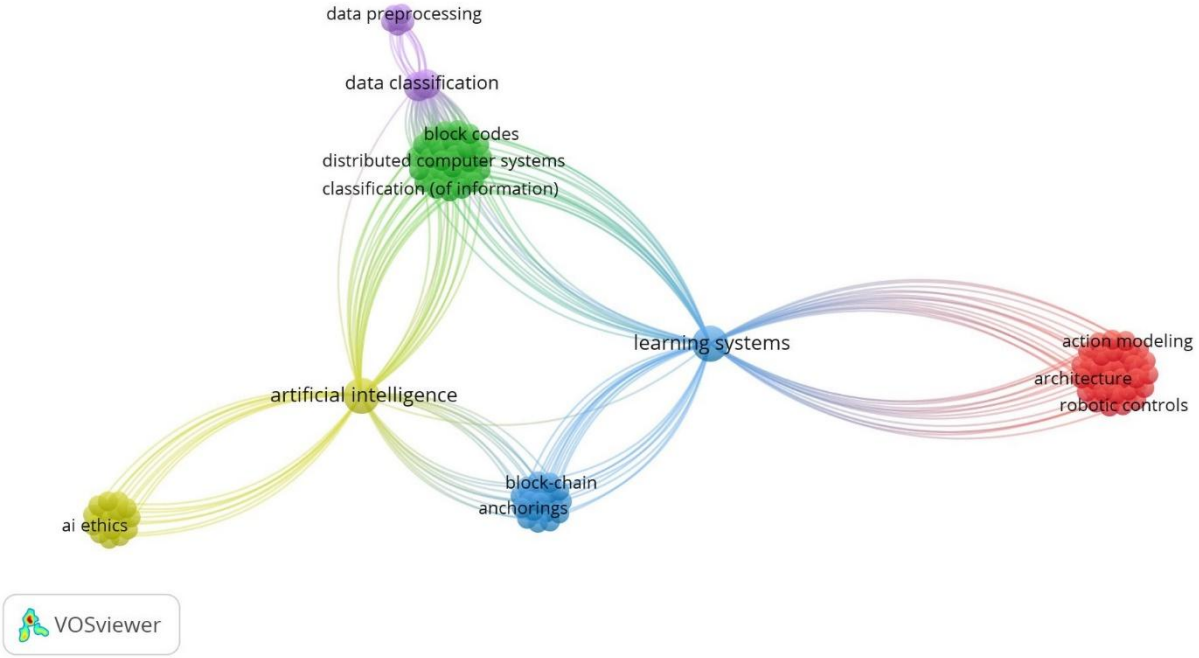
Source: created by the authors using VOSviewer (version 1.6.20) (Leiden University, 2026), retrieved from the database Scopus on 1 March 2026 (Elsevier, 2026).

While 'blockchain anchoring' is depicted in the purple cluster, the exact keyword 'cybersecurity' is absent, or its influence is too low to be noticed. However, the study shows a disconnect between keywords and clusters related to cybersecurity and robotics. This tendency can be explained by the fact that such topics may be more widespread in patent databases because of their engineering focus and may be restricted from publication due to their confidential status. The general map of Ukrainian science describes non-similarities and scientific gaps. Comparing the visualised map with the Foresight priorities 2021 and 2024, we observe noncompliance aspects between the strategic vision of experts and publication output. Figure 4 shows that Ukrainian S&T is focused on implementing AI-based healthcare applications, such as 'cancer mortality' and 'cancer diagnosis' and less focused on machine learning approaches, such as 'federated learning', and on cybersecurity issues, such as 'blockchain anchoring' as a method to ensure data integrity and immutability. The map shows a gap between experts' proposed priorities for a 5-10-year perspective and publication output in Scopus, particularly in robotics, cloud and grid technologies, cloud computing, and cybersecurity and autonomous AI systems.

The Computer Science keyword map visualises the trend where 'artificial intelligence' and 'learning systems' indicate the most frequent occurrence in the Scopus dataset (Figure 5).

Figure 5

Network visualisation map of Ukraine's keyword co-occurrence clustering from the database Scopus within the Computer Science subject area, 2022-2026



Source: created by the authors using VOSviewer (version 1.6.20) (Leiden University, 2026), retrieved from the database Scopus on 1 March 2026 (Elsevier, 2026).

The Computer Science map characterises five scientific clusters in different colours and identifies sub-domains of the Computer Science field. The map reveals the AI and AI ethics of the yellow cluster, where the close connection to 'AI ethics' suggests that Ukrainian Computer Science emphasises the ethical foundations of AI and does not focus solely on coding and engineering tasks. Such a tendency directly aligns with the priority №9 'Ethical and transparent AI' in Foresight 2024, with 35% of the top relevance indicator. However, the keyword 'cybersecurity' is not shown on the map, its components, such as 'distributed systems', 'black codes', 'blockchain' and 'anchorings' that focus on vulnerabilities in networked infrastructure, data protection, and security solutions, are highly visible.

The red automation and robotics cluster is far from the keyword 'artificial intelligence', suggesting that robotics research focuses more on hardware architecture than on purely AI software models. The robotics cluster corresponds to the themes of priorities №2 'Swarm intelligence of self-moving objects', №3 'Cybersecurity of unmanned and robotic systems' and №4 'Cybersecurity of robotic process automation' of the Foresight 2024 with 81%, 76% and 65% of top relevance indicator, respectively. The Computer Science map confirms that Ukrainian Computer Science is pivoting to robotic control solutions, learning systems, components of cybersecurity issues with AI integration, but shows a lag in the areas of quantum computing and autonomous 'strong AI' systems.

The general map shows a strong representation of healthcare and medicine (e.g., cancer diagnosis, AI-based biomarkers, aortic stenosis), while the Computer Science map indicates a shift toward 'learning systems' and components related to cybersecurity ('blockchain', 'anchorings', 'black codes', 'distributed computer systems') and 'robotic controls'. In both maps, AI has the highest total link strength and the most co-occurrences among other keywords. A cybersecurity noncompliance issue has been noted in both scientific maps. Though cybersecurity is a high priority according to the experts' opinions in Foresight 2021 and 2024, this keyword is not presented in either map. The relatedness of AI ethics to 'artificial intelligence' in both maps testifies to Ukrainian S&T's engagement with the moral and legal foundations of AI use, not solely with coding. AI usage plays a central role in Ukrainian S&T research and is responsive to global AI trends.

Conclusions

1. The study defines S&T priorities of the Foresight 2021 that still remain highly relevant due to experts' responses in the conditions of full-scale war: 'Critical infrastructure cybersecurity' (83%), 'Research-to-innovation breakthrough conversion' (82%), 'IT in healthcare' (75%).
2. Experts propose new S&T priorities according to the Foresight 2024 survey: 'Adaptive cybersecurity systems' (88%), 'Swarm intelligence of self-moving objects' (81%), 'Cybersecurity of unmanned and robotic systems' (76%), 'Cybersecurity of robotic process automation' (65%).
3. Two-thirds of experts responded that Ukraine's S&T potential in ICT, DT, AI robotics and

cybersecurity is utilised at only 25% to 50% of its capacity, whereas in the sphere of national security and defence, the level of S&T utilisation is much higher, 50-75%. To increase the utilisation of S&T potential, Ukraine should implement and develop dual-use technologies for civilian and defence applications, and build bridges between industry, science, international R&D centres, and foreign venture capital.

4. The experts outline the first of all S&T policy measures for stopping the 'brain drain': 'Reducing outflow abroad' (89%), 'Support for young scientists' (83%), 'Return of scientists to Ukraine' (67%).

5. The general map and Computer Science map discover a scientific landscape that reflects AI as a core and key structural engine of digital technologies development, while there is a gap between Scopus academic output and experts' strategic sightseeing of S&T in the spheres of robotics, cloud and grid technologies, cloud computing, autonomous AI systems and partly in cybersecurity. There is a clear need to align the existing themes of academic research with the S&T priorities, as experts have indicated, to ensure the state's existence, sovereignty and survival.

6. Ukrainian AI research is deeply involved in healthcare and medical applications, including diagnosis, cancer diagnosis, cancer mortality, AI-based biomarkers, animal experiments, and aortic stenosis, thereby improving diagnostic quality and early-stage treatment of diseases by actively using AI applications to increase productivity in accordance with global trends of S&T development.

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SHEEP MEAT PRODUCTION POTENTIAL IN LATVIA

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Abstract
Sheep farming is a traditional branch of Latvian agriculture, yet in recent years the sector has shown a clear downward trend in production capacity. The aim of this study is to evaluate the development potential of the Latvian sheep meat sector by identifying structural imbalances between domestic production capacity, live animal exports, and the value-added composition of foreign trade. The research applies monographic analysis and synthesis, quantitative statistical analysis, polynomial regression, and the graphical method. Data from the Rural Support Service of Latvia and the Central Statistical Bureau of Latvia for the period 2015–2025 were used. The results show a contraction of the domestic raw material base. Between 2020 and 2024, slaughtered lambs declined by 27.3% and adult sheep by 21.1%. Polynomial trend analysis reveals that shed slaughter declined at a faster relative rate than slaughterhouse volumes, indicating a gradual structural shift towards formal slaughter channels. Live animal exports increased after 2020, further reducing the volume available for domestic processing. Foreign trade analysis reveals a structural asymmetry: exports are dominated by carcasses, half-carcasses, and live animals, whereas imports increasingly consist of more processed and consumer-ready products. This is confirmed by unit prices — import prices remained consistently higher than export prices throughout the observation period. The study concludes that the main development challenge is not only production volume, but also insufficient domestic value-added creation. Long-term sector development requires stronger integration between primary production, slaughtering, processing, and the marketing of higher value-added products.
Key words: sheep meat, sheep farming, value chain, exports, Latvia.

Introduction

The aim of this study is to evaluate the development potential of the Latvian sheep meat sector by identifying structural imbalances between domestic production capacity, live animal exports, and the value-added composition of foreign trade. The global sheep meat market is characterized by a highly asymmetric structure: exports are concentrated, while production and imports are relatively dispersed (Ramírez-López et al., 2020). The study analysed 151 countries between 2003 and 2013, and the authors found that the classification of export markets corresponds to a highly concentrated market. New Zealand and Australia together provide approximately 68% of global sheep meat exports, while production and import markets are significantly less concentrated. Morris (2009) points out that only a relatively small part of the total sheep meat production volume enters international trade. Therefore, for small producing countries, including Latvia, competition on the global market based solely on volume is limited. This means that a sustainable market position is more likely to be sought in niche strategies, quality differentiation, geographical proximity to consumers or higher value-added products.

Ramírez-López et al. (2020) also describe socially oriented sheep farming systems, where production serves to sustain rural communities rather than aggressively expand exports. Participants in such systems are usually characterized by several interrelated features: they are unable to enter export markets, do not create advantages to compete with specialized exporters, and remain uncompetitive.

A similar picture is also presented by UNCTAD (2021) value chain review of Mongolia. Although the institutional context is not directly comparable to Latvia, the identified mechanism is similar: slaughterhouses focus on carcass exports, thus a significant part of value creation is shifted outside the country. In the Latvian context specifically, Trapiņa et al. (2024) examined the economic parameters of intensive lamb fattening, finding that feed costs and growth efficiency indicators — including Kleiber's ratio — are critical determinants of the profitability of primary sheep meat production. This underlines that the economic viability of the domestic raw material base depends not only on market structure, but also on production-level efficiency.

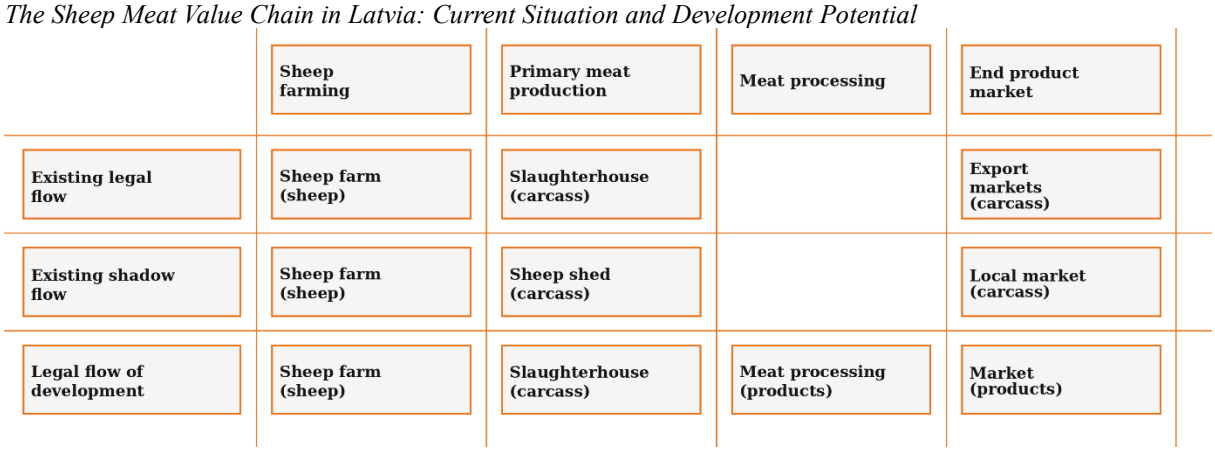
Value chain analysis is the most important tool in this line of research, helping to identify at what stage and why value added may be lost in the Latvian sheep meat sector.

The value chain scheme (Figure 1) illustrates the main theoretical problem of the Latvian sheep sector by distinguishing between the principal stages of value creation and the alternative product flows that may emerge in practice. The first stage, sheep farming, represents primary livestock production, where animals are bred, raised, and prepared for sale. At this point, value is created through animal husbandry, genetics, feeding, and farm management, but this is only the initial stage of the chain. The second stage, primary meat production, refers to slaughtering and the conversion of live animals into carcasses. This stage is essential because it legally transforms agricultural output into meat products suitable for further commercial circulation. However, if slaughterhouses sell carcasses immediately without further processing, only a limited share of potential value added is retained domestically. The third stage, meat processing, includes cutting, deboning, portioning, packaging, and the production of higher value meat products. This stage is particularly important because it generates additional economic value, creates more specialised employment, and strengthens linkages with retail, food services, and

branding. The final stage, the end product market, is where processed meat products are distributed to final consumers through local or export channels and where the highest commercial margins are often realised.

Figure 1

The Sheep Meat Value Chain in Latvia: Current Situation and Development Potential



Source: authors' creation, based on Mandolesi et al., 2020; Toma et al., 2021; UNCTAD, 2021; Franks et al., 2023; Wanyoike et al., 2023.

The scheme further distinguishes between three different flows. The existing legal flow describes the formal market channel in which sheep move from farms to slaughterhouses and then, in many cases, carcasses are exported directly. Although this flow is legal and transparent, it does not necessarily maximise national economic benefit, because a substantial part of further processing and the associated value added takes place outside Latvia. The existing shadow flow refers to an informal or weakly regulated channel in which carcasses may bypass formal slaughter and processing structures and be sold directly on the local market. In this case, part of the product reaches consumers, but value creation remains fragmented, difficult to monitor, and only partly integrated into the formal economy. The legal flow of development represents the strategically desirable model, in which sheep move from farms to slaughterhouses, then to domestic meat processing enterprises, and finally to the market as processed products rather than as raw carcasses. In this development path, a larger share of value added is retained within Latvia through processing, packaging, branding, and final sale.

Thus, the scheme demonstrates that the central theoretical issue is not only whether production takes place legally, but also at which stage the product leaves the national economy. Even within the formal chain, value added may fail to remain in Latvia if slaughterhouses primarily export unprocessed carcasses instead of supplying domestic processors. Consequently, the key development challenge for the sector is to strengthen the downstream stages of the chain, especially meat processing and product marketing, so that economic benefits, employment, and value added are captured domestically rather than transferred abroad.

Mandolesi et al. (2020), studying consumer perceptions in seven EU countries, identify several structural constraints in the European sheep meat market: carcass imbalances, insufficient product variety, high price perceptions and lack of consumer knowledge about preparation. These findings are important in the Latvian context, as they indicate that expanding supply by itself does not guarantee an increase in demand. For the sheep meat market to develop, not only production is needed, but also market development, consumer education and product portfolio development.

Theodoridis et al. (2021), analysing the sheep meat sector across European countries, demonstrate that efficiency gaps between farms are substantial and that the adoption of best practices and innovations at the production stage can significantly improve sector competitiveness. These findings suggest that value chain development requires not only downstream investment in processing, but also efficiency improvements at the primary production level.

Franks et al. (2023) study on the resilience of the private kill slaughterhouse network in the United Kingdom indicates that slaughterhouses can be considered a strategic infrastructure of the food system, as their availability affects both traceability, market access and the ability of farms to operate in the formal chain (Franks et al., 2023).

UNCTAD (2021) value chain analysis and Wanyoike et al. (2023) system dynamic model complement each other, describing the mechanism by which an export strategy without local processing can hinder the development of the sector. Although Wanyoike et al. (2023) analyses the situation in Somaliland, not a European Union member state, the study is useful as an illustration of the mechanism, namely, if the value chain lacks investment, coordination and formal market infrastructure, the growth of the sector becomes unstable.

Transferring this logic to the Latvian context, it can be assumed that slaughterhouses that focus only on the export of raw carcasses function as a narrow link in the

value chain, in which the added value is not significantly increased. Therefore, not only maintaining exports, but also strengthening local processing and product differentiation capabilities may be essential for long-term development.

Materials and Methods

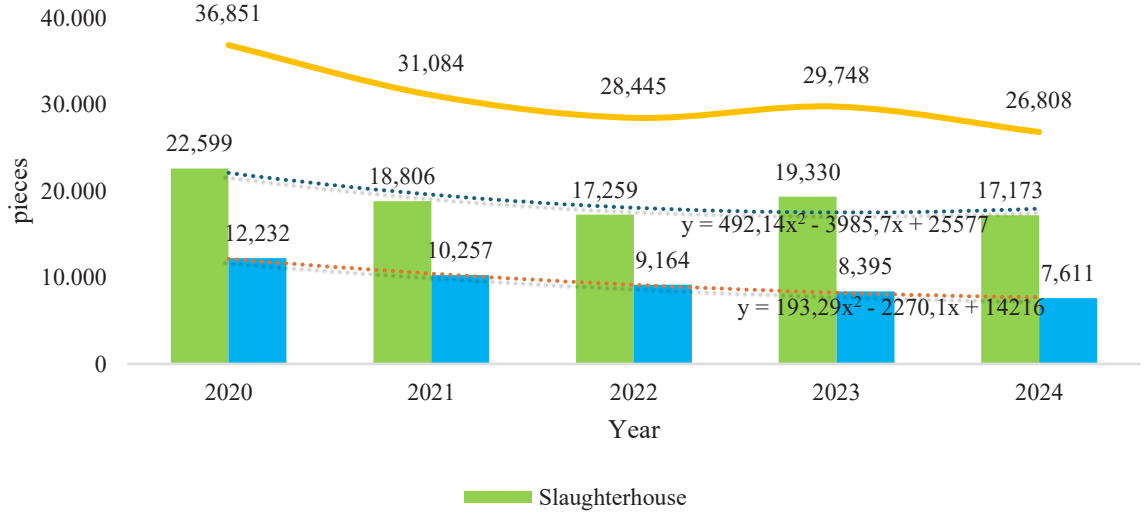
This study applies monographic analysis and synthesis, quantitative analysis of statistical data, and the graphical method. The empirical analysis is based on data obtained from the Rural Support Service of Latvia and the Central Statistical Bureau of Latvia. Data on slaughtered lambs and sheep in Latvia were analysed for the period 2020–2024, while foreign trade data on live animals and sheep meat products were examined for 2015–2025. The analysis includes trade volumes, product structure by CN groups, and unit price dynamics calculated as the ratio between trade value and quantity. The combination of these data sources allows assessment
of raw material availability, trade orientation, and value-added distribution within the Latvian sheep meat value chain.

Results and Discussion

The collected data show that the Latvian sheep sector is simultaneously experiencing a narrowing of the local raw material base and structural differentiation of foreign trade. The information presented in the figures allows us to evaluate the volumes of slaughtered production, the movement of live animals, the foreign trade balance of sheep meat, changes in product structure and price levels, thus allowing us to draw conclusions about the development directions of the sector and the opportunities for creating added value.

Figure 2

Dynamics of the number of slaughtered lambs in Latvia, 2020-2024



Source: authors' creation, based on Rural Support Service of Republic of Latvia, 2025.

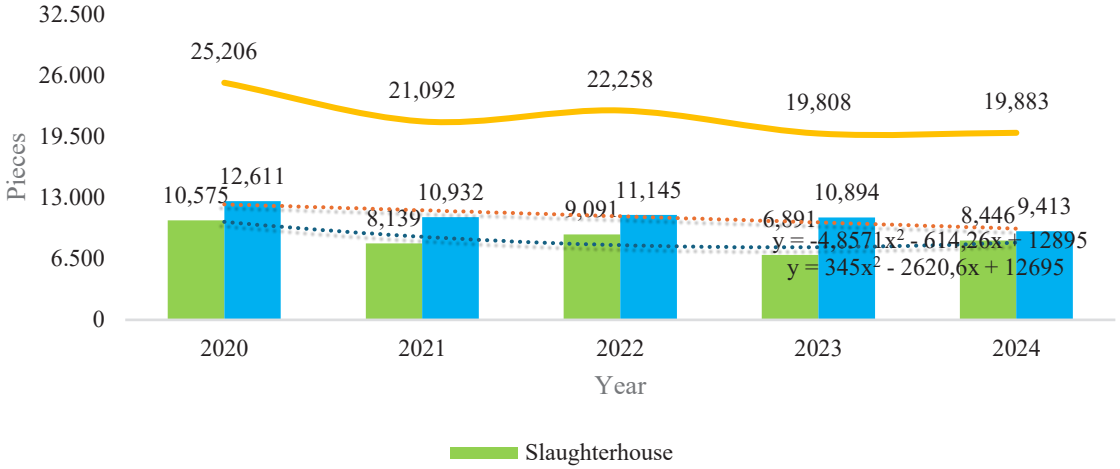
During the period from 2020 to 2024, the total slaughtered volume of lambs in Latvia fell from 36,851 to 26,808 animals, representing a decline of 27.3% (Figure 2). This decrease was recorded in both slaughter channels; however, the proportional contraction was more pronounced in shed slaughter, which fell by 37.8% (from 12,232 to 7,611 animals), compared to 24.0% in slaughterhouses (from 22,599 to 17,173 animals). This is further supported by the polynomial trend equations: the slaughterhouse trend ($y = 492.14x^2 - 3985.7x + 25577$) shows a moderating downward trajectory with deceleration towards the end of the observation period, whereas the shed trend ($y = 193.29x^2 - 2270.1x + 14216$) reflects a steeper and more sustained relative decline. These dynamics suggest a gradual structural shift of remaining slaughter activity towards the formal slaughterhouse channel. At the same time, the overall contraction of the domestic raw material base implies not only lower meat production volumes, but also reduced capacity utilisation in slaughterhouses and processing enterprises, thereby limiting opportunities to achieve economies of scale.

During the period from 2020 to 2024, the total number of slaughtered adult sheep in Latvia decreased from 25,206 to 19,883 animals, representing a decline of 21.1% (Figure 3). This contraction was recorded in both slaughter channels; however, the dynamics differed between them. Slaughterhouse volumes fell from 10,575 to 8,446 animals, a decline of 20.2%, yet followed a volatile trajectory — dropping sharply to a low of 6,891 animals in 2023 before partially recovering in 2024.

This pattern is reflected in the polynomial trend equation ($y = 345x^2 - 2620.6x + 12695$), where the positive quadratic coefficient indicates a U-shaped trajectory with stabilisation towards the end of the period.

Figure 3

Dynamics of the number of slaughtered sheep in Latvia, 2020–2024



Source: authors' creation, based on Rural Support Service of Republic of Latvia, 2025.

Shed slaughter, by contrast, declined more gradually from 12,611 to 9,413 animals, or by 25.4%, following a near-linear path as indicated by the near-zero quadratic coefficient in the trend equation ($y = -4.8571x^2 - 614.26x + 12895$). These dynamics suggest that shed slaughter experienced a steadier structural decline, while slaughterhouse volumes were subject to greater short-term variability, potentially reflecting changes in farm-level marketing decisions or capacity pressures at processing facilities. The overall contraction of the domestic raw material base reduces not only output volumes, but also the operational efficiency of slaughtering and processing enterprises, as lower throughput makes it more difficult to spread fixed costs and achieve economies of scale.

Figure 4

Dynamics of live sheep and lamb export volume in live weight, 2015–2025



Source: authors' creation, based on Central Statistical Bureau, 2026b.

The decrease in local supply to slaughterhouses is further exacerbated by the export of live animals. According to the live weight assessment, export volumes increased significantly after 2020, reaching 201,3 thousand kg in 2023 and 131,9 thousand kg in 2024 (Figure 4). When converted into the approximate number of animals, these volumes correspond to the export of around 2–5 thousand animals per year. This means that part of the livestock that could potentially strengthen the domestic processing resource base is instead directed to foreign markets. As a result, live animal exports reduce the depth of the local value chain, since the animals are not slaughtered, processed, and transformed into higher value-added products in Latvia. In other words, a share of potential value creation is transferred abroad at an early stage of the chain, before domestic slaughtering, meat processing, packaging, branding, and marketing activities can take place.

At the same time, import volumes remain relatively limited and are insufficient to offset the decline in local supply. Import flows are shaped mainly by the mutual circulation of animals within the Baltic States, as well as by individual consignments of live animals intended for further breeding in pedigree and breeding farms. Consequently, the role of imports in the sector is

complementary rather than compensatory, and it does not counterbalance the reduction in domestic raw material availability or the weakening of downstream value chain activities.

Figure 5

Trade balance of sheep meat in Latvia, 2015–2025



Source: authors' creation, based on Central Statistical Bureau, 2026b.

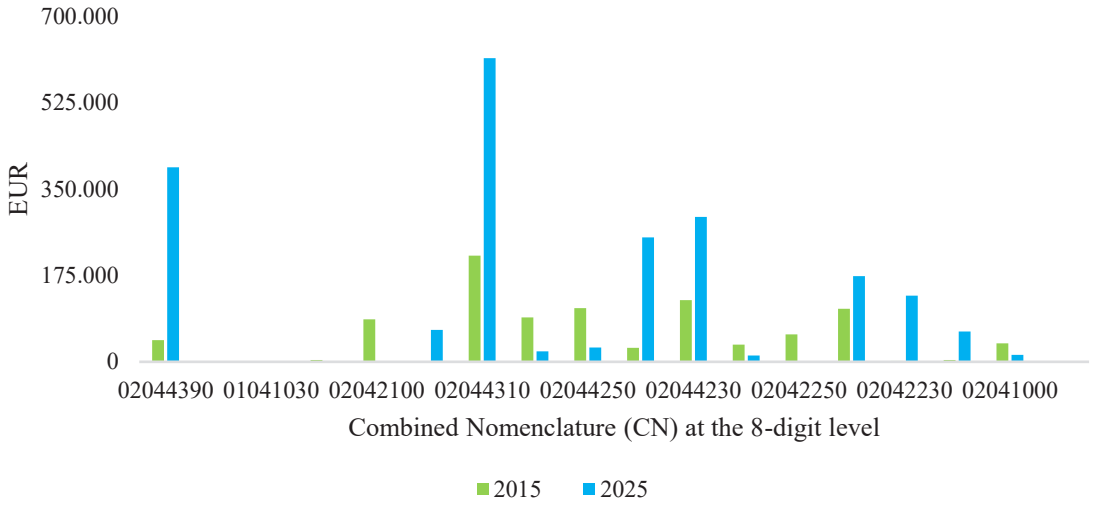
The overall market situation reveals several positive trends. In the period from 2015 to 2025, the foreign trade balance of sheep meat in Latvia remained relatively volatile; however, from 2020 onwards, exports exceeded imports in several periods (Figure 5). Comparing the levels recorded in 2015 and 2025, export volumes increased from 98,8 thousand kg to 204,6 thousand kg, while imports rose from 130,3 thousand kg to 174,6 thousand kg. This indicates that export growth outpaced import growth and suggests an increasing orientation of the sector towards external sales channels. Nevertheless, export growth alone cannot be regarded as a sufficient indicator of sectoral development if the export structure remains concentrated in low-processed product segments. If exports consist mainly of carcasses and other minimally processed products, a substantial share of potential value added is still generated outside Latvia in the later stages of processing, packaging, branding, and final marketing. Therefore, export performance should be assessed not only quantitatively but also structurally, with particular attention to whether export expansion reflects upgrading towards higher value-added products or merely a larger outflow of raw or semi-processed materials. If the latter prevails, export growth may improve trade performance in the short term, but it does not necessarily strengthen domestic value retention, employment, or processing capacity. Consequently, a more meaningful indicator of sectoral development would be an increasing share of processed sheep meat products in total exports rather than export volume growth alone.

The observed import pattern points to a process of market upgrading in the sheep meat sector, in which demand increasingly favours a consumer-oriented product structure rather than low-processed carcass-based trade (Figure 6). The growing importance of boneless meat, divided cuts, and more prepared product categories suggests not only a quantitative expansion of sheep meat demand, but also a qualitative shift in market preferences towards products that are easier to distribute, retail, and consume. This indicates that value in the sector is increasingly created in the downstream stages of the chain, particularly in cutting, deboning, packaging, and product adaptation to final market requirements. However, the fact that these product groups are growing mainly in imports reveals a clear domestic processing gap: the Latvian sheep sector has not yet developed sufficient local capacity to transform primary output into higher value-added products that correspond to changing market demand. As a result, a substantial share of potential value-added retention is lost, because the economic benefits associated with deeper processing are captured outside Latvia. From a sectoral development perspective, this implies that future competitiveness will depend not only on increasing production volumes, but also on strengthening domestic slaughtering and processing linkages, expanding the range of processed sheep meat products, and aligning local supply with the evolving structure of demand.

In the export structure, in contrast to imports, products with a lower degree of processing continue to dominate. In 2025, the largest export values were recorded for other fresh or chilled sheep carcasses and half-carcasses (937,1 thousand EUR), fresh or chilled lamb carcasses and half-carcasses (356,9 thousand EUR), and other live lambs up to one year of age (307,5 thousand EUR) (Figure 7).

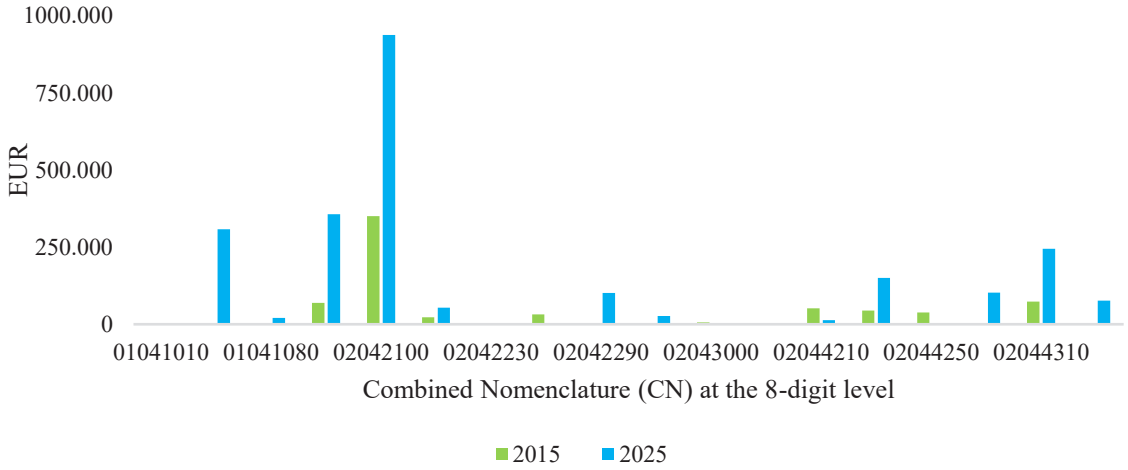
Although exports of individual cuts and boneless meat have also increased, the overall composition of exports indicates that the Latvian sheep sector remains concentrated in the earlier stages of the value chain.

Figure 6
Sheep meat import structure by product group in value terms, 2015 and 2025



Source: authors' creation, based on Central Statistical Bureau, 2026a
(02044390, Other frozen boneless sheep meat; 01041080, Other live sheep, per head; 01041030, Other live lambs up to one year old, per head; 02044100, Other frozen sheep carcasses and half-carcasses; 02042100, Other fresh or chilled sheep carcasses and half-carcasses; 02042290, Other fresh or chilled bone-in cuts of sheep meat; 02044310, Frozen boneless lamb meat; 02044210, Frozen short forequarters of sheep carcasses; 02044250, Frozen sheep legs; 02044290, Frozen bone-in cuts of sheep meat, not elsewhere specified; 02044230, Frozen sheep loins and/or hindquarters; 02043000, Frozen lamb carcasses and half-carcasses; 02042250, Fresh or chilled sheep legs; 02042210, Fresh or chilled short forequarters of sheep carcasses; 02042230, Fresh or chilled sheep loins and/or hindquarters; 02042300, Fresh or chilled boneless cuts of sheep meat; 02041000, Fresh or chilled lamb carcasses and half-carcasses; 01041010, Purebred breeding sheep, per head).

Figure 7
Sheep meat export structure by product group in value terms, 2015 and 2025



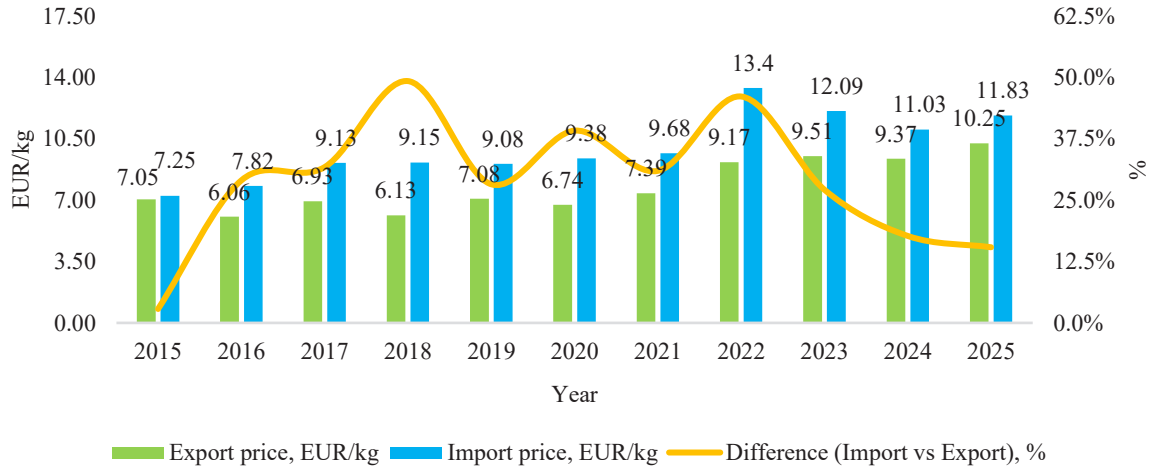
Source: authors' creation, based on Central Statistical Bureau, 2026a:
(01041010, Purebred breeding sheep, per head; 01041030, Other live lambs up to one year old, per head; 01041080, Other live sheep, per head; 02041000, Fresh or chilled lamb carcasses and half-carcasses; 02042100, Other fresh or chilled sheep carcasses and half-carcasses; 02042210, Fresh or chilled short forequarters of sheep carcasses; 02042230, Fresh or chilled sheep loins and/or hindquarters; 02042250, Fresh or chilled sheep legs; 02042290, Other fresh or chilled bone-in cuts of sheep meat; 02042300, Fresh or chilled boneless cuts of sheep meat; 02043000, Frozen lamb carcasses and half-carcasses; 02044100, Other frozen sheep carcasses and half-carcasses; 02044210, Frozen short forequarters of sheep carcasses; 02044230, Frozen sheep loins and/or hindquarters; 02044250, Frozen sheep legs; 02044290, Frozen bone-in cuts of sheep meat, not elsewhere specified; 02044310, Frozen boneless lamb meat; 02044390, Other frozen boneless sheep meat).

This suggests that the sector is still oriented primarily towards the sale of live animals and minimally processed products rather than towards the export of higher value-added meat products. When the export structure is compared with the import structure, a clear asymmetry becomes visible: products that are more processed and better prepared for final consumption are imported relatively more often, whereas exports

are dominated by carcasses, half-carcasses, and live animals. Such a pattern indicates that a substantial share of value added is created outside Latvia, in the downstream stages of cutting, deboning, packaging, product preparation, and final marketing. Therefore, while export growth may signal market activity, it does not automatically imply value chain upgrading, as long as the export basket remains concentrated in low-processed product segments.

Figure 8

Unit price dynamics of sheep meat imports and exports, 2015–2025



Source: authors' creation, based on Central Statistical Bureau, 2026b.

The price analysis complements the structural trends identified above. Comparing the levels reflected in the Figure for 2015 and 2025, the export unit price increased from 7.05 to 10.25 EUR/kg, or by 45.4%, while the import unit price increased from 7.25 to 11.83 EUR/kg, or by 63.2% (Figure 8). Throughout the observation period, import prices remain higher than export prices, although the difference becomes smaller towards the end of the period. This confirms that imported products have, on average, a higher degree of processing and added value than the products dominating export flows.

Conclusions

1. The Latvian sheep sector demonstrates a consistent contraction of the domestic raw material base. The total number of slaughtered lambs declined by 27.3% between 2020 and 2024 (from 36,851 to 26,808 animals), while adult sheep slaughter volumes decreased by 21.1% (from 25,206 to 19,883 animals). This downward trend limits the development capacity of both primary production and meat processing stages of the value chain.
2. The export of live animals further constrains the availability of raw materials for domestic slaughterhouses. After 2020, live animal export volumes increased significantly, reaching 201,280 kg in 2023, which is equivalent to approximately 2,000–5,000 animals annually. Since import flows serve primarily complementary or breeding functions rather than compensating for the decline in domestic supply, the net effect is a reduction in the resource base available to Latvian processing enterprises.
3. A structural asymmetry exists between the export and import product mix of sheep meat in Latvia, reflecting a value-added gap. In 2025, exports were dominated by fresh or chilled sheep carcasses and half-carcasses (937,1 thousand EUR) and live lambs (307,5 thousand EUR), while imports were led by frozen boneless lamb (614,7 thousand EUR) and other ready-to-use cuts. This asymmetry is further confirmed by the consistently higher unit prices of imports compared to exports – 11.83 EUR/kg versus 10.25 EUR/kg in 2025 – indicating that Latvia exports lower-processed goods and imports higher value-added products.
4. The long-term development of the Latvian sheep meat sector depends not only on production growth, but also on deeper domestic value chain integration. Strengthening slaughtering, meat processing, and the production of higher value-added products would allow a larger share of value added to remain in Latvia.

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TRENDS IN THE POLISH AGRICULTURAL LAND MARKET

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Abstract
Agricultural land is viewed by the public in many countries as a resource of particular importance; for this reason, agricultural land ownership and transfers are closely monitored. The article aims to identify key trends in Poland's agricultural land market over 2015-2024. It examines trends in agricultural land transactions by volume, value and area, as well as agricultural land prices. Empirical analyses were based on data from Statistics Poland (GUS). The basic research method involves the descriptive statistical analysis of GUS data on agricultural land turnover and prices. The study found a significant decrease in agricultural land turnover in Poland in 2016, driven by the introduction of higher legal barriers to market access. Low levels of activity on the agricultural land market persisted until the COVID-19 pandemic outbreak. In 2020 and 2021, there was a significant increase in transaction numbers, value and land area sold. Despite a slight decline in market activity in subsequent years, transaction volume and values remained higher than before the pandemic. Agricultural land prices increased systematically throughout the study period, albeit at varying rates. The highest growth rates were observed during the pandemic. Interestingly, in the examined period, lower-quality land saw higher price growth than higher-quality land. In effect, the difference in land prices according to quality was gradually decreasing. Therefore, it can be said that the price of agricultural land is becoming increasingly independent of its quality, and that the importance of other factors, such as speculation or changing lifestyle patterns, is growing.
Keywords: agricultural land, rural areas, agricultural land market, agricultural land prices, COVID-19 pandemic.

Introduction

In many countries, agricultural land is regarded as an asset of particular importance. This is due to several factors. Historically, land ownership has been the foundation of socio-economic status of individuals. Land ownership was associated with the rights held by the owner and the income derived from it (Aston & Philpin, 1987; Grabski, 2004). As Abubakar et al. (2024) have pointed out, land ownership continues to play a fundamental role in shaping social structures and economic opportunities, particularly in developing regions. According to the World Bank (World, 2026), in 2023, in 40 countries worldwide, the share of agriculture in male employment exceeded 40%, so for roughly this proportion of the population, land ownership – or the lack thereof – is crucial. Despite the highly developed global trade in food products, in many countries, land ownership by citizens is considered a fundamental factor in ensuring national food security.

Transfers of agricultural land leading to changes in ownership may take place through market or non-market channels (inheritance, gifts, adverse possession). The significance of these two forms varies from country to country. It depends on several factors, such as legislation, tradition, demographics, and the economy. For example, research by Marks-Bielska et al. (2017) shows that in Poland, non-market (family) transfers of agricultural land play an important role, as over two-thirds of respondents received a farm from their parents or parents-in-law, and a further 13% inherited it from close relatives. According to Karwat-Woźniak et al. (2024), the share of non-market agricultural land transactions in Poland in total transactions from 2015 to 2023 amounted to 50%.

Agricultural land is a fundamental factor of agricultural production. The transfer of agricultural land serves several functions in agriculture. These include:

- counteracting the decline in land productivity,
- ensuring the continuity of farms through generational succession,
- improving the relationship between the basic factors of production (land, labour and capital),
- stimulating structural changes (Chadrzynski et al., 2020; Marks-Bielska, 2010).

Land is a factor of production, and demand for it, just like for other factors of production, stems from the demand for the outputs of these factors used in production. In the case of agricultural land, demand stems from the demand for agricultural products. Changes in demand and the associated changes in farm profitability may therefore affect the land market. However, it is now emphasised that agriculture not only produces agricultural products but also provides various public goods. The list of these is quite extensive. It includes environmental goods (biodiversity, water balance, carbon sequestration and storage) as well as socio-cultural goods (agricultural landscape, social and cultural vitality of rural areas). The provision of these goods forms the basis for state intervention and justifies the income received by farmers under the Common Agricultural Policy (Cooper et al., 2009; Danilowska, 2015; Vanni, 2014). Demand for land may also stem from regulations governing agricultural production. According to a study by SCSI (2023), in Ireland, changes to environmental policy aimed at protecting water quality may prompt some farmers to seek additional land. Agricultural land has also become an attractive target for capital investment. Numerous platforms, such as The Land Geek, Estateguru, Insoil Finance and other platforms, encourage investment in agricultural land, highlighting the steady rise in its prices, the fact that it

can serve as strong collateral due to its non-replicability (land area is limited), and as a portfolio diversifier (spreads persons' investment risks).
The supply of agricultural land is limited and, due to competition from numerous non-agricultural uses, is steadily decreasing. Although Mandryk et al. (2015) note that there are still land reserves in some parts of the world that can be converted into agricultural land, the market supply of land is generally severely limited because land cannot be transferred to regions with the greatest demand. This influences the perception of agricultural land as an increasingly scarce and therefore increasingly valuable resource. The debate on the need to protect agricultural land has been ongoing for decades (Pasour, 1982; Wilkin, 2018). However, at a given place and time, the supply of land depends on a combination of factors: social, demographic, and economic. In Ireland, executor/probate sales are the most active type of farmland sale. A total of 36% of respondents reported that probate sales are very active in their location. Farmers who are no longer interested in agricultural activity or have retired are also an important source (SCSI, 2023). In the case of Poland, Sikorska (2013) indicates that the primary factor influencing land sales is the exodus of the population from agriculture and their taking up employment in other professions.
This article aims to identify key trends in the Polish agricultural land market. In the paper, some questions were raised: (i) What were the trends in the number, value, and area of agricultural land transactions in Poland? (ii) What was the role of the agricultural land segment in the land market in rural areas in Poland, and how has it changed? (iii) What were the trends in agricultural land prices? (iv) What were the differentiations between the prices of various types of agricultural land?

Materials and Methods

The period under review spans 2015–2024. This ten-year research period has enabled the identification of trends in the trading of agricultural land in Poland.
The main source of data for the empirical analysis was the annual publications of the Central Statistical Office (GUS) on property sales.
This article uses the English terminology employed by the Central Statistical Office (GUS) to describe various types of real estate.
The general classification of real estate used by GUS comprises residential premises (residential and non-residential), built-up land properties, and undeveloped properties.
The term 'undeveloped land/properties' refers to land on which there are no buildings or other structures.
According to GUS, agricultural land belongs to the group of undeveloped properties (land), which includes: undeveloped agricultural properties (agricultural land), properties for development, and undeveloped forest properties.
The stock of agricultural land comprises arable land (land under crops and fallow land), permanent crops (including orchards), kitchen gardens, permanent grassland, permanent pasture and other land (agricultural land that is not in use and not maintained in good agricultural condition). The article focuses mainly on transactions involving agricultural land located in rural areas.
Three measures were used to assess developments in the agricultural land market: the number of transactions, the transaction value and the area of agricultural land sold/purchased. The transaction values were expressed in nominal terms.
The basic research method involves the descriptive and statistical analysis of GUS data on agricultural land turnover and prices. To examine price differentiation, the variation coefficient was used.
The agricultural land price analysis was carried out at nominal and constant prices (2015 as the base year). The constant-price calculation was based on price indices for sold agricultural products.

Results and Discussion

In 2015, the stock of agricultural land in Poland amounted to 14.55 million ha (Table 1). During the period under review, it increased slightly by approximately 1% and, in 2023, stood at 14.72 million hectares. Approximately 99% of agricultural land was in good agricultural condition.

Table 1
Area of agricultural land in Poland by type of land (thousands of ha)

Specification	2015	2018	2020	2023
Agricultural land area (ha)	14.545,000	14.669,000	14.953,000	14.723,000
-sown area	10.753,000	10.829,000	10.962,000	11.081,000
- permanent crops	391,000	352,000	380,000	344,000
- permanent meadows	2.658,000	2.754,000	2.788,000	2.670,000
- permanent pastures	434,000	395,000	415,000	344,000
-kitchen gardens	27,000	28,000	22,000	20,000
-others	281,000	310,000	386,000	264,000

Source: GUS (2026, February 25).

In 2015, when looking at agricultural land use, the largest share – approximately 74% – was accounted for by sown area. Meadows ranked second with a share of 18.3%, and pastures ranked third with a share of 3%. The share of permanent crops was 2.7%. The share of kitchen gardens was small, but their contribution to

rural households' fruit and vegetable supply was substantial. Over the years 2015-2023, the structure changed slightly. The sown area increased by 328 thousand ha (by 3%), which was reflected in the increase in its share in total area by 1.4 percentage points. The area of permanent meadows remained nearly the same, while the area of permanent pastures decreased noticeably: in absolute terms by 90 thousand ha and in relative terms by 20%. In both cases, the share in total agricultural land area decreased by 0.2 and 0.7 percentage points, respectively. The area of permanent crops also decreased by 47 thousand ha (12%), reflected in a 0.4 percentage-point drop in the share. The spectacular slide occurred in the kitchen gardens, which amounted to 7 thousand ha (26%). As the share of this type of land was very small, the decrease in total share was not big either.

Throughout the entire period under review, approximately 91% of agricultural land was owned by private farms carried out by individuals. The remaining land belonged to the state (State Treasury land). A state agency administers state-owned land. In 2016, a ban on the sale of land from the State Treasury's land stock was introduced (ISAP 2016, April 14), so from that year onwards, the supply of land on the market has come solely from private entities.

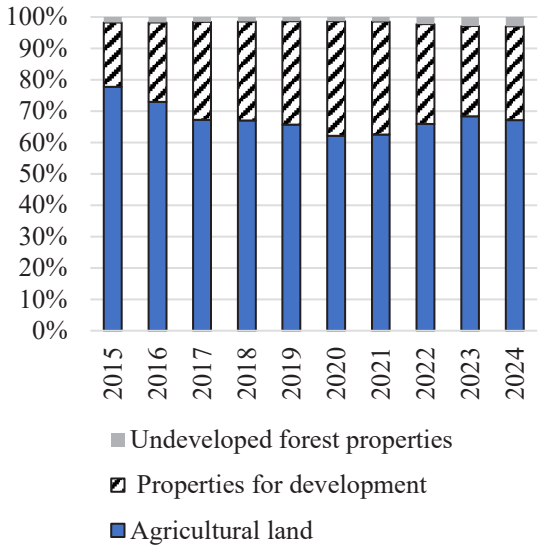
Access to agricultural land in Poland (the right to purchase it) is regulated by the state. Poland is not unique in this respect, as regulations governing access to the agricultural land market exist in many countries. Vranken et al. (2021) identify five categories of regulation, three of which relate to purchase/sale transactions. These are: measures to protect the farmland owner, measures to prevent fragmentation, and other measures targeting agricultural land markets. Around 2020, measures to protect farmland owners included restrictions on the nationality of buyers for legal entities (Hungary, Poland), restrictions on the residence of buyers, maximum sale prices, pre-emptive rights for neighboring farmers, and limits on the maximum area that could be transacted or owned. Measures to prevent land fragmentation include: a lower minimum plot size and a pre-emptive right for co-owners. Other measures regulating the land market include: a requirement to publish sale offers; procedures for the sale of public land; pre-emptive rights for state or public bodies; pre-emptive rights for family members; and a moratorium on transferring ownership after acquisition or on the sale of public land. The analysis shows that access to the agricultural land market in Poland and Hungary is the most restrictive among the 23 European Union countries examined. Of the 17 potential measures across the three categories mentioned, 12 restrictions were found in both Poland and Hungary. At the other end of the spectrum was Ireland, where there were no restrictions at all.

Access to the agricultural land market in Poland became significantly more restricted in 2016. That year, the Act on the suspension of the supply of agricultural land from the state reserve of agricultural real estate and on other changes (ISAP 2016, April 14) had a radical impact on the agricultural land market. The Act not only suspended the supply of agricultural land from the state reserve of agricultural real estate but also led to a significant change in the Act, shaping the agricultural system in Poland (ISAP 2016, July 6). Both Acts completely transformed access to the agricultural land market. Under them, only farmers who meet certain requirements may purchase agricultural land. The requirements for farmers wishing to purchase agricultural land are very strict. A purchaser could be a farmer (a natural person, not a legal entity) who operates on less than 300 hectares of agricultural land, holds agricultural qualifications, has lived for at least five years in the municipality where the land being purchased is located, and has personally carried out agricultural activities there for at least five years. The purchase of land could not result in the farmer's total area of agricultural land exceeding 300 hectares. The purchaser was required to carry out agricultural activities for 10 years following the purchase and was not permitted to sell the property before the end of that period. Plots of up to 0.3 hectares were exempt from the provisions of the Act. The restrictions also applied to pre-emptive rights and prices. In 2019, the regulations were slightly liberalised (ISAP, 2019, April 26). Entities other than individual farmers were permitted to purchase land with an area of less than 1 ha (though several restrictions regarding the purchaser's characteristics and the right of first refusal remained in place). A further liberalisation was introduced in 2023 and concerned the exclusion of the application of the provisions on the agricultural system to plots larger than 0.3 ha that contained less than 0.3 ha of agricultural land, as well as the broadening of the concept of a 'close person' (ISAP, 2023, July 13). It should be noted that these liberalisation measures clarified the provisions of the Act on the Shaping of the Agricultural System, but did not significantly reduce systemic barriers (Klusek et al., 2025).

As noted above, the agricultural land market is a segment of the undeveloped land market. The significance of this market for the undeveloped land market in rural areas is illustrated in Figures 1 and 2.

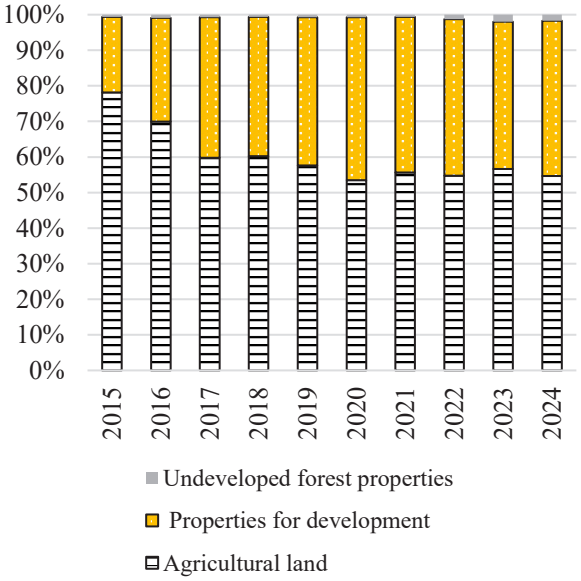
The data analysis shows that the agricultural land market dominates the segment. Its share in transaction numbers in the first year of the analysis reached 78%. However, in subsequent years, this sector's market share declined to around 61% in 2020. In the following years, the trend reversed and the share rose to meet the 2017 level. Similar trends were observed in the value structure. In the first year of the analysis, the share of agricultural land sale value in total segment sale value was 78%, similar to the share in transaction numbers. In the following years, this share declined, though more pronouncedly than the share of transaction numbers. In 2021, the share increased, and in subsequent years it stabilised at around 55%.

Figure 1
Structure of the number of undeveloped land properties sold in rural areas by property type in 2015-2024



Source: Own study based on GUS (2026, March 3).

Figure 2
Structure of the value of undeveloped land properties sold in rural areas by property type in 2015-2024

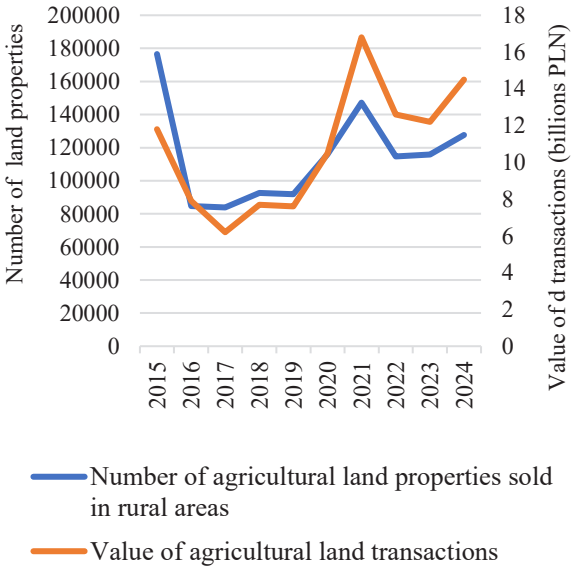


Source: Own study based on GUS (2026, March 3).

Perhaps this phenomenon indirectly points to a process of gradual diversification of activities and functions in rural areas. Agricultural activity, which is fundamental to rural areas, is becoming less significant to their functioning. Due to the development of technical infrastructure, including transport networks, and the possibility of remote working, rural areas are increasingly seen as a convenient place to live (either permanently or as a second home) and to run a business.

Figure 3 illustrates the shock to the agricultural land market caused by the introduction of the aforementioned restrictions on access to this resource. In 2016, the number of undeveloped agricultural properties sold fell by over 50% (by around 90,000). In terms of transaction value, the decline was slightly smaller, around 33%. In 2017, the first full year the market access restrictions were in force, the decline deepened, particularly in sales value. The following two years saw adjustments to the new situation. These resulted in an increase of around 10% in the number and value of plots sold in 2018, followed by a slight decline in 2019. During the pandemic, the number and value of transactions rocketed. It stemmed from the town's inhabitants' interest in having a spare place in rural areas. As the trends are consistent with the trend in the area of sold agricultural land (presented in Figure 4), the explanation of the phenomenon is similar to that given for the area of sold agricultural land in rural areas.

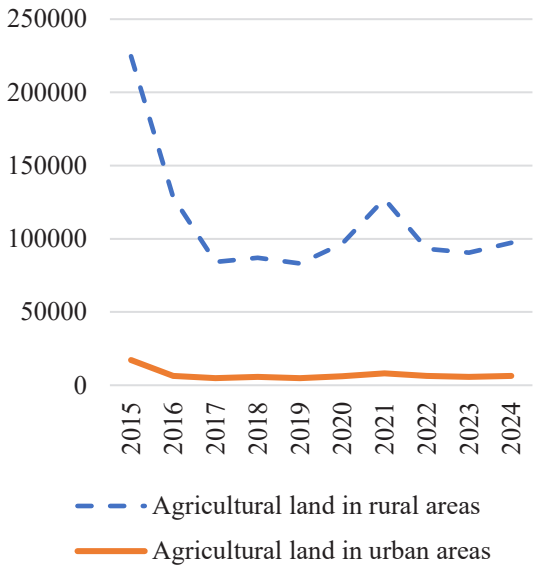
Figure 3
Number and value of agricultural land properties sold in rural areas in 2015-2024



Source: Own study based on GUS (2026, March 3).

As shown in Figure 4, sales of agricultural land in 2015 amounted to approximately 240,000 ha. The transactions mainly involved land in rural areas, accounting for around 93% of total sales. In 2016, the total area sold fell by around 107,000 ha, of which 96,000 ha (57%) were in rural areas, and 11,000 ha (63%) were in urban areas. In 2017, the decline deepened. The area of agricultural land sold in 2017 accounted for just 37% of the area sold in 2015, including 38% in rural areas and only 28% in urbanised areas. Over the following two years, it stabilised at the 2017 level.

Figure 4
Area of agricultural land properties sold in 2015-2024 by location (ha)

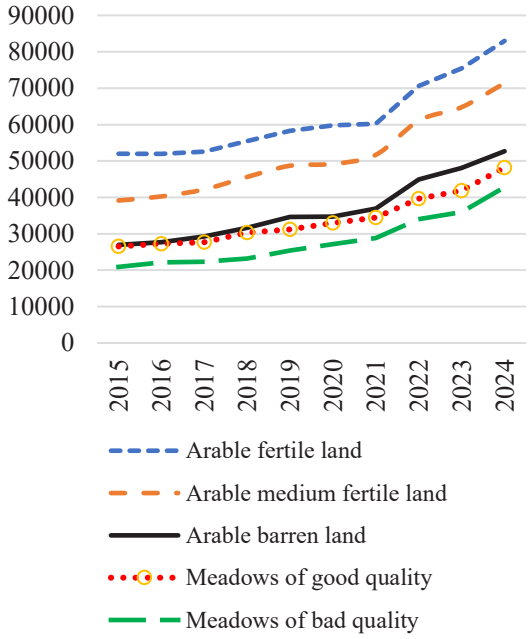


Source: Own study based on GUS (2026, March 3).

A significant change was observed in both locations during the first year of the COVID-19 pandemic. In 2020, compared to 2019, the area of land sold increased by approximately 13,000 ha (17%). In 2021, the increase was even greater, at over 31%. This growth over the two years can be attributed to two factors: the easing of barriers to accessing the agricultural land market and the COVID-19 pandemic. As the easing of barriers was not significant, this trend points to the pandemic's dominant role. The increase in the volume and value of agricultural property transactions stemmed from the public's desire to mitigate the hardships of the lockdown, the duration of which was difficult to predict; the introduction of both remote working and remote learning enabled or facilitated decisions to acquire property offering greater comfort during the current lockdown and any potential future lockdowns. The role of the pandemic in the agricultural land market is also evident in the fact that, when restrictions were lifted or significantly eased in 2022, the area of land sold fell, and this decline continued into 2023. In 2024, a fairly significant increase of around 8% was observed, which in turn can be explained by the aforementioned further relaxation of regulations on the trading of agricultural land (which came into force in 2024).

The introduction in 2016 of very significant restrictions on access to agricultural land brought about a standstill in changes to the area structure of agricultural holdings in Poland. This is evidenced, first, by the fact that over the 10 years under review, a total of 1.185 million hectares of agricultural land were sold, accounting for only 8% of Poland's agricultural land stock in 2015. Secondly, although the transactions concern agricultural land, a significant proportion are likely to be conducted by individuals who are not interested in farming and can purchase a plot of less than 0.3 ha. The average size of the properties sold was small by farm standards. In 2015, it stood at 1.3 ha; in 2016, at 1.5 ha; but from 2017 onwards, it has steadily decreased, reaching 0.76 ha in 2024. Of course, some transactions involved larger areas, but a few would have significantly increased the size of existing farms or formed the basis for new ones. The price of agricultural land was influenced by its quality (Figure 5).

Figure 5
Nominal prices of a particular kind of agricultural land property sold in 2015-2024



Source: Own study based on GUS (2026, February 25) and GUS (2026, February 28).

This is to be expected when it comes to agricultural land prices. The price differences between arable land categories and between grassland categories were significant. In 2015, prices for good-quality arable land were approximately 93% higher than those for poor-quality land, and prices for good-quality grassland were 27% higher than those for lower-quality grassland.

The creation of barriers to access to the agricultural land market, combined with demand-side factors, led to steady increases in agricultural land prices across land types and qualities. Prices for poor-quality arable land and lower-quality grassland rose the most. This led to a narrowing of the price gap between land of different qualities. In 2024, the price spread between the best and worst quality arable land fell to 58%, and to 13% in the case of grassland.

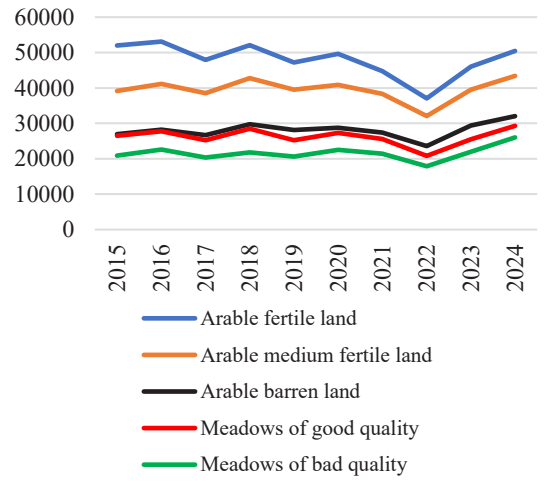
Over 10 years of analysis, the price differentiation declined noticeably (Table 2). The coefficient of variation of agricultural land prices decreased by 9.3 percentage points. This indicates a growing shortage of land supply and the increasing importance of demand factors unrelated to agricultural activity, such as speculation and changing lifestyle patterns.

Table 2
Coefficient of variation of agricultural land prices in 2015-2024

Year	2015	2017	2019	2021	2024
V(x)	37.7%	35.4%	34.0%	30.7%	28.4%

Source: Own calculation based on GUS (2026, February 25) and GUS (2026, February 28).

Figure 6
Prices of a particular kind of agricultural land property sold in 2015-2024 in 2015 prices[1]



[1]*Price index for agricultural products sold was used.*
Source: Own study based on GUS. (2026b, March 3) and GUS, (2026, February 28).

Until 2022, the growth rate of nominal agricultural land prices was modest (Figure 5). In 2022, the growth rate rose sharply. In the following years, it remained at a fairly high level, and by 2024, nominal prices were distinctly higher than in 2015- for example, the prices of low-quality arable land and meadows had doubled. However, this increase was largely due to inflation.
If one takes into account the price index for agricultural products sold, which rose noticeably during the pandemic (141.4 in 2022 compared to 2021), it can be concluded that over the 10 years under review, the real price of top-quality arable land fell slightly, whilst the real prices of all other types of arable land and grassland rose modestly (Figure 6).

Conclusions

1. The agricultural land market constitutes a significant segment of the undeveloped property market in rural areas. However, its importance is declining as other segments develop rapidly.
2. The study revealed a significant drop in agricultural land transactions in Poland in 2016, caused by the introduction of high legal barriers to market access. Low levels of activity in the agricultural land market persisted until the COVID-19 pandemic. In 2020 and 2021, there was a significant increase in the number and value of transactions, as well as in the area of land sold. Despite a slight decline in market activity in subsequent years, the number of transactions and their value remained higher than before the pandemic, but the area of land sold returned to the pre-pandemic level.
3. Agricultural land prices in nominal terms rose steadily throughout the study period, albeit at varying rates. The highest growth rates were recorded from 2021 onwards. From the farmers' perspective, prices in constant terms (prices 2015=100) were quite stable until the pandemic, when they began to decline. Since 2022, that trend has reversed. As a result, in 2024, the price of arable fertile land was lower than in 2015, while other types of land prices were a little higher.
4. Prices for arable land were higher than those for grassland. Prices of lower-quality land rose faster than those of higher-quality land. As a result, the difference in land prices depending on quality gradually narrowed. This indicates a growing shortage of land supply and the increasing importance of demand factors unrelated to agricultural activity, such as speculation and changing lifestyle patterns.

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VEGANISM IN THE CONTEXT OF SUSTAINABLE FOOD SYSTEMS: GLOBAL TRENDS AND THE LATVIAN CASE

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Abstract
This paper examines veganism as a potential driver of sustainable food systems through global statistical trends and empirical evidence from Latvia. It addresses how shifts toward plant-based diets translate into actual consumption behavior and sustainability outcomes at the national level. The study aims to evaluate the role of veganism in sustainable food systems by analysing global data and assessing dietary preferences among Latvian residents. The methodology combines quantitative analysis of international and local data on food consumption, environmental impacts, and dietary trends with a structured survey of Latvian residents. The survey explores dietary preferences, motivations, and barriers to adopting vegan diets. Descriptive and comparative statistical methods are applied to identify relationships between dietary choices and sustainability-related factors, including resource awareness and consumption patterns. The results indicate a steady global increase in vegan and plant-based diets, associated with lower environmental impact. However, in Latvia, veganism remains relatively uncommon. Survey findings show that diets are still dominated by animal-based products, while health and environmental concerns play a secondary role in influencing change. Key barriers include price sensitivity, cultural habits, and limited product availability. The study concludes that veganism currently has a limited impact on the sustainability of Latvia's food system. Despite global momentum toward plant-based diets as a strategy to reduce environmental pressure, adoption in Latvia remains constrained by cultural and economic factors.
Keywords: veganism, sustainable food systems, dietary preferences.

Introduction

The growing urgency of climate change mitigation has intensified the search for effective strategies to reduce greenhouse gas (GHG) emissions across food systems. Among these, dietary shifts toward plant-based consumption patterns have emerged as a particularly impactful approach. Veganism, alongside the development and increasing availability of vegan animal product analogues, offers a viable pathway to significantly lower emissions associated with livestock production, which remains one of the most resource-intensive and environmentally burdensome sectors globally. By replacing conventional animal-derived foods with plant-based alternatives, it is possible to reduce not only GHG emissions, but also land use, water consumption, and biodiversity loss.

Agriculture is widely recognized as one of the key sectors influencing greenhouse gas (GHG) emissions worldwide, including in Latvia. Although methane (CH_4) and nitrous oxide (N_2O) are emitted in smaller quantities than carbon dioxide (CO_2), their global warming potential is significantly higher—approximately 21 and 310 times greater than that of CO_2, respectively. Globally, agriculture accounts for roughly 12% of total anthropogenic GHG emissions. At the same time, atmospheric concentrations of greenhouse gases continue to rise. It is estimated that agriculture is responsible for more than 80% of anthropogenic N_2O emissions and approximately 70% of anthropogenic ammonia (NH_3) emissions, largely resulting from the application of animal manure and inorganic fertilizers. In addition, around 40% of anthropogenic methane emissions originate from agriculture, primarily due to enteric fermentation in livestock (Chataut et al., 2023; Shakoor et al., 2021).

In the Republic of Latvia, the energy sector generates the largest share of GHG emissions, while agriculture represents the second-largest source. The highest volume of agricultural emissions is observed in the Vidzeme planning region. In 2022 and 2023, the agricultural sector accounted for approximately 23% of the country's total greenhouse gas emissions. Within the agricultural sector itself, nitrous oxide (N_2O) and methane (CH_4) constitute the largest shares of emissions, representing about 49% and 47% of agricultural GHG emissions in Latvia, respectively (Official Statistics Portal, 2026).

In the context of the European Union's sustainability agenda, these transitions are closely aligned with the objectives of the European Green Deal, which aims to achieve climate neutrality by 2050. The Farm to Fork Strategy, as a core component of this framework, explicitly emphasizes the need to promote sustainable food systems, encourage healthier diets, and reduce the environmental footprint of food production and consumption. Vegan products and animal-based food substitutes are therefore not merely niche innovations, but integral elements of a broader systemic transformation envisioned at the EU level (European Commission, 2024).

However, the successful implementation of such transitions depends not only on technological innovation and policy frameworks, but also on societal acceptance and behavioral change. Understanding public perceptions, attitudes, and willingness to adopt vegan products is particularly important in national contexts such as Latvia, where dietary traditions, cultural norms, and economic factors may influence consumer choices. Assessing the opinions of Latvia's inhabitants regarding veganism and animal product substitutes provides critical insight into potential barriers and drivers of adoption. This knowledge is essential for designing targeted policies, educational initiatives, and market strategies that can effectively

support sustainable consumption patterns.

Therefore, examining both the environmental potential of vegan alternatives and the societal readiness to embrace them is key to advancing sustainability goals. Integrating consumer perspectives with environmental imperatives ensures that the transition toward lower-emission food systems is not only technically feasible, but also socially inclusive and resilient.

One possible way to reduce agricultural greenhouse gas emissions is the organic cultivation of protein-rich food crops for the production of plant-based proteins in Latvia, which does not require the use of additional fertilizers. Protein-rich plants that can serve as raw materials for the production of plant-based alternatives, such as animal-based food products such as meat and fish, are legumes. One of the unique pea varieties grown in Latvia is the gray pea, whose crude protein reaches up to 34% (The European Parliament and the Council, 2015).

Developing such alternatives can help reduce dependence on livestock farming and thus reduce associated greenhouse gas emissions. To explore this possibility, the author conducted a study aimed at assessing potential consumer demand for vegan alternatives to meat, fish and other animal products. In addition, the nutritional value of plant-based meat analogues and raw materials serving as a source of protein were evaluated.

Materials and Methods

The study was conducted using a quantitative survey method. Data were collected through an electronic questionnaire distributed to respondents in digital format. The survey link was shared via online communication channels, allowing participants to complete the questionnaire remotely and anonymously. This approach enabled efficient data collection from a relatively large number of respondents while ensuring accessibility and convenience for participants.

During the period from July 2025 to October 2025, a survey of the population of Latvia was conducted. The survey questions were uploaded to Google Forms, and the link to the questionnaire was sent to the residents' individual emails and via phone using the WhatsApp distribution tool. In August 2025, the author conducted a webinar at the Latvian Chamber of Commerce and Industry titled ‘Crisis Management. Development of Standard Requirements and Procedures’, where participants had the opportunity to fill out the questionnaire by scanning a QR code with a mobile device (Latvian Chamber of Commerce and Industry, 2025). Additionally, the link to the questionnaire was posted on social networks such as Facebook, Instagram, and LinkedIn, both on an individual profile and in thematic groups such as No Vegan Latvia (approximately 4,700 members) and Vegan Latvia (approximately 12,800 members). The number of emails sent was 350, while the number of links sent by phone was about 150. Despite the time resources invested, the feedback is quite small.

The final sample comprised 259 respondents. While this sample size provides a valuable snapshot of current trends, it is predominantly skewed toward an urban, highly educated demographic, with 78% of participants residing in the Riga region. Consequently, the findings primarily reflect the perspectives of urban consumers and may not be fully representative of the rural population or older age cohorts in Latvia. The distribution of respondents is 35% men (91 respondents) and 65% women (168 respondents). The questionnaire included several groups of questions designed to capture both demographic characteristics and consumer-related information.

The survey instrument contained questions regarding place of residence, allowing respondents to indicate the region or type of settlement in which they live (for example, urban or rural areas). In addition, respondents were asked to identify their age category and income level, which made it possible to classify participants into relevant socio-demographic groups.

The collection of these demographic variables provides important analytical value. The information about the place of residence allows the researcher to evaluate potential regional differences in consumer attitudes and purchasing behavior, as well as to understand whether demand for plant-based products may vary between urban and rural populations. Age distribution helps to identify generational patterns in dietary preferences and openness to vegan or plant-based alternatives. Meanwhile, income level data allow for an assessment of the relationship between purchasing power and the willingness to consume or purchase plant-based alternatives to animal products.

Together, these variables enable a more detailed interpretation of the survey results and make it possible to analyze potential demand for vegan alternatives across different demographic and socio-economic groups. Such segmentation improves the reliability of conclusions regarding market potential and consumer acceptance of plant-based products derived from leguminous crops in Latvia.

In addition, an analysis of available statistical data on consumption benefits was conducted both globally and in Latvia. The statistical analysis of global trends was conducted using the Statista database, while in Latvia the range of available data is very limited. For example, the Official Statistics Portal's website does not provide information on the proportion of vegans and vegetarians in the country. However, the 2021 press release on overall dietary trends and consumption of fruits and vegetables is available. Nevertheless, studies were conducted within the territory of the Republic of Latvia, which were published in various electronic newspapers, specifically in 2017, 2018, and 2021. A compilation of the data published by these newspapers is included in this article.

Results and Discussion

The prevalence of vegetarianism varies considerably across countries due to cultural, religious, economic and lifestyle factors. Data on the proportion of vegetarians in individual countries suggests that some regions have a significantly higher prevalence of vegetarianism than others. Unfortunately, statistical data on the prevalence of veganism worldwide is not available.

According to the 2025 Statista Consumer Insights survey, India has the highest share of vegetarians in the world compared to other selected countries. Over a third of Indian respondents reported following a vegetarian diet, compared to only six percent in the United Kingdom. However, the United Kingdom, Germany, and the U.S. hold second and third place respectively for the highest share of vegetarians in the world in 2025. Both countries have also increased their production of vegetarian and vegan meat substitutes in recent years. Germany's meat substitute production increased by over 109 percent between 2019 and 2024 and amounted to 126.480 metric tons. Consumption in the UK is forecast to exceed 62,000 metric tons by 2030.

In 2025, Germany had the highest share of polled individuals aged between 18 and 29 years of age who were vegetarian or vegan in Europe. All countries had a share of vegetarians that was higher than the share of vegans. In Europe in 2024, 26 percent of consumers that stopped, reduced, or had never eaten red meat were motivated by environmental concerns. Reducing consumption of meat and dairy products would likely be a somewhat efficient method of reducing the environmental impact of the agricultural industry on the planet (Ozbun, 2026a, 2026b).

Historically, Latvian cuisine has been deeply rooted in the country's local agricultural practices and the natural resources available within its territory. This has shaped a dietary pattern that is heavily centered around animal-derived products and traditional staple foods, reflecting both environmental conditions and cultural heritage. The reliance on locally sourced ingredients developed over centuries, as communities adapted to seasonal availability, climatic constraints, and the need for nutritionally dense foods to sustain rural populations.

Among the most prominent and culturally significant components of Latvian cuisine is rye bread, which has long held a symbolic and practical role in everyday life. It is not only a dietary staple but also an important element of national identity, often associated with traditions, rituals, and a sense of continuity across generations. Similarly, fish has historically been a key part of the Latvian diet, largely due to the country's geographic access to the Baltic Sea as well as its abundance in rivers and lakes. This has enabled the development of diverse fish-based dishes that remain popular today.

Dairy products also occupy a central position in Latvian food culture. Milk, sour cream, butter, and especially various types of cheese are widely consumed and are integral to both daily meals and traditional recipes. The prominence of dairy reflects the long-standing importance of cattle farming in Latvia's agricultural sector. In addition, pork has traditionally been one of the most commonly consumed meats, highlighting the historical significance of pig farming. Pork-based dishes are deeply embedded in Latvian culinary traditions and are often featured in festive meals and seasonal celebrations.

Overall, Latvian cuisine illustrates a strong connection between food, environment, and cultural identity, where animal products have historically played a dominant role due to both necessity and tradition. (Beitane et al., 2021).

Despite these long-standing dietary traditions centered on animal-based products, several studies have examined the prevalence of vegetarianism and veganism in Latvia in recent years. These studies indicate that although plant-based diets are gaining some attention, the majority of the population still follows an omnivorous diet.

For example, in August 2017, a study conducted by the Latvian retail chain Maxima and published on the BNN (Baltic News Network) portal reported that one in four Latvian residents was considering reducing their meat consumption or becoming vegetarian or vegan. At the same time, the study showed that 55% of respondents did not plan to change their eating habits, 5% planned to expand the types of meat in their diet, and 6% intended to reduce their meat consumption (BNN, 2017).

Another survey conducted in 2018 by the research company SKDS indicated that vegetarianism remained relatively uncommon in Latvia. According to the survey results, 93% of respondents disagreed with the statement 'I am a vegetarian', while only 5% of the population agreed with it (Leta, 2018).

More recent data were reported in March 2021 by the portal tv3.lv. According to the results of the study, the majority, or 83%, of Latvia's population are omnivores, which means that they consume animal-based products in their diet. Only 12% follow a flexible diet, so-called flexitarians, and eat meat or fish occasionally. Meanwhile, 3% are vegetarians – they do not eat meat and fish but consume other animal-based products, such as eggs or honey, and 1% do not eat meat but eat fish. Compared to the overall Baltic and Nordic context, only Lithuania has a slightly higher percentage of omnivores than Latvia – 86%, while in Estonia the proportion of such diet followers is similar to Latvia.

Vegans, or those who completely exclude animal-based products from their diet, in Latvia make up only 1%. However, relatively many – a total of 47% of Latvia's population – have tried vegetarian or vegan products, although almost as many, or 42%, have not tried such products, and the remaining are unsure whether they have eaten them. The most commonly

tried vegan products in Latvia are plant-based milk, vegan or vegetarian pizza, followed by vegan/vegetarian burgers. About one fifth, or 21%, of Latvian residents believe that the range of vegan and vegetarian products in their usual store is sufficient, while 26% neither agree nor disagree with this statement, and 24% disagree. For the majority, or 76% of residents in Latvia, the taste is important when buying plant-based products.

The study also found that 57% of residents in Latvia do not want to constantly eat more vegetarian and vegan products, 22% neither agree nor disagree with this statement, and 17% want to switch to that. In Latvia, 66% disagree with the statement that they eat less meat due to climate change, 23% somewhat agree, 6% significantly agree, and 4% completely agree that they eat less meat for that reason.

The study analyzed not only the daily dietary habits of the population but also attitudes towards sustainability, daily sustainability, and packaging. The most important environmental issue in Latvia is the amount of waste generated and its recycling, followed by concerns about global warming and climate change, which in 2020 overtook concerns about plastic pollution in the oceans, which were more important in 2019. In 2020, concerns about deforestation ranked third in relevance among environmental problems.

Regarding daily habits in 2020, 2% of respondents fully agreed that they were not ready to make climate-friendly choices, while 20% somewhat agreed with the statement. Meanwhile, 27% remained neutral, and 49% expressed a willingness to adopt more climate-friendly behaviors. When asked about purchasing habits, 52% of participants reported trying to buy sustainable brands and products, 32% were undecided, 3% did not know, but the remaining made no effort to buy sustainable products. Younger people and women, who have more positive attitudes and environmentally friendly habits, are most worried about climate change. Representatives of these population groups want to eat less meat and consume less plastic. Study respondents were also asked what personal actions each is willing to take to reduce their impact on the climate on a daily basis. The majority or 66% of Latvians are willing to sort waste, 48% – to reduce daily electricity consumption, as well as to move around on foot or by bicycle just as much, 40% would like to buy more environmentally friendly products or services, but 28% – reduce overall consumption, a fifth of the population is ready to move more by public transport or ride an electric car, an equal amount of people (16%) could eat less meat and fly less often, But only 10% would be willing to give up a car in their possession. Only 4% are not ready to change anything in their daily lives (Goba, 2021).

Overall, these findings demonstrate that although traditional Latvian dietary patterns remain dominant, interest in reducing meat consumption and exploring plant-based diets has begun to emerge, reflecting broader global trends related to health, environmental sustainability, and ethical food choices.

In 2021, the Official Statistics Portal's press release indicated that fruit and vegetable eating habits differ significantly between men and women. In 2019, similar to 2014, the trend remained that women consume more fruits and vegetables – 41.3% of women eat fruits at least once a day, while 43.6% of women eat vegetables and salads (excluding potatoes). Daily, fruits are most frequently consumed by women aged 55 to 64 (47.4%). Men consume more vegetables than fruits – 27.8% of men ate fruits daily, whereas 34.2% of men ate vegetables.

Four to six times a week, 29.8% of the Latvian population consume fruits in their diet, and vegetables and salads (excluding potatoes) – more than a third (36.1%) of the population. One to three times a week, 27.3% of the population eat fruits, while 19.8% consume vegetables. Less than once a week or not at all, 7.6% of the population eat fruits, and 4.7% eat vegetables (Official Statistics Portal, 2021).

The survey instrument captured comprehensive socio-demographic data, including place of residence, regional distribution, and educational attainment. These variables facilitate a nuanced understanding of the participants' profiles and enable a more rigorous interpretation of consumer attitudes toward plant-based alternatives.

The results indicate that the majority of respondents live in urban areas. Specifically, 89% of participants identified themselves as city residents (231), while only 11% reported living in rural areas (28). The results are summarized in Table 1. This distribution suggests that the survey sample is strongly represented by urban populations, which may influence attitudes toward dietary changes and the adoption of plant-based food alternatives.

The data indicate that the respondent sample is predominantly composed of females (168) compared to males (91), suggesting a gender imbalance that may influence overall dietary pattern interpretations. In terms of residence, the majority of respondents live in urban areas (231), while rural representation is relatively low (28), which should be considered when generalizing the findings to the broader population.

Respondents were also asked to indicate the region of Latvia in which they live. The results show that the largest proportion of respondents (78%) are from Riga, the capital city and the largest urban center in Latvia. Other regions are represented to a much smaller extent: Vidzeme accounts for 9% of respondents, Zemgale for 6%, Kurzeme for 4%, and Latgale for 3%.

The overwhelming majority of respondents identified as omnivores (94%), meaning they consume both plant and animal-based products. The remaining 6% of the respondents are divided into tiny fractions across four different specialized diets:

- Dynamic or flexible diet: Eat fish or meat occasionally, but overall prefer vegan food (2%).

- Lacto-ovo: Include animal-derived products like eggs and dairy, but exclude meat and fish (1%).
- Pescatarian: Consume eggs, milk, fish, and seafood, but exclude meat (2%).
- Vegan diet: Avoid all animal-derived products (1%).

Age-specific patterns reveal that:

- The 36–45 age group has the highest number of respondents (94 total) and mirrors the overall trend, with an overwhelming majority identifying as omnivores (89).
- Younger respondents (under 25) show slightly more diversity in dietary choices, including pescatarian and flexitarian options, although omnivores (25) still dominate.
- The 26–35 age group is heavily skewed toward omnivores (45 out of 46), indicating very limited adoption of alternative diets in this segment.
- In the 46–55 age group, there are small but notable instances of vegan and lacto-ovo diets, though omnivores (56) remain dominant.
- Older groups (56+) show almost no variation, with nearly all respondents following an omnivorous diet.

From a geographic perspective, alternative diets are almost exclusively observed among urban residents, suggesting that access, availability, and exposure to vegan or plant-based products are likely concentrated in cities. Rural respondents show minimal dietary diversity and remain almost entirely omnivorous.

Table 1

Distribution of respondents by age groups, genders, populated region, and diet preferences

Age group	Gender		Residence		Type of Diet				
	Male	Female	City	Rural	Vegan	Lacto-ovo	Pescatarian	Flexible	Omnivore
Less than 25 years	16	15	28	3	0	1	4	1	25
26-35 years	7	39	31	15	0	0	0	1	45
36-45 years	23	71	87	7	1	0	0	4	89
46-55 years	23	35	56	2	1	1	0	0	56
56-64 years	15	8	22	1	0	1	1	0	21
More than 65 years	7	0	7	0	0	0	0	0	7
Total number of respondents	91	168	231	28	2	3	5	6	243

The educational level of respondents is relatively high. The largest group, 39% of respondents, reported having a Master's degree or higher education level. Additionally, 27% hold a bachelor's degree, indicating that a significant share of participants possesses higher education qualifications.

Other respondents reported lower levels of education: 15% have completed secondary education, 14% have secondary vocational or trade education, and 5% reported basic education.

Overall, the educational structure of the respondents suggests that the survey sample consists largely of well-educated individuals. Higher education levels are often associated with greater awareness of environmental issues, health considerations, and sustainability topics, which may also influence attitudes toward plant-based diets and vegan food alternatives.

Taken together, the demographic results indicate that the survey primarily reflects the views of urban, highly educated residents, most of whom live in Riga. This demographic profile provides important context for interpreting the survey findings related to potential demand for plant-based alternatives to animal-derived food products.

As part of the broader survey analyzing food consumption trends, participants were asked the demographic question: 'Do children under the age of 18 live in your household?' The responses from the 259 participants were nearly evenly divided, indicating a highly balanced sample group. 51% of the respondents (132 persons) answered that they do have children under 18 living in their household, but 49% of the respondents (127 persons) answered that they do not have children under 18 living with them. This factor is critical as it influences the opinion that animal products are rich in various nutrients and are necessary for the growth and development of children's bodies shapes dietary traditions in each individual family.

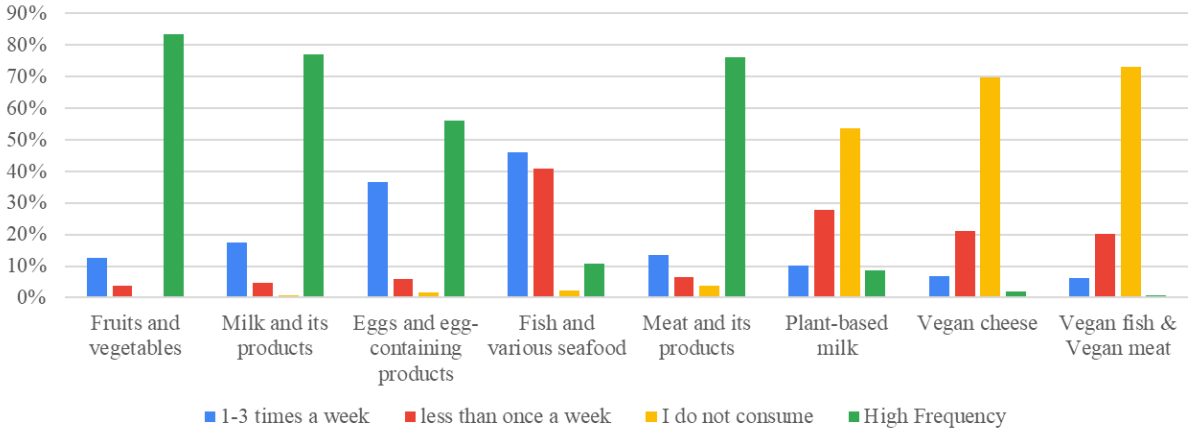
The Figure1 illustrates the self-reported frequency of consumption of various food categories, including both conventional animal-based products and plant-based alternatives. Consumption frequencies are grouped into four categories: 1–3 times per week, high frequency (4–5 times per week or every day), less than once per week, and do not consume.

Fruits and vegetables show the highest frequency of daily consumption, with the majority of respondents consuming them every day (64%). Regular consumption (multiple times per week) is also prominent, while non-consumption is negligible.

Milk and dairy products are widely consumed, with a strong skew toward daily and frequent weekly intake. 53% of respondents consume milk every day.

Figure 1

Frequency of consumption of different product groups



Eggs and meat products show moderate consumption frequencies, typically in the range of 1–5 times per week. 43% of respondents consume meat every day. 37% of respondents have responded that they consume eggs up to 3 times a week, while fish and seafood are consumed 1-3 times a week or even less (a total of 87% of respondents). Products such as smoked meats and sausages show a more dispersed pattern, with fewer daily consumers and more respondents consuming them occasionally.

Plant-based milk alternatives (e.g. soy or almond milk) show mixed consumption patterns, including both regular users and a significant proportion of non-users. A dominant share of respondents (approximately 70–75%) do not consume vegan cheese, vegan fish and vegan meat products.

Traditional food categories (especially fruits, vegetables, and dairy) are well integrated into regular diets. In contrast, plant-based analogues remain niche products, with high levels of non-consumption and limited habitual use.

Several limitations must be acknowledged. The reliance on digital distribution channels (e.g., WhatsApp, Facebook, LinkedIn) for survey dissemination may have introduced a self-selection bias. This approach likely attracted respondents with a pre-existing interest in dietary habits or environmental sustainability, potentially overstating the general public's readiness for plant-based transitions.

Conclusions

1. A significant majority of respondents consume animal products on a daily basis. The data indicate a clear dietary pattern dominated by conventional foods, while plant-based alternatives have not yet achieved widespread adoption, being consumed only occasionally or not at all by the majority of respondents.
2. Across all age groups, the omnivorous diet clearly dominates, accounting for 243 respondents overall. This confirms that traditional dietary habits, centered around animal-based products, remain deeply entrenched in Latvia. In terms of agriculture, this could mean that the demand for animal products remains high, which does not contribute to the reduction of greenhouse gases.
3. The findings strongly suggest that veganism and related dietary alternatives currently have very limited penetration across all demographic groups in Latvia, regardless of age, gender, or residence. While there are minor indications of diversification among younger and urban populations, these shifts are not yet substantial enough to influence overall dietary trends. As a result, the current contribution of veganism to food system sustainability in Latvia is limited. Although plant-based diets are widely recognized for their potential to reduce greenhouse gas emissions, resource use, and environmental pressure, these benefits are not yet being realized at scale within the Latvian context.
4. Policies should focus on subsidizing local plant protein production (e.g., Grey Peas) to lower the price barrier identified by consumers. Furthermore, public health campaigns should address the 'nutritional myth' that animal products are indispensable for children, as 51% of households cite this as a concern.
5. Future studies should employ a stratified sampling method to better capture the views of rural populations. Additionally, a longitudinal study could track if the ‘trial’ of vegan products (reported by 47% of the population) eventually leads to long-term dietary shifts.

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DIGITALISATION OF THE DEVELOPMENT OF SUBJECTS OF REGIONAL AGRARIAN ECONOMY: EVIDENCE FROM UKRAINE

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Abstract
Under the conditions of contemporary economic transformations, the digitalisation of regional agrarian economic entities has emerged as a fundamental prerequisite for enhancing the efficiency, competitiveness, and sustainability of the agricultural sector. The purpose of the article is to study the role of digital technologies in the development of regional agrarian entities and to identify priority directions for their effective implementation. The study examines the main areas of digitalisation in the agrarian economy, paying particular attention to the impact of digital solutions on increasing productivity, optimising resource use, and improving managerial decision-making across diverse agribusiness categories. It is emphasised that digitalisation contributes to the integration of agrarian enterprises into regional markets, the development of value chains, and the strengthening of cooperation within territorial communities. At the same time, the article identifies key constraints to the digital transformation of the regional agrarian economy, experimentally evaluated through a sociological survey conducted across territorial communities in the Mykolaiv region, Ukraine. These limitations include insufficient infrastructure, limited investments, a shortage of qualified specialists, and critical digital divides among smallholders. The necessity of adapting digital tools, such as hardware automation and specialised software systems, to regional specialties and production scales is substantiated. The article concludes that a comprehensive and systematic approach to digitalisation, combining state support, human capital development, innovation activity, and public-private partnerships, is essential for ensuring the sustainable development of subjects of the regional agrarian economy.
Keywords: digitalisation, regional development, agrarian economy, agribusiness categories, hardware automation.

Introduction

In the context of the accelerating global digital transformation, the agricultural sector is undergoing a paradigm shift, increasingly integrating advanced digital technologies into core production and management frameworks. For the Mykolaiv region, which is traditionally one of the leaders in agricultural production, the issue of digitalisation has moved from the area of theoretical discussions to the area of practical survival. Given its geographical positioning within a high-risk farming zone, further exacerbated by critical security challenges, the region requires sophisticated, innovative approaches to resource management. Digitalisation of subjects of the regional agricultural economy provides not only the automation of individual processes, but also the creation of a holistic ecosystem, where data becomes the main asset for making management decisions. The use of information and communication technologies, automated production management systems, digital platforms, precision farming tools and analytical data processing systems allows to increase production efficiency, optimise the use of natural and financial resources, as well as improve the quality of management decisions in agriculture. At the same time, the digital transformation of the agricultural sector is accompanied by low challenges, in particular, an insufficient level of digital infrastructure, limited access to financial resources, a shortage of qualified specialists and an uneven level of digital literacy among the subjects of the agricultural economy.

The structural transformation of the agrarian sector is intrinsically linked to broader objectives of regional development. In high-risk environments, the systematic digitalisation of agricultural economic entities serves as a critical catalyst for the economic resilience of territorial communities by optimising resource allocation and streamlining supply chains. However, achieving systemic competitiveness requires transitioning from fragmented technology adoption to synchronised digital ecosystems.

Recent scholarship emphasises that agribusiness efficiency is determined by the analytical capacity of data frameworks rather than land bank scale. While global literature covers macro-level digital shifts, an acute research gap remains regarding how spatial and structural factors within localised clusters dictate the adoption velocity of hardware automation and farm management software (FMS). This study bridges this empirical divide, outlining pathways for enhanced regional competitiveness and corporate sustainability in Ukraine. Consequently, it is relevant to study the processes of digitalisation of the development of subjects of the regional agricultural economy and to determine the priority areas for the effective implementation of digital technologies in the activities of agricultural enterprises.

Key drivers and tools of digitalisation

Recent scientific studies indicate that the digitalisation of the agricultural sector is one of the key factors in increasing the efficiency of the regional economy and the competitiveness of agricultural enterprises.

Modern studies emphasize that digital agricultural technologies, in particular GPS navigation systems, sensor monitoring systems, unmanned aerial vehicles and farm management systems, can significantly increase production efficiency and contribute to a more rational use of resources. Such technologies allow for the use of precise application of fertilizers and plant protection products, which ensures increased yields and reduced negative impact on the environment.

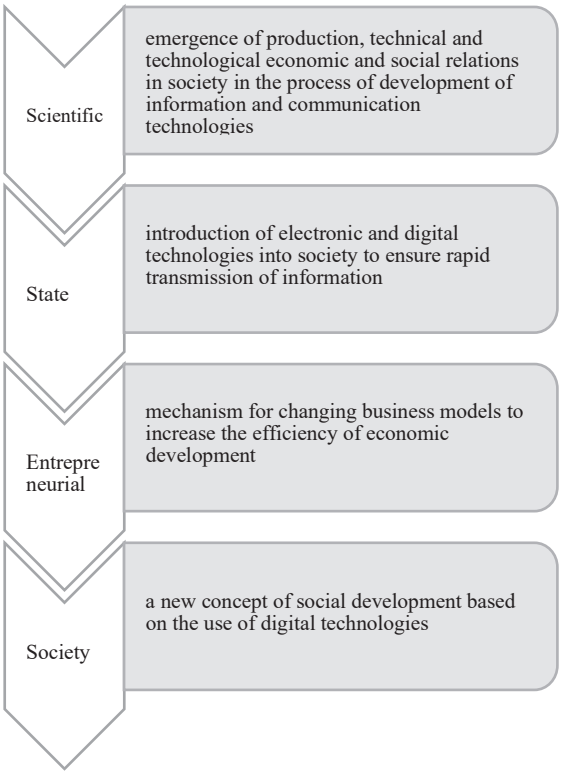
Researchers also emphasize the significant economic effect of the introduction of digital technologies in agriculture. Thus, the use of digital tools for

agricultural product management allows reducing production costs, improving product quality and increasing the level of economic efficiency of subjects of the regional agrarian economy.

Shabatura (2019) believes that digitalisation is a tool for obtaining the desired socio-economic effect, which becomes a platform for meeting the needs of society and surplus profits for owners of domestic businesses. The author emphasizes that business owners who seek to implement the principles of digitalisation in economic development should focus on automating production and management processes to increase the efficiency of functioning and taking into account that, depending on the scope of application, the concept of 'digitalisation' is noticeably modified, considers it necessary to differentiate it at four levels - the state, scientists, entrepreneurs, society (Figure 1).

Figure 1

Characteristics of the definition of 'digitalisation' from different perspectives



Source: Compiled by the authors based on Shabatura, 2019.

Ponomarenko & Mishchenko (2025) consider key innovations that allow agricultural production to adapt to climate change and the resource base – precision agriculture (GPS, drones, IoT sensors), artificial intelligence, biotechnology, vertical farms, robotics, questionnaires, digital twins, drones and automatic control systems; integrated application of modern tillage technologies (Full-till, Mini-till, Strip-till, Verti-till); use of GPS and precision agriculture to optimise crops, fertilizer application and plant protection; environmentally friendly technologies – erosion control, increasing humus content, reducing the use of chemical protection agents. Based on the conducted research of modern innovation-intensive technologies in the development of the agricultural sector, the authors note that this type of production allows to increase the yield by 15-30% compared to traditional systems, while simultaneously reducing energy and resource costs (Ponomarenko & Mishchenko, 2025).

Tytarchuk (2025) emphasizes that the implementation of online monitoring and telematics systems is a crucial factor in the competitiveness of agricultural enterprises, proposing a differentiated approach to their integration depending on the scale of the business entity. The author notes that one of the problems of the modern domestic agricultural sector is the extensive technical deterioration of equipment (average age over 15 years), and based on an analysis of the experience of the companies 'Kernel' and 'MHP' confirms the high economic return from predictive maintenance systems (payback 1.5-2.5 years) (Tytarchuk, 2025).

Sirenko et al. (2025) examine how digital technologies, including artificial intelligence, blockchain, and cloud systems, improve financial management in the agricultural sector of Ukraine during wartime. The authors discuss how digital tools increase transparency, speed, and security while reducing financial risks in crisis settings (Sirenko et al., 2025).

The study of digitalisation within regional agrarian entities is of paramount importance, as the implementation of digital technologies enhances production efficiency, optimises resource allocation, and strengthens regional competitiveness.

The purpose of the article is to study the role of digital technologies in the development of subjects of the regional agrarian economy and determine the priority areas of their effective implementation to increase the efficiency, competitiveness and sustainability of the agricultural sector.

The objectives of the study are:

1. To investigate the main directions and tools of digitalisation (information and communication technologies, digital platforms, precision agriculture) and their role in the integration, formation of value chains and cooperation of subjects of the regional agrarian economy.
2. To assess the impact of digital solutions on increasing productivity, optimising the use of natural and financial resources, reducing transaction costs and improving the quality of management decisions at the regional level.
3. To identify key obstacles to the digital transformation of the agricultural sector (infrastructure, financial, personnel) and to justify a comprehensive approach to overcoming them, taking into account regional specifics, the scale of production, the development of human capital and public-private partnership.

Materials and Methods

The information base of the research comprises materials of the European Commission, the Government Portal, statistical and analytical data of the Ministry of Economy, Environment and Agriculture of Ukraine, resources of the analytical platforms YouControl and YC.Market, publications of AgroPortal, as well as official web resources of agricultural enterprises located in the Mykolaiv region.

To achieve the research objectives, the methodological framework integrates a complex of general scientific and special economic methods. A systematic approach is used to evaluate the digitalisation of the agrarian economy as a multi-component system covering technological, economic, organisational, and social dimensions. The methods of analysis and synthesis are applied to generalise contemporary theoretical perspectives and define the fundamental components of digital transformation. A comparative analysis is employed to assess the current adoption velocity of digital technologies among regional agricultural enterprises based on their corporate data. The sociological method is operationalised via a questionnaire survey to determine digitalisation maturity, evaluate digital tool utilization, and identify primary implementation barriers. Statistical analysis is used to process quantitative findings from the field survey, verify sample reliability, and execute stratified calculations. Finally, graphical and tabular methods are utilised for the systematic visualisation of empirical results through thematic tables and figures.

To ensure empirical replication and rigorous scientific validation, the field research design conceptualises digitalisation through a synchronised matrix of spatial, structural, and operational parameters within the Mykolaiv region, Ukraine. To achieve structural granularity, data collection was systematically executed across 12 distinct territorial communities representing diversified geographic and logistical zones. The targeted sampling framework incorporates a multi-strata design to capture the entire operational hierarchy of the regional agrarian economy, distinguishing between micro-scale private farmers (FOPs), small and medium agrarian enterprises, and large export-oriented corporations.

Out of the region's total institutional landscape, which comprises 10,508 active agricultural entities (including 8,757 enterprises and 1,751 individual entrepreneurs), a specialised population pool of approximately 4,800 consistently reporting, commercially active agrarian entities was identified as the baseline for this study. From this target framework, a representative sample size of N = 482 valid respondents was selected (Table 1). Evaluated using standard stratified sampling, algorithms, this framework operates at a 95% confidence level with a 4.2%, margin of error, confirming the regional dataset's statistical reliability.

The survey instrument was organised into three thematic digital dimensions, focusing on general profile and structural metrics, hardware automation and precision field technologies, and specialised software systems alongside administrative cloud infrastructure.

Table 1

Empirical research matrix, sampling framework, and survey dimensions

Survey Cluster / Agricultural Scale	Main Target Respondents	Sample Size (n = 482)	Core Analytical Focus & Addressed Survey Themes
Micro-scale & Private Farmers (FOPs) *(Land bank: < 100 ha)*	Individual producers, family farm owners, rural entrepreneurs	n_1 = 312 *(Representative pool; approx. 10.3% of regional stratum)*	Focus: Baseline digital literacy, affordability barriers, and state digital platform integration. Themes: Mobile banking, state registry utility, and basic GPS indicators.
Small & Medium Agrarian Enterprises *(Land bank: 100 – 2,000 ha)*	Agricultural directors, chief agronomists, farm managers	n_2 = 130 *(Random sampling; approx. 10.1% of regional stratum)*	Focus: Cost-efficiency transitions, mechanical automation, and operational blockages. Themes: Parallel driving systems, fuel telemetry, and crop monitoring software.
Export-Oriented Entities *(Land bank: > 2,000 ha / Logistics)*	Agribusiness owners, corporate logistics executives, IT directors	n_3 = 40 *(Targeted census; approx. 8.9% of regional stratum)*	Focus: High-tier corporate competitiveness, AI integration, and international supply chain certification. Themes: Autonomous autopilot machinery, enterprise ERPs, and cloud FMS platforms.

Results and Discussion

Digitalising regional agrarian economic entities has shifted from an optional extra to a strategic necessity, opening key avenues for regional economic growth:

1. Institutional digitalisation and transparency of management (State Agrarian Register – SAR and eFishing)

SAR has become the only digital opportunity for access to state and donor support, which allows farmers to transparently receive assistance, identify land plots and apply for available programs. According to statistics, as of 2025, SAR united over 210 thousand registered users, and over 80% of public funds to support the domestic agricultural sector were distributed through the platform. The transfer of SAR to full state ownership creates the basis for its further

scaling and transformation into a basic digital channel for interaction between agricultural producers and the state. The main emphasis is on small agricultural producers, for whom access to support programs was previously difficult. Submitting an application through SAR takes a few minutes, which is paramount in a full-scale war, when small farmers need quick solutions and minimising bureaucratic barriers.

Therefore, the main goal of SAR is to digitalise the agricultural sector to ensure transparent distribution of state support and minimise the bureaucratic burden on farmers. As part of the systemic reform of the industry, the 'eFishing' system was introduced as a digital solution that minimizes corruption risks, increasing the economic efficiency of managing state resources on the ground and has already provided about UAH 170 million in additional revenues to the state budget.

2. Formation of a digital scientific and innovative environment (Agricultural Knowledge and Innovation System - AKIS)

Integration into the European space requires new approaches to information exchange. With the support of the EU, the Ministry of Economy, Environment and Agriculture of Ukraine is implementing the Agricultural Knowledge and Innovation System (AKIS) with a corresponding web portal integrated with the State Agrarian Register to provide farmers with convenient access to professional knowledge, advice and European standards. In the EU, AKIS serves as an end-to-end mechanism for achieving the strategic objectives of the Common Agricultural Policy (CAP).

For Ukraine, its development is aligned with the National Strategy for the Development of Agriculture and Rural Areas until 2030, which provides for priorities in terms of competitiveness, innovation, digitalisation and effective knowledge exchange (Cabinet of Ministers of Ukraine, 2024). At the regional level, AKIS is a practical mechanism for bridging the gap between science and practice by providing farmers and rural communities with access to knowledge and innovation needed to increase competitiveness and comply with European standards. The integration of professional knowledge and European requirements into digital platforms allows Ukrainian producers to adapt to the competitive conditions of the EU market and ensure the sustainable development of rural areas.

3. Digital technologies, digital monitoring and resource control

According to the Digital Agenda of Ukraine (2016), in the next 50 years, the level of development of the agricultural sector of Ukraine and its ability to compete in global markets will be determined by precision (3.0) and digital (4.0) agriculture, that is, in fact, by digital technologies. From a financial perspective, precision agriculture involves the use of modern technologies to maintain or increase yields and allows plants to receive the necessary amount of resources. Technologies help in making strategic decisions at the field level, as well as in operational actions at the processing stage, which makes it possible to optimise the costs of agricultural production without losing yield. In the Strategy for the Development of Agriculture and Rural Areas in Ukraine for the period up to 2030, namely, within the framework of strategic goal 6. 'Modernization of the agricultural sector: development of processing, innovation, digitalisation and knowledge exchange', among the tasks it is worth highlighting 'Task 3. Digitalisation', the implementation of which is provided for in the areas: digitalisation of agriculture and digital agricultural advisory services' (Cabinet of Ministers of Ukraine, 2024). The introduction of digital technologies opens up additional potential for growth, increasing the accuracy of operations, ensuring environmental sustainability and profitability of agricultural enterprises. An example of a digital economy in the agricultural sector is presented in Figure 2.

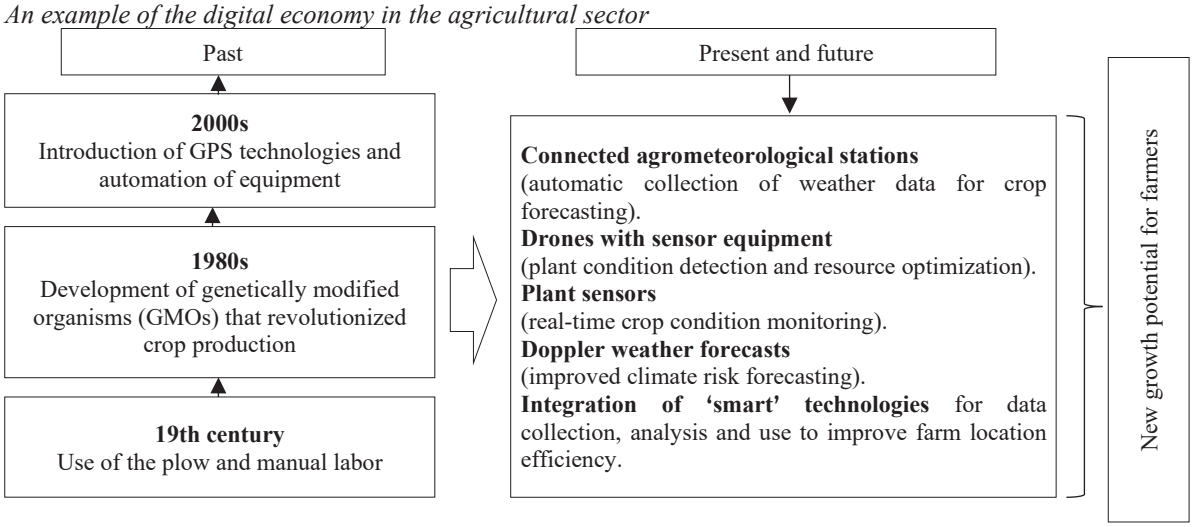
One example of the digitalisation of the agricultural sector in Ukraine is the DigitalAgriBusiness digital transformation project of agribusiness, which was launched in early 2016 at Kernel-Trade LLC.

The goal of the project was to ensure growth and efficiency through the digitalisation of agricultural production based on Big Data.

For the purpose of remote control of agricultural lands, the Cropwise Operations digital platform was developed, which includes operational monitoring of the state of sown areas, auto-documentation, forecasting and planning of agricultural operations. The system helps to increase the efficiency of agriculture and reduce the cost of agricultural operations through early identification of problem areas in the fields and rational use of resources.

The implementation of GPS navigation systems, drones for field monitoring, IoT sensors and data management platforms (AgriChain – a comprehensive system for agribusiness management, GeoPard – an unbiased cloud-based analytical platform for precision agriculture) allows for the optimisation of resource use, which allows for an increase in yield by 15-25% and a reduction in costs by 10-20%. Production digitalisation covers not only crop production (through precision agriculture systems, IoT sensors and platforms such as AgriChain or GeoPard), but also the sphere of natural resource protection. The implementation of the pilot project 'eInspector' is aimed at transforming fish protection activities through digital accountability. This allows for the optimisation of the use of bioresources, where automated control and monitoring become safeguards against abuse, which, together with agricultural technologies, ensures an increase in the productivity of the industry by 15-25 percent.

Figure 2
An example of the digital economy in the agricultural sector



4. Financial instruments and investment attractiveness

In modern conditions, the state is activating the formation of new financial mechanisms to support the agricultural sector, in particular through grant programs, cost compensation, specialised funds to support agricultural producers and war risk insurance systems. The war risk insurance mechanism for businesses is particularly important. It covers losses from hostilities - including property, equipment, and infrastructure damage - while providing partial state reimbursement for insurance premiums. The program is administered by the Export Credit Agency (ECA), and in 2026 the government expanded its capabilities by increasing the maximum amount of compensation for damaged or destroyed property from UAH 10 million to UAH 30 million and compensation for insurance premiums to UAH 3 million. At the same time, the digitalisation of financial and management processes plays an important role in increasing the investment attractiveness of the agricultural sector. The use of digital services, in particular the State Agrarian Register (SAR), electronic verification and automated management systems, contributes to reducing the administrative burden, increasing the transparency of financial flows and creating a more predictable investment environment for domestic and foreign investors. Transparency, ensured by the integration of financial instruments into digital services, together with the development of risk guarantee mechanisms through international financial institutions and partnership programs with the World Bank and European insurance agencies, creates the basis for the formation of a stable investment environment and stimulates the inflow of capital into regional agro-industrial projects.

5. Digital certification and simplification of access to international markets

Digital solutions that automate the collection and systematisation of data for international certification, in particular Global G.A.P., which is an essential condition for exporting products to the markets of the European Union, are becoming increasingly important for small and medium-sized agricultural producers. The use of digital platforms allows for electronic accounting of agro-technological operations, control of the use of fertilizers, plant protection products and water resources, as well as ensuring product traceability in accordance with international safety and quality standards. This significantly simplifies the audit process, reduces the administrative burden and reduces the time spent on preparing documentation for certification. At the same time, the digitalisation of certification processes contributes to increasing the export potential of agricultural enterprises, building the trust of international partners and integrating Ukrainian producers into global supply chains. The use of digital verification systems and electronic product identification in accordance with the requirements of Global G.A.P. allows agricultural producers to increase the competitiveness of their products and simplify access to European markets.

The agricultural sector of Mykolaiv region is characterized by a significant concentration of business entities and a high level of competition, which increases the need to implement modern digital and management solutions to ensure the efficiency of enterprises. As of 2026, there were 10,508 active agricultural entities in the region, of which 8,757 were enterprises and 1,751 were individual entrepreneurs. A significant role in shaping the competitive environment of the region is played by large agricultural companies, in particular, LLC SP 'NIBULON' (Mykolaiv city territorial community), LLC 'Euromet-Mykolaiv' (Mykolaiv city territorial community), LLC 'Agritek' (Mykolaiv city territorial community), STOV 'Promin' (Blagodatne rural territorial community), LLC 'PAEK-Pivden' (Shyrokove rural territorial community), PSP Agrofirma 'Rodnichok' (Shevchenkove rural territorial community), LLC 'Prodinvest Service' (Mykolaiv city territorial community), LLC 'PAEK-Agro' (Yelanets settlement territorial community), LLC 'Zolota Nyva' (Vesnyane rural territorial

community) and PE agrarian enterprise ʻBlagodatnenskyi ptahoprom' (Blagodatne rural territorial community), which form the basis of regional agribusiness and contribute to the introduction of modern technologies and digital solutions in the agriculture of the region. An analysis of leading enterprises in the Mykolaiv region - home to over 10,000 agribusiness entities - highlights how digital technologies are actively deployed to maintain efficiency under martial law (Table 2).

Table 2
Digital technologies and results of their implementation in the activities of agricultural enterprises of Mykolaiv region

Name of the enterprise and field of activity	Implemented digital technologies and solutions	Key technological and economic effects
LLC SP ʻNIBULON' *(Integrated management, logistics and export)*	New general IT architecture (strategy together with KPMG); ERP system for elevators (ʻdigital twin', investments 1 million USD); Modernization of ACS TP (sensors and automation, 2 million USD); Application for logistics 'Driver's cabin'; Digital HR systems.	Adaptation of business processes to work in war conditions; Payback of the ʻdigital twin' is less than 1 year, reduction of grain losses to 1%; Precise control of grain and resource quality; Elimination of truck queues at terminals (elimination of downtime); Acceleration of management decision-making.
LLC ʻPAEK-Pivden', LLC ʻPAEK-Agro' *(Agricultural production)*	Automated irrigation systems (IoT) with soil moisture control; remote control of equipment and AgriTech solutions for demining agricultural lands.	Optimisation of water resources use and automation of irrigation processes; possibility of safe return of mined lands to agricultural circulation; reduction of personnel risks and increase of safety of field work.
LLC ʻZolota Nyva' *(Agricultural production and precision farming)*	A comprehensive system of precision farming: digitisation of the land bank and accounting of fields; satellite monitoring (NDVI) and the use of agrodrones; GPS-control of equipment and autopilot systems; creation of task maps and differentiated fertilizer application; digital technological and financial planning systems.	Full digital control of the production cycle; reduction of resource costs (in particular, fuel and fertilizer by eliminating overlaps); increased yield; ensuring a transparent economy of each hectare; making management decisions based on data (Data-driven) with integration into the company's logistics.
STOV ʻPromin', PSP Agrofirma ʻRodnichok' *(Agricultural production)*	GPS-monitoring of equipment, satellite analysis of crops (Cropio/EOS), field mapping, differentiated fertilizer application.	Reduction of costs for fuel and lubricants (FMM), precise control of technological operations, increased yield.

In order to map the broader adoption context across the territory, the structural parameters of the surveyed enterprises-categorized by urban, settlement, and rural community zones-reveal key operational trends. While large companies are actively implementing ERP/FMS systems, IoT solutions, and automation of production processes, most small and medium-sized agribusiness entities use only individual digital tools. The use of digital technologies allows agricultural enterprises to receive timely information about the state of soils, crops, climatic conditions and market trends, which helps to increase productivity and reduce production risks. In addition, digitalisation contributes to the formation of new business models in agriculture, the development of innovative activities and the integration of agricultural enterprises into regional and global markets. Despite the active development of digital services, the transformation is accompanied by a number of obstacles, in particular, low digital readiness of some farmers, the high cost of technologies, destruction due to war and personnel shortages (Table 3).

The empirical data reveals a profound, structurally determined digital asymmetry across agribusiness categories. Large export-oriented entities and corporate holdings (such as LLC SP Nibulon, LLC PAEK-Agro, LLC Agrytek, and STOV Promin) display advanced, integrated deployments of field hardware and enterprise software, with investments in digital twins reaching up to $1.000,000.

Table 3
Challenges of digital transformation of the agricultural sector and strategic vectors for overcoming them

Sphere	Key challenges and regional gaps	Strategic vectors for overcoming
Infrastructure and digital readiness	Low digital readiness; deep regional disparity in access to technologies.	European integration and standardization: development of regional IT infrastructure.
Financing and investments	High cost of technologies; cyclicality of small farmers' incomes; large-scale destruction of logistics due to the war.	Stimulating innovation: financial support for small farms and cooperatives to create regional test hubs of AgTech solutions on their basis.
Human and socio-cultural potential	Insufficient level of digital literacy; weak traditions of cooperation in the triangle 'business - science - state'.	Human capital development: implementation of targeted educational programmes; advanced training for working with Big Data and intelligent systems.
Ecology and resources	Climate change; irrational use of water and land resources; high carbon footprint.	Eco-orientation: using digital solutions to develop a circular economy, minimize waste and increase climate resilience.

Empirical Results and Structural Analysis of Agribusiness Digitalisation

In the hardware segment, large-scale crop producers (> 2,000 ha) utilise high-precision autonomous autopilot steering systems (2 cm accuracy) paired with variable rate application (VRA) tools like GeoPard and John Deere Operations Center. Telemetry data synchronises via CAN-bus readers and fuel monitoring systems, closing the 'field-to-elevator' visibility chain. On the software side, these entities exhibit near-total penetration of automated warehouse management (reducing inventory buffers by 66%), electronic document management (60-80% paperless workflow), and AI-driven crop telemetry.

Conversely, medium and small agribusiness scales operate under constrained models. Medium-sized entities focus primarily on isolated cost-control hardware (GPS fleet trackers and fuel sensors) to protect thin margins, omitting advanced VRA or IoT networks. The micro-scale sector (FOPs) is largely decoupled from hardware innovations due to prohibitive capital expenditures, relying exclusively on basic digital tools like smartphone apps, state registries, or commercial trading platforms.

Scientific Discussion: Digital Transformation vs. Corporate Sustainability

These empirical findings correlate directly with contemporary scientific literature regarding the mechanisms of digital corporate efficiency. As established by global agrarian economic models, digital adoption directly enhances competitiveness by shifting management from retrospective reporting to real-time proactive mitigation. For instance, the deployment of continuous satellite crop monitoring (NDVI) integrated into specialised Farm Management Systems (FMS), as heavily observed in the Mykolaiv regional cluster, delivers an average resource savings of 15-20% in fertiliser and fuel utilisation.

However, our study highlights that the 'digital divide' poses a severe threat to balanced regional development. While high-tier agribusinesses use Big Data and cloud-based financial controllers to secure international trade agreements and maximize supply chain efficiency, smallholders face structural stagnation. This uneven distribution of digital literacy and technological access impedes the aggregate resilience of territorial communities. Without localized institutional intervention and targeted financial support for shared digital services, digitalisation risks accelerating land consolidation - marginalizing small-scale family farms that are vital to rural demographic stability.

Thus, effective digital transformation of the agricultural economy is impossible without a combination of four vectors: infrastructural European integration, financial support for innovations, training of specialists, and environmental responsibility. The implementation of these strategic directions will allow not only to level the consequences of the war, but also to overcome regional disparities, ensuring the transition to a sustainable model of agricultural production.

Conclusions

Under the conditions of a full-scale war and global economic transformations, digitalising regional agricultural entities in the Mykolaiv region has shifted from an optional technological advantage to a strategic imperative for survival, resilience, and competitiveness. The practice of leading regional enterprises, such as LLC SP 'NIBULON', LLC 'PAEK-Agro', and LLC 'Zolota Nyva', demonstrates that the integration of digital tools, precision farming platforms like Cropwise, and automated management systems delivers significant technological and economic effects. These solutions streamline logistics, reduce production costs, and serve as an essential guarantee for the economic viability of agribusiness under high-risk environments.

Based on the study conducted, the following main

conclusions can be drawn:

1. Digitalisation as a driver of integration and transparency. Digital tools, particularly the State Agrarian Register (SAR), facilitate the integration of different agribusiness layers into regional and national markets, streamline supply chains, and foster cooperation within territorial communities. The automation of administrative and certification workflows, including compliance with international standards like Global G.A.P., reduces transaction costs, lowers corruption risks, and significantly improves the quality of managerial decision-making at the regional level.
2. The structural digital divide and regional constraints. Despite the clear benefits of innovative technologies, a profound digital divide persists across the region's 10,508 active agricultural entities.
3. Strategic vectors for sustainable transformation. Overcoming regional technological disparities and ensuring balanced agrarian development requires a comprehensive, systematic approach based on public-private partnerships and state support, structured around four essential vectors:

Infrastructural European integration – expanding regional IT networks and standardising state digital channels;

Financial support for innovations – introducing risk insurance mechanisms and target funding to make technologies affordable for small-scale producers;

Human capital development – implementing specialised training programmes to improve digital literacy and data processing skills among rural entities;

Eco-orientation – utilizing precision farming tools and IoT monitoring to build circular, climate-resilient agricultural models.

Ultimately, synchronising these strategic directions will mitigate the consequences of wartime destruction and ensure the long-term, sustainable development of subjects within the regional agrarian economy of Ukraine.

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INSTITUTIONAL CAPACITY AND THE EMERGENCE OF BIOREGIONAL INITIATIVES IN RURAL LATVIA: A GOVERNANCE PERSPECTIVE

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Abstract
Rural regions in Latvia and Europe increasingly operate within institutional environments characterised by fragmented governance structures, uneven administrative capacity, and misalignment between policy objectives and local implementation. In such contexts, bioregional initiatives have emerged in several European countries as place-based responses to perceived limitations of existing regional development and smart specialisation frameworks. This paper examines the emergence of bioregional initiatives in rural Latvia as a response to institutional and governance constraints rather than as a predefined development model. Building on institutional economics and regional development literature, the study interprets bioregional initiatives as empirical signals of governance stress, reflecting attempts by local and regional actors to address coordination gaps, administrative capacity limitations, and policy incoherence within multi-level governance systems. The analysis applies an institutional mapping approach combined with a qualitative assessment of governance arrangements in rural Latvia to identify patterns of institutional fragmentation and coordination challenges across governance levels. Rather than evaluating the effectiveness of bioregional initiatives as policy instruments, the study focuses on the structural conditions under which such initiatives emerge. By framing bioregional initiatives as responses to institutional constraints, the paper contributes to rural development research by highlighting the governance contexts where alternative, place-based organisations emerge and by emphasising how institutional capacity and coordination shape territorial development.
Keywords: bioregional initiatives, institutional capacity, multi-level governance, rural development.

Introduction

Rural regions increasingly operate within complex institutional environments characterised by fragmented governance structures, overlapping policy frameworks, and uneven administrative capacities. In many European contexts, the implementation of regional development strategies requires coordination among multiple governance levels, including European Union institutions, national ministries, regional planning bodies, municipalities, and local community actors. While such multi-level governance systems provide a wide range of policy instruments to address environmental, economic, and social objectives, they also generate coordination challenges that may affect policy implementation in practice.

In recent years, the concept of bioregional development has gained growing attention in discussions on sustainable territorial governance, particularly in relation to the bioeconomy, ecosystem-based management, and place-based development approaches. Bioregions are commonly understood as territorially defined areas where ecological boundaries, socio-economic activities, and cultural identities are considered jointly in shaping development strategies. Previous studies emphasise the potential of bioregional initiatives to support sustainable resource management, strengthen territorial identity, and foster cooperation among stakeholders across sectors and governance levels. A study on bioregional development in Latvia has analyzed both the territorial factors that influence the potential formation of bioregions and the governance dilemmas that shape their development paths (Megne & Naglis-Liepa, 2025; Naglis-Liepa et al. 2025).

However, much of the existing literature approaches bioregional development primarily as a normative or strategic framework for sustainability-oriented regional development. Less attention has been devoted to examining the institutional conditions under which such initiatives emerge in practice. In particular, differences in institutional capacity, governance coordination mechanisms, and administrative structures across territories may influence how and where place-based initiatives develop. In governance systems characterised by fragmented policy environments and uneven administrative resources, these institutional factors may play a significant role in shaping opportunities for locally driven development initiatives.

Latvia provides a relevant context for examining these dynamics due to its strong policy emphasis on bioeconomy development and sustainable rural transformation, reflected in national policy frameworks such as the Bioeconomy Strategy 2030 and the National Development Plan of Latvia 2021–2027 (Cabinet of Ministers of Latvia, 2020). Rural regions in Latvia operate within a governance framework that combines European Union policy instruments, national development strategies related to the bioeconomy and regional development, and locally driven initiatives. Although these frameworks collectively aim to promote sustainable development and territorial cohesion, coordination challenges between policy objectives and local implementation capacities remain evident in several areas of regional development policy implementation (Borrás & Edler, 2020; Hooghe & Marks, 2020), particularly in municipalities with limited administrative resources.

The aim of this paper is to explore the institutional conditions associated with the emergence of bioregional initiatives in rural Latvia. The analysis focuses on institutional capacity, governance coordination, and policy interactions across governance levels, applying institutional mapping and qualitative

assessment of governance arrangements as analytical tools. By examining these institutional dimensions, the paper contributes to a better understanding of how institutional environments may influence the development of alternative place-based initiatives in rural regions.

Literature background

The concept of bioregions has gained increasing attention in discussions on sustainable territorial development, particularly in the context of environmental governance, rural development, and bioeconomy transitions. Early interpretations of bioregionalism emphasised the importance of aligning human activities with ecological systems and natural boundaries. In this perspective, bioregions are understood as territorially defined areas where ecological characteristics, economic practices, and cultural identities interact within a shared spatial framework (Aberley, 1999; Sale, 2000; Hubbard, 2023; Wearne, 2023). Such approaches highlight the potential of bioregional thinking to reconnect environmental management with place-based governance, ecological stewardship, and community participation.

Bioregional thinking has also been linked to broader discussions on sustainability transitions and territorial resilience. Scholars argue that governance systems capable of integrating ecological knowledge, local resources, and social cooperation may better support sustainable territorial development (Berkes & Folke, 1998; Folke et al., 2005). These perspectives are closely related to research on sustainability transitions and adaptive governance, which emphasises the importance of institutional learning and coordination in complex socio-ecological systems (Loorbach et al., 2017; Geels et al., 2017). In this context, bioregional approaches are often associated with adaptive governance frameworks that emphasise collaboration, learning processes, and the management of socio-ecological systems across multiple institutional levels (Chaffin et al., 2016).

More recent research has connected the concept of bioregional development with debates on sustainable regional economies and bioeconomy transitions. Studies focusing on rural development and bioeconomy strategies emphasise the role of local resources, territorial specialization, and collaborative governance arrangements in enabling sustainable regional transformation (Dias et al., 2021; Pike et al., 2017; Dax et al., 2016). Within this literature, bioregions are frequently interpreted as governance frameworks that facilitate cooperation between public institutions, local communities, businesses, and civil society actors in the pursuit of sustainability-oriented development pathways.

The growing interest in bioeconomy strategies within the European Union has further strengthened the relevance of territorially embedded development approaches. These policy directions are further reinforced by broader EU strategic frameworks, including the European Green Deal, which emphasises the role of sustainable resource management and circular bioeconomy in achieving climate neutrality (European Commission, 2019). Bioeconomy policies aim to promote sustainable resource use, innovation in biological production systems, and the transition toward circular and low-carbon economies (Bugge et al., 2016; European Commission, 2018). Rural regions are often considered particularly important in this transition due to their natural resource base and agricultural production systems. However, research also indicates that bioeconomy development may produce uneven regional outcomes depending on governance structures, institutional coordination, and regional capacities (Birch et al., 2010).

These place-based perspectives are closely related to broader debates on territorial development and regional governance. The place-based approach emphasises that development strategies should reflect territorially specific resources, institutional structures, and socio-economic conditions (Barca et al., 2012; Rodríguez-Pose, 2013). From this perspective, regional development outcomes depend not only on policy design but also on the institutional environments within which policies are implemented. Institutional frameworks influence how actors coordinate development initiatives, mobilise resources, and adapt policy instruments to local contexts.

In the European context, rural development and bioeconomy policies operate within complex multi-level governance systems involving interactions between European Union frameworks, national policy instruments, regional planning structures, and local governance arrangements. Multi-level governance systems can provide opportunities for policy innovation and territorial adaptation; however, they may also generate coordination challenges and inconsistencies between policy objectives and implementation practices (Hooghe & Marks, 2020; Borrás & Edler, 2020; Marks & Hooghe, 2004).

From an institutional perspective, such governance systems can also be understood as polycentric arrangements in which multiple centres of decision-making operate simultaneously across different levels (Ostrom, 2010). Polycentric governance frameworks emphasise the importance of coordination, institutional learning, and adaptive institutional arrangements in addressing complex socio-ecological challenges. Within such governance systems, the capacity of institutions to coordinate actors and policy frameworks becomes a critical factor influencing development outcomes.

Recent governance research highlights that institutional capacity plays a critical role in shaping the effectiveness of territorial development initiatives. Institutional capacity refers not only to formal administrative structures but also to the ability of

governance systems to coordinate actors, align policy objectives across sectors, and adapt to territorially specific conditions (Peters & Pierre, 2016; Peters & Fontaine, 2020). Governance systems characterised by strong institutional capacity may be better positioned to manage complex policy environments and support the emergence of innovative development initiatives.

Differences in institutional capacity across regions may therefore influence the ability of local actors to mobilise resources, establish partnerships, and initiate place-based development initiatives. In rural areas with limited administrative resources, fragmented governance arrangements may constrain the implementation of development strategies and reduce opportunities for collaborative initiatives (Rodríguez-Pose & Crescenzi, 2008).

Despite growing attention to governance aspects of regional development, the literature on bioregional initiatives still tends to focus primarily on conceptual models, sustainability objectives, and examples of successful implementation. Comparatively less attention has been devoted to examining the institutional conditions under which such initiatives emerge across different territorial contexts. Empirical research in Latvia has begun to address this gap by analysing territorial factors influencing the potential formation of bioregions across municipalities, revealing substantial socio-economic and environmental heterogeneity between regions (Naglis-Liepa et al., 2025). In particular, the role of institutional capacity, governance coordination, and policy interactions within multi-level governance systems remains insufficiently explored in relation to the emergence of bioregional initiatives in rural regions.

Addressing this gap, the present study examines how institutional environments may influence the emergence of bioregional initiatives in rural Latvia. Rather than evaluating bioregions as normative development models, the analysis focuses on the governance conditions within which such initiatives may arise as potential responses to institutional fragmentation and coordination challenges.

Analytical perspective

Institutional conditions play an increasingly important role in shaping territorial development processes, particularly in rural regions characterised by limited administrative resources and complex policy environments. Within multi-level governance systems, regional development outcomes depend not only on the availability of policy instruments or development strategies but also on the capacity of governance arrangements to coordinate actors, align policy objectives, and support implementation across institutional levels.

In this context, institutional capacity can be understood as the ability of governance systems to mobilise resources, facilitate collaboration among stakeholders, and manage interactions between regulatory frameworks and local development initiatives (Peters & Pierre, 2016; Peters & Fontaine, 2020). Previous research examining bioregional development in Latvia has also highlighted governance dilemmas arising from tensions between environmental objectives, legal frameworks, and local development interests (Megne & Naglis-Liepa, 2025). Institutional capacity therefore extends beyond formal administrative structures and includes coordination mechanisms, policy coherence, and the ability of institutions to adapt to territorially specific challenges. Differences in institutional capacity between regions may significantly influence the capacity of local actors to initiate and sustain place-based development initiatives.

Rural governance environments typically involve interactions between multiple policy domains, including environmental protection, regional development, agriculture, and bioeconomy strategies. These domains are often governed through overlapping institutional frameworks operating simultaneously at European, national, regional, and local levels. While such arrangements may create opportunities for integrated governance, they may also generate coordination gaps, inconsistencies between policy objectives, and administrative burdens for local actors.

Within this analytical perspective, bioregional initiatives are not interpreted primarily as predefined development models but rather as phenomena that may emerge under specific institutional conditions. In particular, place-based initiatives may develop where governance systems face coordination challenges or institutional fragmentation that limit the effectiveness of existing policy frameworks.

From this viewpoint, bioregional initiatives can be interpreted as potential institutional responses to coordination gaps within multi-level governance systems. Their emergence may therefore reflect attempts by local actors to organise development activities in ways that better align environmental, economic, and territorial governance objectives.

This perspective allows bioregional initiatives to be examined within the broader institutional environments in which regional development policies are implemented. Rather than focusing solely on normative interpretations of bioregions, the analysis emphasises the governance contexts in which such initiatives arise and the institutional conditions that shape their development.

Materials and Methods

The research is grounded in an institutional perspective on regional development, which emphasises the role of governance structures, policy coordination, and administrative capacity in shaping territorial development processes. Within multi-level governance contexts, territorial development initiatives emerge through interactions between policy frameworks, institutional arrangements, and the capacities of actors

operating at different governance levels.

From this perspective, particular attention is given to how institutional conditions influence the ability of local actors to initiate and implement place-based development initiatives. The analysis therefore focuses on examining how governance structures and policy objectives interact in practice and how these interactions may create either enabling conditions or constraints for territorial development initiatives.

The study applies an integrated analytical approach that examines governance conditions shaping territorial development processes. The analysis focuses on identifying coordination gaps, differences in institutional capacity, and potential institutional constraints affecting the implementation of development initiatives.

The research therefore explores how policy objectives, governance arrangements, and institutional practices interact in territorial contexts. This approach allows the study to identify factors influencing the ability of local actors to initiate place-based development initiatives and to assess how institutional conditions may affect the development of such initiatives.

The analysis is based on a qualitative institutional mapping of governance structures relevant to rural development and bioeconomy policy in Latvia, including policy documents, governance frameworks, and institutional arrangements across governance levels. The institutional mapping was based on the analysis of selected European Union and national policy documents relevant to rural development and bioeconomy governance in Latvia. The analysed materials included the Common Agricultural Policy (European Parliament & Council, 2013), the European Green Deal (European Commission, 2019), the Latvian Bioeconomy Strategy 2030 (Ministry of Agriculture of Latvia, 2018), and the National Development Plan of Latvia 2021–2027 (Cabinet of Ministers of Latvia, 2020). Documents were selected according to their relevance for rural development, bioeconomy governance, territorial planning, and institutional coordination.

The analysis followed a qualitative institutional mapping approach. The selected documents were reviewed to identify governance actors, policy instruments, implementation responsibilities, coordination mechanisms, and interactions between governance levels. Particular attention was paid to the distribution of responsibilities across governance levels and the coherence of policy objectives related to rural development and bioeconomy governance. The identified findings were subsequently grouped into broader analytical categories reflecting recurring governance patterns across the analysed documents. Based on this process, five institutional dimensions were identified: institutional capacity, governance coordination, multi-level governance, policy integration, and local institutional networks. These dimensions served as the analytical framework for interpreting governance conditions associated with the emergence of bioregional initiatives in rural Latvia.

Results and Discussion

The governance context of rural development in Latvia is shaped by interactions between multiple institutional levels and policy domains. Rural development policies are implemented within a multi-level governance system that combines European Union policy frameworks, national strategies, regional planning mechanisms, and local governance arrangements. While this institutional architecture provides a broad policy framework for promoting sustainable development, differences in institutional capacity and coordination mechanisms across governance levels influence how development initiatives are implemented in practice.

To illustrate the institutional environment of rural development governance, Table 1 outlines the main governance levels, key actors, and policy instruments relevant to rural development in Latvia.

Table 1

Governance levels and institutional responsibilities influencing rural development in Latvia

Governance level	Main policy actors	Key policy instruments	Relevance for rural development governance
European Union	European Commission, EU institutions	Common Agricultural Policy (CAP), European Green Deal, Cohesion Policy, Horizon Europe	Establishes strategic objectives, regulatory frameworks, and funding mechanisms
National	Ministries, national agencies	Bioeconomy Strategy 2030, environmental legislation, national development plans	Defines regulatory frameworks and strategic development priorities
Regional	Planning regions	Regional development strategies, spatial planning instruments	Coordinates development priorities across municipalities
Local	Municipalities, local communities, NGOs	Municipal development programmes, community initiatives	Implements development projects and local initiatives

The interaction between these governance levels creates a complex institutional environment in which multiple policy instruments and regulatory frameworks operate simultaneously. While such arrangements provide opportunities for integrated governance, they may also generate coordination challenges and administrative complexity for local actors.

Uneven institutional capacity across governance levels

The institutional environment of rural development in Latvia is characterised by interactions between multiple governance levels. Although these institutional arrangements provide a broad policy framework for sustainable development, the capacity to implement and coordinate policies varies significantly across territorial levels.

At the European Union level, policy instruments such as the Common Agricultural Policy, the European Green Deal, and cohesion policy establish strategic objectives related to sustainability, environmental protection, and bioeconomy development. However, the practical implementation of these policies depends largely on national and regional governance systems.

At the national level, several policy documents and strategies address themes related to bioregional development, including the Bioeconomy Strategy 2030, environmental protection legislation, and regional development frameworks. While these strategies outline long-term development priorities, their implementation often requires coordination between multiple ministries and sectoral policy domains.

Regional and municipal governance levels play a crucial role in translating policy objectives into concrete development initiatives. However, administrative resources, institutional capacity, and governance structures differ considerably across municipalities. Smaller rural municipalities frequently operate with limited administrative capacity, which may constrain their ability to coordinate complex development initiatives or participate effectively in multi-level governance processes (Rodríguez-Pose & Crescenzi, 2008). These differences in institutional capacity and institutional fragmentation create uneven conditions for policy implementation across territories and may influence the ability of local actors to initiate or support place-based development initiatives.

To synthesise the main institutional factors influencing the emergence of place-based initiatives, Table 2 presents key analytical dimensions identified in the analysis.

Table 2

Institutional dimensions influencing the emergence of place-based initiatives in rural Latvia

Institutional dimension	Characteristics in rural Latvia	Implications for place-based initiatives
Institutional capacity	Uneven administrative resources and expertise across municipalities and regional institutions	Limited ability to initiate and coordinate complex development initiatives
Governance coordination	Fragmented interaction between policy domains (environmental protection, regional development, agriculture, bioeconomy)	Difficulties aligning development priorities across sectors
Multi-level governance	Policy frameworks operating simultaneously at EU, national, regional, and local levels	Implementation gaps between strategic objectives and local practice
Policy integration	Overlapping strategies and regulatory instruments with partially competing objectives	Need for adaptive and place-based governance solutions
Local institutional networks	Varying levels of collaboration between municipalities, community organisations, and economic actors	Opportunities for locally driven initiatives where cooperative networks are strong

Coordination challenges in multi-level governance

The analysis of governance arrangements in rural Latvia highlights several coordination challenges arising from interactions between policy frameworks operating at different institutional levels. Although many policy instruments pursue broadly compatible objectives related to sustainability, regional development, and environmental protection, their implementation often requires coordination across sectoral policy domains and governance levels.

One of the main challenges concerns the alignment of policy objectives between environmental protection frameworks and economic development strategies. Environmental regulations frequently impose restrictions on land use and natural resource management, while development-oriented policies promote economic diversification, innovation, and increased productivity in rural areas. Balancing these objectives requires coordination mechanisms that are not always clearly defined within existing governance arrangements.

Additional coordination challenges arise from the distribution of responsibilities across governance levels. National ministries typically define strategic

priorities and regulatory frameworks, while regional and municipal authorities are responsible for implementation and local development planning. This division of responsibilities can generate gaps between policy design and practical implementation, particularly in territories with limited administrative capacity (Morrison et al., 2019; Charron et al., 2014). Furthermore, many rural development initiatives require cooperation between public institutions, private sector actors, and civil society organisations. Establishing and maintaining such collaborative arrangements may be difficult in governance environments characterised by fragmented institutional structures and limited coordination mechanisms (Candel & Biesbroek, 2016).

Institutional space for place-based initiatives

Within these governance conditions, place-based initiatives may emerge as attempts by local actors to address coordination challenges and adapt development strategies to territorially specific circumstances. In rural regions, where institutional capacity and administrative resources are limited, alternative forms of cooperation and organisation may become particularly relevant for mobilising local resources and coordinating development activities.

Bioregional initiatives can be interpreted within this broader context of place-based governance experimentation (Megne & Naglis-Liepa, 2025). Rather than representing a universally applicable development model, such initiatives may reflect attempts by local communities, organisations, and institutions to navigate complex policy environments and respond to coordination gaps between governance levels.

The emergence of these initiatives may therefore be influenced not only by environmental or economic conditions but also by the institutional environment within which rural development policies are implemented (Naglis-Liepa et al., 2025). Differences in governance capacity, coordination mechanisms, and policy integration may create varying opportunities for the development of place-based initiatives across territories.

In analytical terms, the emergence of place-based initiatives can be interpreted as a process shaped by interactions between multi-level governance structures, institutional capacity, coordination mechanisms, and institutional fragmentation within territorial governance systems.

The analysis presented in this study highlights the importance of institutional conditions in shaping the context within which place-based initiatives may emerge in rural regions. While bioregional initiatives are frequently discussed in the literature as sustainability-oriented development models or governance frameworks, the findings of this study suggest that their relevance is also closely connected to the institutional environments in which regional development policies are implemented.

The institutional dimensions identified in Table 2 indicate that rural development governance in Latvia operates within a complex multi-level framework where policy instruments, regulatory frameworks, and development strategies interact across several institutional levels. Although these frameworks collectively pursue objectives related to sustainability, bioeconomy development, and regional competitiveness, their implementation requires coordination across sectors and governance levels. In practice, such coordination may be difficult to achieve due to differences in institutional capacity, administrative resources, and policy priorities.

These findings align with broader research on multi-level governance and policy coordination, which emphasises that development outcomes are shaped not only by policy design but also by institutional arrangements and governance capacity. In governance systems characterised by overlapping policy frameworks and fragmented responsibilities, implementation gaps may emerge between strategic objectives and local development practices. Such gaps may create conditions in which local actors explore alternative forms of cooperation or territorial organisation in order to address coordination challenges.

Recent studies continue to emphasise the importance of institutional capacity and governance coordination in addressing sustainability transitions and territorial development challenges. Research on bioeconomy policy implementation highlights that policy coherence and institutional capacity remain critical factors influencing the effectiveness of governance arrangements across governance levels (Faulkner et al., 2024). Similar challenges have been identified in Latvia, where limited institutional capacities and fragmented stakeholder coordination continue to constrain environmental governance processes and participatory approaches (Ernšteins et al., 2025). Recent research further suggests that place-based governance solutions and stronger cooperation between national and local governance levels may improve the implementation of sustainability objectives and enhance territorial resilience in the context of the European Green Deal (Beizītere et al., 2026). These findings provide additional support for the argument that institutional conditions play a crucial role in shaping opportunities for the emergence of place-based initiatives.

From this perspective, bioregional initiatives may be interpreted as part of a broader spectrum of place-based governance responses that emerge within complex institutional environments. Rather than representing universally applicable development models, such initiatives may reflect attempts by local communities, institutions, and organisations to navigate policy fragmentation and adapt development strategies to territorially specific conditions.

The findings also highlight the role of local institutional networks in shaping opportunities for place-based initiatives. Where collaboration between

municipalities, community organisations, and economic actors are relatively strong, initiatives may be more likely to emerge despite institutional constraints. Conversely, in territories characterised by limited administrative resources and weaker cooperation networks, the capacity to initiate such initiatives may remain limited.

These observations suggest that institutional capacity and governance coordination should be considered important analytical dimensions when examining the development of place-based initiatives in rural regions. While environmental and economic factors are often emphasised in discussions on bioregional development, the institutional environment within which regional development policies are implemented may play an equally significant role in shaping the conditions under which such initiatives arise.

At the same time, the present study adopts an exploratory perspective and does not attempt to provide a comprehensive explanation of the mechanisms underlying the emergence of bioregional initiatives. Further research combining empirical regional data, comparative regional analysis, and quantitative modelling would be required to examine how institutional capacity, governance coordination, and territorial characteristics interact in shaping the development trajectories of bioregional initiatives in rural contexts.

Conclusions

1. The study demonstrates that rural development governance in Latvia operates within a complex multi-level institutional framework involving European Union policies, national strategies, regional planning mechanisms, and local governance structures.
2. Differences in institutional capacity and administrative resources across governance levels create uneven conditions for the implementation of development initiatives in rural territories.
3. Fragmented policy frameworks and coordination challenges between governance levels may generate institutional constraints that affect the practical implementation of rural development policies.
4. Under such institutional conditions, place-based initiatives, including bioregional initiatives, may emerge as locally driven responses aimed at addressing coordination gaps and adapting development strategies to territorially specific circumstances.
5. The findings confirm that examining institutional capacity and governance coordination provides an important analytical perspective for understanding the emergence of alternative territorial development initiatives in rural regions.
6. The results highlight the need for further empirical research examining how variations in institutional capacity, governance coordination mechanisms, and territorial characteristics shape the emergence of place-based initiatives in rural regions, including comparative regional studies and quantitative analyses of institutional capacity and territorial development dynamics.

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IDENTIFYING UKRAINE'S RESEARCH PRIORITIES IN EFFICIENCY AND SAFETY OF ENERGY BY TECHNOLOGY FORESIGHT

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Abstract
The efficiency, reliability, and safety of energy are matters of paramount importance for Ukraine's survival as a sovereign state. The energy sector plays a fundamental role in the stability of defence industry development, ensuring the functioning of the civilian service sector, stable exports of goods, including agricultural products, and the growth of real GDP. Due to missile, artillery and drone strikes, power generation plants, fuel storage, energy distribution facilities, and research infrastructure sustained severe damage. Enhancing the stability of energy supply, improving its productivity, and restoring damaged energy generation are questions of national security, defence capability and sustainable development. The study aims to identify the research priorities of Ukrainian science and technology (S&T) in the context of full-scale war, within the thematic block 'Efficiency, Reliability and Safety of Energy'. The study uses a three-round Delhi survey in which 543 experts from the NAS of Ukraine and sectoral national academies share their expertise. The study was conducted from July to December 2024. The top relevance indicator (percentage of experts who gave the highest relevance score) identifies the promising priority research areas as: 'Security, resilience and robustness of the country's energy system, installations and systems against terrorist acts and military actions' (83%), 'Development of means to ensure the safety of nuclear power plants' (76%), 'Cybersecurity of large information exchange systems in the energy sector against cyber-espionage and cyber-terrorism' (68%). The study identifies the drawbacks of today's S&T policy and calls for the necessary measures to address the problem. 47% of experts consider that S&T potential in energy efficiency is currently being used only half of its capabilities. The study proves that the government couldn't formulate an adequate S&T policy for the current situation (69% of responses).
Keywords: technology foresight, S&T policy, Delphi survey, energy safety, energy efficiency.

Introduction

Today, technology foresight is increasingly becoming a strategic governance tool rather than simply a forecasting method for determining research priorities across various areas of technological development. In this context, technology foresight is generally defined as a systematic approach to studying possible future events and forming shared visions to support strategic decision-making (Iden et al., 2017). Such research trends are particularly relevant for energy efficiency and safety, as energy systems often involve technological uncertainty, complex regulation, and intricate infrastructure. Review studies show that technology foresight relies on tools such as Delphi surveys, horizon scanning, scenario planning, roadmaps, expert workshops, structural analysis, and cross-impact analysis (Veen & Ortt, 2026). Since no single method can adequately address deep uncertainty, these tools are increasingly used in combination within broader technology foresight programmes. The Delphi method is widely used because it allows for structured expert assessments, iterative feedback, and controlled anonymity. At the same time, it has certain limitations. Research indicates risks such as biased panel selection, excessively long questionnaires, and weak linkages between results and implementation when exercises are limited to ranking priorities rather than translating them into action plans. To address these concerns, Delphi is increasingly embedded in wider foresight frameworks that quantify expectations about technological change and policy options (Beiderbeck et al., 2021). In the energy sector, technology foresight based on the Delphi method is frequently applied to identify priority technologies and policy instruments for national strategies. For example, a Delphi survey on Poland's energy sector looking ahead to 2030 ranked technologies and policy tools by expected importance, diffusion time, and contribution to energy security and environmental goals (Czaplicka-Kolarz et al., 2009). Egypt's strategic priority areas in renewable energy efficiency have been identified using similar large-scale Delphi studies. It shows how expert consensus can guide long-term planning and indicate where research funding should focus (Rezk et al., 2019). This is why Delphi-based technology foresight is so often used to support long-term planning in the energy sector. Therefore, a combination of Delphi surveys and scenario analysis is currently considered a best practice for identifying research priorities, particularly in the field of energy efficiency. Thus, scenario planning combines qualitative analysis methods with quantitative parameters of technological change and public policy, allowing for testing which options remain effective across different possible futures (Alizadeh et al., 2016). Delphi-based scenario studies emphasise the need to select relevant variables, carefully document expert assessment, and establish clear criteria for translating the scenarios' conclusions into specific research priorities (Schmalz et al., 2021). The use of such an approach underscores the need to develop an integrated system of indicators and multi-criteria scenario assessment to identify priority areas for technological change (Batechko et al., 2021).

Scenario planning, horizon scanning, and roadmaps are also used to study possible paths to decarbonise the economy, develop renewable energy, and transform the national energy system (Vakulenko et al., 2024). Although these studies are not always formulated as technology foresight, they perform a similar function by identifying strategic research priorities and reform directions in the context of Ukraine's long-term energy transition.

Some papers suggest identifying S&T priorities using data from the registration cards of scientific projects and dissertations (Bulkin, 2021), while others define priorities in food security, bioeconomy (Koretskyi et al., 2025) and natural science (Kavunenko & Chernohaeva, 2025) using the Delphi method. At the same time, there is a lack of in-depth research on defining S&T research priorities for energy efficiency, reliability, and safety under the conditions of a full-scale war in Ukraine. Specifically, further analysis is needed to assess the prospects for Ukrainian S&T development and to identify policy measures that motivate researchers by creating favourable innovation environments. Furthermore, expert perspectives are required to determine the primary challenges of implementing the scientific discoveries, restoring human resources, and transitioning toward a more attractive, talent-oriented S&T policy. Thus, this paper aims to fill this gap.

The study aims to define whether the priorities of S&T that experts recognised in foresight research 2021 remain relevant, as well as to determine new promising research directions adequate to the conditions of full-scale war, propose S&T policy measures to restore scientific personnel, implement and promote innovations and propose new, alternative ideas for efficiency, reliability and safety of energy development.

Materials and Methods

The study was held in three rounds from July to December 2024 by 543 experts, mainly from the NAS of Ukraine and sectoral national academies (Popovych et al., 2024), in accordance with the latest methodological guidance from the RAND Corporation (Khodyakov et al., 2023) and drawing on the previous experience (Popovych, 2022). The Delphi method lets experts analyse the anonymous responses of other professionals in the survey, clarify their own responses, and provide well-supported arguments (Table 1). The experts processed the responses and identified the most promising research areas that deserved priority support. The experts examined nine thematic blocks, including 'Efficiency, Reliability and Safety of Energy', which involved 56 experts. In addition to the questionnaire on promising research areas, there were questions about enhancing S&T policy and restoring human talent resources. The assessors provided their responses through Google Forms questionnaires. Experts evaluated the priority research areas by five-point scores according to the following criteria: 1. Relevance, areas that deserve the priority support; 2. Talent, availability of qualified personnel; 3. Contributions, obtained results, the research is actively underway; 4. Equipment, available infrastructure to conduct world-class research; 5. International cooperation, active partnership with leading world research centres and conducting prestigious joint projects. The percentage of experts who gave the highest relevance score (5 points) determined the top relevance criteria. Research directions that obtained 50% or more of the top relevance indicator were defined as priority ones.

Table 1

General scheme of the Delphi survey

1st round	2nd round	3rd round
Assessing the relevance of research directions defined in 2021. Formulating ideas for new priorities and policies.	Clarification of research directions defined in 2021 in relation to the current conditions. Preliminary assessment of new ideas.	Final evaluation of new ideas concerning research directions, priorities and policies

Source: authors' approach based on the recommendations of the RAND Corporation (Khodyakov et al., 2023).

The first round of the survey aimed at a preliminary assessment of the research areas' relevance, as defined in 2021, and at generating new ideas concerning the priorities and S&T policy proposals. The first, second and third rounds consisted of questions on priority determination and S&T policy. In addition to the existing questions, experts could also express their own vision and proposals. For this purpose, the questionnaire included special fields to submit additional proposals. All three rounds consisted of two sections: first, defining research priorities; and second, S&T policy suggestions. There were additional questions to clarify the study, for example, to suggest priority areas that were not taken into account, outline areas essential for defence strengthening, and recommend experts to participate in the Delhi survey on the thematic area. Besides, experts had the opportunity to provide responses on the S&T policy, such as which stages of the innovation cycle require the most significant state support or which changes to the state innovation policy are essential.

In the second round, the experts reviewed the response statistics and assessed the expanded list of priorities from the first-round survey. They could adjust the evaluations they gave in the first round if they considered it appropriate, and evaluate the new anonymous list of ideas for enhancing S&T policy. It is also essential to identify ideas that significantly differ from the prevailing, general position, and, if necessary, ask experts to provide additional arguments for their non-standard proposals.

The third round aims to evaluate the supplemented lists of research priorities and S&T policy proposals based on generalised, anonymous results from the second

round. Experts reviewed the visualisation and statistical data on the most popular proposals and new ideas from the second round and made adjustments to their responses. Experts could present additional arguments that would be included in the research as separate ones.

Results and Discussion

Ukrainian post-war recovery considers using energy infrastructure capacity to rebuild the economic and defence sectors, increase productivity, and ensure that Ukrainian science and business remain competitive. At the same time, it is evident that limited funds and capital should be invested in the most promising, priority areas of S&T that could achieve technological breakthroughs and leadership. To define the priority research areas of 'Efficiency, Reliability and Safety of Energy', we use the previous experience and results of Foresight 2021. In the second round, the experts assessed and updated the priorities, taking into account new trends of the full-scale war (Table 2).

Table 2

Research directions within the research block: 'Efficiency, Reliability and Safety of Energy' according to the 2021 list, and the current assessment of their relevance and potential

№	Research direction	TOP RELEVANCE (percentage of experts who gave the highest relevance score - 5 points, %)	Average score				
			Relevance	Talent	Equipment	Contributions	International cooperation
1	Development of new and improvement of existing technologies for energy resource conservation and increasing the share of renewable energy sources and alternative fuels in Ukraine's energy balance	82%	4.68	3.73	3.28	3.77	3.39
2	Development of alternative, environmentally friendly technologies, equipment and materials for creating modern autonomous power sources	78%	4.58	3.69	3.15	3.36	3.21
3	Development of modern technologies for manufacturing reactor, turbine, thermohydraulic and electrical equipment for domestic nuclear power plants (NPP)	76%	4.59	3.90	3.29	3.59	3.38
4	Development of technologies and systems to extend the lifespan of complex energy infrastructures and traditional, renewable electricity systems	75%	4.64	3.73	3.34	3.73	3.20
5	Improvement of electrical and semiconductor converters to enhance energy quality in networks of traditional, renewable, and autonomous energy sources and for implementing advanced industrial electrotechnologies	67%	4.54	3.69	3.21	3.38	2.87
6	Creation of technologies and equipment for producing materials resistant to extreme thermal and mechanical impacts in energy systems	66%	4.50	3.58	3.03	3.29	2.97
7	Enhancing the energy efficiency, reliability and safety of power transmission systems in industrial regions and megacities of Ukraine, particularly using modern power cables with solid nanostructured insulation	63%	4.45	3.58	3.03	3.24	2.79
8	Development of new technologies and electrical equipment implementing artificial intelligence in Ukraine's energy sector to improve safety, reliability and energy resource efficiency	59%	4.41	3.43	2.98	3.12	2.85
9	Increasing the energy and environmental efficiency of technologies using carbon-containing raw materials (coal, mine methane), hydrogen and industrial waste	59%	4.41	3.71	3.15	3.54	2.98
10	Enhancement of monitoring systems for energy quality and diagnostics of reliability and environmental safety of traditional, renewable and NPP facilities	54%	4.31	3.72	3.21	3.39	3.0
11	Scientific support for the development and modernisation of turbines, compressors, improvement of thermal schemes of power units	50%	4.10	3.70	3.23	3.35	2.83

Source: authors' calculations based on the results of the experts' survey.

The shown results demonstrate the highest level of relevance for the research direction 'Development of new and improvement of existing technologies for energy resource conservation and increasing the share of renewable energy sources and alternative fuels in Ukraine's energy balance' (82%). The importance of the abovementioned research direction is explained by the need to conserve energy and use it during peak consumption periods. The critical energy supply in Ukraine in January and February 2026 emphasises this statement. Using renewable and alternative energy sources helps diversify the energy supply and

strengthen the energy system's balance. Such S&T areas are important for reducing energy consumption and unit production costs. As Ukraine moves toward EU standards, it's essential to comply with decarbonisation policies and develop sustainable solar, biomass, hydrogen, and wind energy sources. Experts evaluated the high level of priority relevance of the next research areas: 'Development of alternative, environmentally friendly technologies, equipment and materials for creating modern autonomous power sources' (78%), 'Development of modern technologies for manufacturing reactor, turbine, thermohydraulic and electrical equipment for domestic NPPs' (76%). The full-scale war showed that autonomous power sources are less vulnerable to disruption. They allow critical infrastructure and domestic consumers to gain a reliable energy supply. On the other hand, modern technologies for NPPs allow extending reactor lifespans and improving safety, thereby reducing fossil fuel consumption. Developing technologies and systems to extend the lifespan of complex energy infrastructures and traditional, renewable electricity systems makes sense given war-related disruptions, outdated equipment, and the need to reduce accident risk. Gradual restoration and lifespan extension make the energy modernisation economically affordable and increase the lifecycle of power generation without complete replacement. The development of energy-efficiency and safety technologies drives the evolution of high-tech engineering and strengthens independence from external suppliers. Table 3 presents new promising ideas for research development within the thematic block 'Efficiency, Reliability and Safety of Energy'.

Table 3

New ideas for promising research areas of the thematic block: 'Efficiency, Reliability and Safety of Energy'

№	Research direction	TOP RELEVANCE (percentage of experts who gave the highest relevance score - 5 points, %)	Average score				
			Relevance	Talent	Equipment	Contributions	International cooperation
1	Security, resilience and robustness of the country's energy system, installations and systems against terrorist acts and military actions	83%	4.57	3.60	3.11	3.28	3.15
2	Development of means to ensure the safety of NPPs	76%	4.47	3.69	3.23	3.27	3.18
3	Cybersecurity of large information exchange systems in the energy sector against cyber-espionage and cyber-terrorism	68%	4.45	3.66	3.18	3.27	3.11
4	Energy storage: development of technologies, equipment and materials for creating modern energy storage systems with a wide range of capacities and power to support critical infrastructure and regulate consumption in energy systems	65%	4.41	3.61	3.15	3.39	3.07
5	Energy recovery, conservation of energy resources	63%	4.30	3.69	3.18	3.36	2.96
6	Scientific support for the creation of a distributed generation system: design, implementation and operation	62%	4.38	3.72	3.45	3.45	3.28
7	Increasing energy efficiency of buildings: development of technologies, equipment, materials and solutions for existing and new buildings	60%	4.30	3.70	3.35	3.49	3.19
8	Smart grids: research on development prospects and implementation of smart technologies to increase the reliability and efficiency of Ukraine's power systems	59%	4.36	3.74	3.28	3.47	3.09
9	Restoration of thermal power plants: improving the reliability and efficiency of equipment, load regulation range	51%	4.06	3.68	3.20	3.57	3.04
10	Development of concepts, creation of energy clusters, smart communities and smart cities to maximise autonomy in energy supply and incorporate all available local energy sources into the energy balance	50%	4.18	3.53	3.17	3.26	2.91

Source: authors' calculations based on the results of the experts' survey.

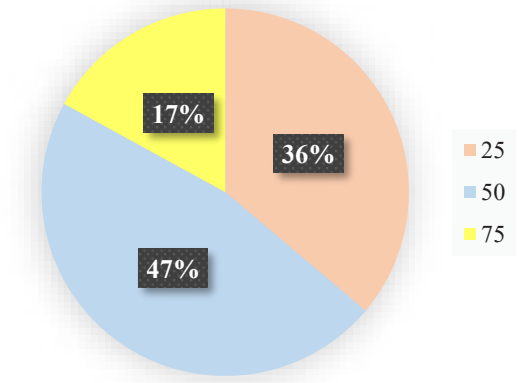
In the third round, the research directions that received 50% or more of the top relevance indicator are considered priorities in S&T. Experts underscore the highest significance of energy systems' security due to terrorist and military actions (83%). The conditions of war proved the physical vulnerability of centralised sources of heating and power generation. Energy facilities require recovery and hardened technologies infrastructure. Other significant responses consider 'Development of means to ensure the safety of NPPs (76%), 'Cybersecurity of large information exchange systems in the energy sector against cyber-espionage and cyber-terrorism' (68%). Such responses can be explained by NPPs generating half of Ukraine's electricity and by their resilience, which provides national security and stability. Energy power-

generating and distributing companies could be vulnerable to cyber-espionage, which is why cybersecurity helps prevent disruptions to critical infrastructure and enables stable functioning.

Figure 1 demonstrates that, in their responses to the thematic block, 36% of experts estimated that Ukrainian S&T potential is currently utilised at 25%. The other 47% of experts estimated the S&T potential utilisation at 50%, and the remaining 17% at 75%, respectively. Based on experts' opinions, Ukraine has a strong capacity to enhance energy efficiency, but due to war-related destruction, a weak link between science and energy enterprises, and a low level of adoption of innovative solutions such as smart grids and renewable technologies, this process remains underdeveloped.

Figure 1

The percentage of the country's S&T potential currently being utilised in efficiency, reliability and safety of energy development (the percentage of experts' responses)

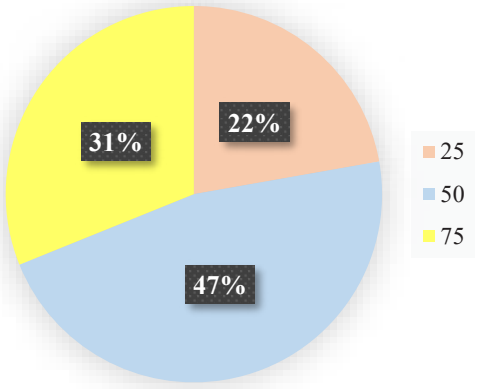


Source: authors' calculations based on the results of the experts' survey.

Figure 2 illustrates experts' responses, with 47% estimating that Ukraine is utilising its S&T potential by 50% and 31% by 75%, respectively, in the area of national security and defence. As we observe, experts are more optimistic about the level of S&T potential utilised in defence tech than about the efficiency, reliability, and safety of energy. This improvement is partially explained by a greater number of targeted funding programs, closer collaboration between engineers and technology users, rapid testing and feedback, which favour a practical approach over a theoretical one on the battlefield. Nevertheless, a third part of the respondents (69%) consider (47% of experts' responses – 50% utilisation level, 22% – 25% respectively) that S&T in the defence and security area is utilised less than 50% of its potential, lacking funding to support long-term S&T projects, meeting operational needs. High opportunities for Ukrainian S&T in the defence area are enabled by foreign grants, the availability of qualified staff, and growing cooperation between military industry, startups and the science community, which can produce competitive breakthrough S&T solutions. Successful examples of startups that put the aforementioned factors into practice include Uforce, which became the first Ukrainian defence tech 'unicorn' (Vestbee Insights, 2026), other private miltech companies that managed to attract investment during the full-scale war: Swarmer – 18.7 mln. $, Osavul – 7 mln. $, AI Bavovna – 2.7 mln. $, Buntar Aerospace – 1.2 mln. $, Himera – 1.1 mln. $ etc. (Defense Tech for Ukraine, 2026).

Figure 2

The percentage of the country's S&T potential currently being utilised in the area of national security and defence (the percentage of experts' responses)

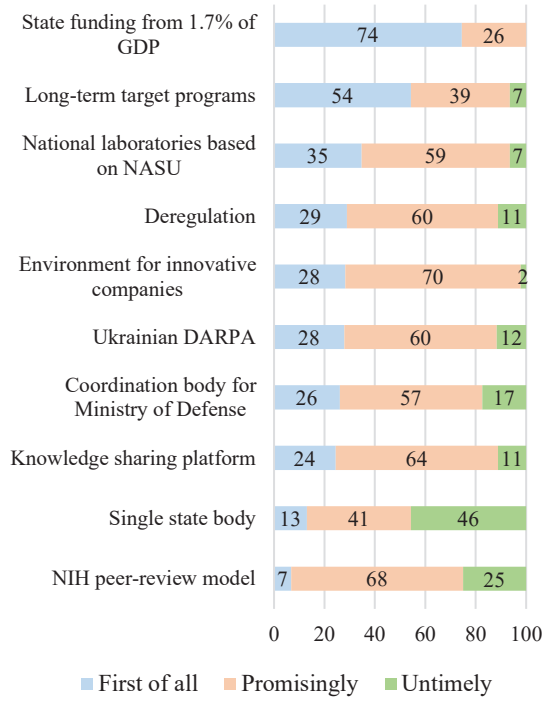


Source: authors' calculations based on the results of the experts' survey.

To achieve favourable conditions for research and innovation, it is vital not only to concentrate limited resources on priorities but also to put in place adequate S&T policy measures and appropriate innovation infrastructure (Figure 3). 74% of experts responded that state funding on R&D should be no less than 1.7% of GDP, as it is declared in Article 48 of the Law of Ukraine 'On Scientific and Scientific Technical Activities'. Many researchers and policymakers emphasise that a sufficient base level of funding is essential to ensure stable S&T development (Malitsky, 2023). Ukraine lags behind EU countries in the indicator of gross R&D expenditures relative to GDP, measured at purchasing power parity. The next important policy measure is the implementation of long-term target programs (54%). It is explained that long-term programs with guaranteed funding can provide stability and confidence for academia, business, the energy industry and their joint projects, serving as an efficient tool to minimise the negative exogenous influence. Experts' responses show that a suitable environment for startups, access to venture capital, business incubators and accelerator services, transfer centres, and infrastructure for innovation clusters are crucial to competitive research and innovation. At the same time, measures such as 'Knowledge sharing platform' (24%), 'Single state body' (13%), and 'NIH peer-review model' (7%) were identified as inefficient for fulfilling S&T policy objectives.

Figure 3

Assessment of the state's scientific priorities and S&T policy measures (the percentage of experts' responses)



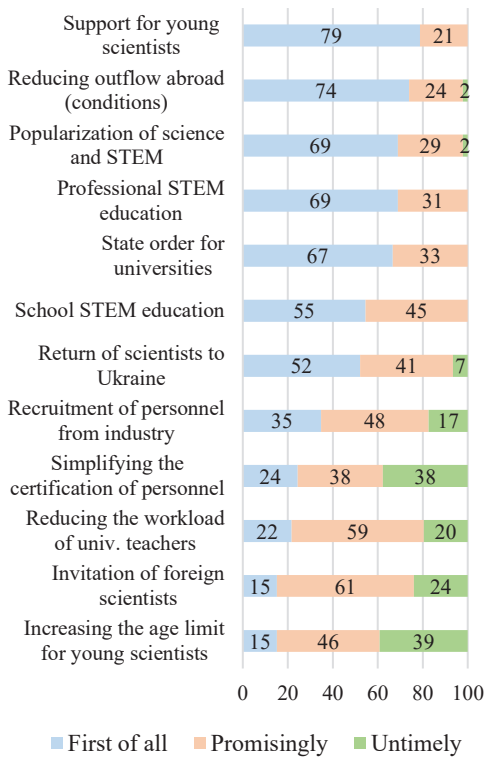
Source: authors' calculations based on the results of the experts' survey.

In the third round, experts assessed the most appropriate (first of all) state's priority measures to restore human resources. The most advisable from the respondents' opinion is: 1. 'Support for young scientists: adequate mentorship, rapid career growth for outstanding scholars' (79% of responses), 2. 'Reducing outflow abroad by creating suitable work conditions' (74%), 3. 'Popularisation of science and STEM' (69%), 4. 'Professional STEM education' (69%), 5. 'State order for universities: increasing the budget quota for deficit specialities' (67%), 6. 'School STEM education' (55%), 7. 'Return of scientists to Ukraine by creating additional bonuses, motivation and grants support' (52%).

Stimulating STEM education in schools and encouraging scientists to return to Ukraine by creating additional bonuses, incentives, and grant support are also considered important policy measures to restore personnel. It should be emphasised that policy tools such as industry recruitment (35%) and the invitation of foreign scientists (15%) were assessed as inefficient. At the same time, the aforementioned measures received comparatively high expert responses among the promising measures, at 48% and 61%, respectively. It means that such policy tools can be quite useful in the long-term perspective. It can be explained that salaries in the Ukrainian industry and EU universities are much higher than in domestic science, which is why it won't yield results under today's conditions.

Figure 4

Assessment of priority measures to restore human resources (the percentage of experts' responses)



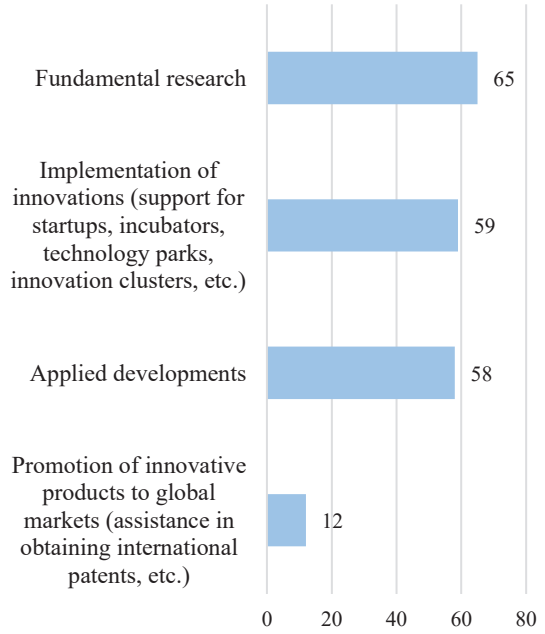
Source: authors' calculations based on the results of the experts' survey.

Responses in Figure 5 show that the state's S&T policy in efficiency, reliability and safety of energy should be focused on directions: fundamental research (65% of responses), implementation of innovations (support for startups, business incubators and innovation clusters, etc.) (59%), applied developments (58%). The above-mentioned directions got a high level of responses. The experts' responses demonstrate the relevance of the interconnection between science and technology commercialisation, which historically has had a weak link. If Ukrainian science could promote its latest R&D solutions, including in energy, and showcase its achievements in society and industry, it would have more funds for modernisation and breakthrough projects. The optimal working model for interacting with, scaling, and promoting S&T startups in energy solutions should be based on the experience of the government defence tech cluster Brave1 (Brave1 Market, 2026). Besides, the organisational and business proficiency of General Cherry Corp and Ukrainian Defence Drones Tech Corp (UDD) manufacturers (U.S. Department of War, 2026) could be useful for developing and implementing innovations in alternative and renewable energy facilities.

Historically, these stages and linkages were weak in Ukraine due to the legacy of Soviet infrastructure, low investment levels, high business risks, weak technology transfer from universities to enterprises,

and limited cooperation between science and industry. To the aforementioned factors were added new negative reasons, such as rapid brain drain of specialists to EU countries and losses due to full-scale war.

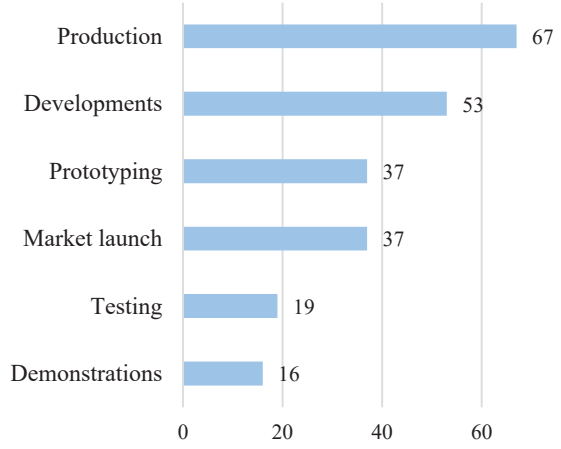
Figure 5
The state's S&T policy should be focused on directions (the percentage of experts' responses)



Source: authors' calculations based on the results of the experts' survey.

Production (67% of responses) and development (53%) are stages of implementing scientific discovery where the most significant problems arise, according to experts' opinions (Figure 6).

Figure 6
The most significant problems arise at the stage of implementing scientific discovery (the percentage of experts' responses)



Source: authors' calculations based on the results of the experts' survey.

Conclusions

1. The study defines the research areas in the thematic block 'Efficiency, Reliability and Safety of Energy' that have not lost their relevance in comparison with the results of the 2021 Foresight, despite the influence of full-scale war (percentage of the top relevance responses): 'Development of new and improvement of existing technologies for energy resource conservation and increasing the share of renewable energy sources and alternative fuels in Ukraine's energy balance' (82%), 'Development of alternative, environmentally friendly technologies, equipment and materials for creating modern autonomous power sources' (78%), 'Development of modern technologies for manufacturing reactor, turbine, thermohydraulic and electrical equipment for domestic nuclear power plants' (76%) etc.
2. The study defines new ideas for priority research areas of S&T in the abovementioned thematic block by the level of top relevance indicator: 'Security, resilience and robustness of the country's energy system, installations and systems against terrorist acts and military actions' (83%), 'Development of means to ensure the safety of nuclear power plants' (76%), 'Cybersecurity of large information exchange systems in the energy sector against cyber-espionage and cyber-terrorism' (68%) etc.
3. 47% of experts responded that S&T potential in the sphere of efficiency, reliability and safety of energy is utilised by only half of its capacity, and 36% by only a quarter, respectively. The S&T potential in the defence and security sphere is utilised better than in the energy sphere in terms of efficiency, reliability, and safety, according to experts' opinions; however, 47% of respondents estimated the level of utilisation at 50%, and 31% at 75%, respectively. The S&T potential of the abovementioned sphere is seriously underutilised, opening up wide opportunities for cooperation and development.
4. Ensuring state funding at 1.7% of GDP for R&D, long-term funding target programs were identified as the most adequate S&T policy measures to enhance research and innovation in energy efficiency. Supporting young scientists, reducing outflow abroad by creating favourable conditions, popularising science and STEM, developing professional STEM education and increasing state order for universities were assessed as the priority S&T policy measures for restoring human resources.
5. The state's S&T policy should primarily focus on fundamental research, the implementation of innovations and applied developments, and the restoration of innovation infrastructure, by attracting investment and increasing cooperation with businesses and leading research centres.

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THE CONTRIBUTION OF AGRICULTURAL MARKETING COOPERATIVES TO THE SUSTAINABLE DEVELOPMENT GOALS: EVIDENCE FROM TÜRKİYE

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Abstract
Agricultural marketing cooperatives play important role in supporting sustainable rural development by strengthening farmers' economic security and production sustainability. In the context of the Sustainable Development Goals (SDGs), cooperatives are expected to contribute not only to economic outcomes but also to broader social and institutional dimensions of sustainability. The aim of the study is to highlight the contribution of oilseed agricultural marketing cooperatives in Türkiye to the Sustainable Development Goals. The study is based on primary data collected through face-to-face surveys with 175 member farmers of agricultural marketing cooperatives in Samsun province, Türkiye. The contribution of cooperatives to the SDGs was assessed using a structured scoring framework comprising a total of 60 five-point Likert-scale statements covering all 17 SDGs. The findings show that agricultural marketing cooperatives make their strongest contributions to SDG 3: Good Health and Well-being (score: 854; mean: 4.88) and SDG 2: Zero Hunger (score: 750; mean: 4.29). These results indicate that cooperatives enhance farmers' quality of life, support production continuity, and contribute to food supply stability, thereby reinforcing resilience in the social and economic dimensions of rural development. In contrast, goals such as SDG 14, SDG 15, SDG 6, and SDG 7 that are more directly related to environmental and institutional dimensions receive relatively lower scores. The findings indicate that the contributions of agricultural marketing cooperatives to sustainable development goals vary across categories. The social dimension shows the highest contribution, followed by the economic dimension, while lower contribution levels are observed in the environmental and cross-cutting dimensions.
Keywords: agriculture, marketing cooperatives, sustainable development goals, Türkiye.

Introduction

In 2015, the United Nations (UN) introduced the Sustainable Development Goals (SDGs), which entered into force on 1 January 2016 and consist of 17 global goals (UN, 2015). More than 150 countries worldwide have committed to achieving these goals, and Türkiye is among them. The SDGs represent one of the most significant challenges that governments, companies, and consumers must address in order to ensure environmental protection and sustainability. They are widely regarded as an acknowledgement that implementing strategies which promote economic growth while meeting social needs such as education, health, social protection, and employment opportunities constitutes the most viable way to definitively eradicate poverty, while simultaneously emphasising climate change mitigation and environmental protection (United Nations Development Programme, 2016). The SDGs constitute a call to action for all countries, high-income, low-income, and lower-middle-income alike, to enhance well-being while protecting the planet. They are based on the recognition that implementing strategies which stimulate economic growth and meet social needs such as education, health, social protection, and employment opportunities represent the most feasible pathway to definitively end poverty, while at the same time emphasising climate change mitigation and environmental protection (Mio et al., 2020).

Cooperatives represent a strong alternative organisational model that goes beyond purely economic functions by acting as drivers of social transformation, being grounded in principles and values, and even offering solutions to environmental challenges. Cooperatives can also contribute to a sustainable economy as well as social and environmental development. In the context of economic crisis, cooperatives are expected to manage social responsibility problems as a competitive priority (Amonarriz et al., 2017). This is viable because cooperatives are expected to be consistent with the principles and values established by the International Cooperative Alliance (ICA).

According to the ICA, cooperatives play a very important role in achieving the SDGs. In 2024, the United Nations conducted an assessment of progress towards the SDGs (2015–2024) and announced that the world is significantly behind in achieving the 2030 Agenda. In this context, the UN has further underlined the critical role of cooperatives in reaching the SDGs by 2030. Accordingly, the year 2025 was declared the International Year of Cooperatives (IYC2025) by the United Nations (ICA, 2024). Various studies and reports also position cooperatives as key actors in achieving the SDGs due to their principles and values (COPAC, 2015, 2017; Díaz de León et al., 2021). The fact that agricultural cooperatives account for approximately 40% of all cooperatives worldwide and nearly half of cooperative members clearly demonstrates the importance of agricultural cooperatives within the cooperative movement (ICA, 2024).

Agricultural marketing cooperatives are a type of agricultural cooperative designed to help producers market their products more effectively, increase their bargaining power, reduce their costs and improve their access to markets. Unlike general agricultural cooperatives, these cooperatives focus more on activities such as the collection, processing, storage and marketing of products. Through these functions, agricultural marketing cooperatives not only contribute to the economic well-being of their members but also play significant roles in numerous areas related to sustainable development goals, such as

rural development, income growth, sustainable production and social welfare. The importance of these cooperatives within the agricultural sector is clearly evident in the case of Türkiye. Indeed, according to 2025 data, there are 338 agricultural marketing cooperatives in Türkiye, with approximately 332 thousand producer members (RofAF, 2025).

A review of the literature has revealed that interest in research on the impact of agricultural cooperatives on the SDGs has increased in recent years. Therefore, this study is of particular importance in addressing this significant gap in the literature. Research has primarily examined the impact of cooperatives on these objectives based on one or more SDGs (Nkpoyen & Awusa, 2019; Martinez-Leon et al., 2020; Díaz de León et al., 2021; Mozas-Moral et al., 2021; González & Alonso, 2022; Andrieu et al., 2023). However, there are very few studies that examine the impact of agricultural cooperatives in the context of all 17 SDGs (González & Alonso, 2022). As evidenced by the literature review, it has been determined that all studies on the role of agricultural cooperatives in the Sustainable Development Goals (SDGs) are found in the foreign literature, and that no field studies have been conducted on this subject in Türkiye. Consequently, a significant gap in the literature on this topic has been identified in Türkiye, and the proposed research is expected to fill this gap. The aim of the study is to highlight the contribution of oilseed agricultural marketing cooperatives in Türkiye to the Sustainable Development Goals.

Materials and Methods

This study focuses on analysing the extent to which oilseed Agricultural Marketing Cooperatives (AMC) in Samsun Province contribute to the Sustainable Development Goals (SDGs). To this end, two AMC operating in Samsun Province were included in the study, and a survey was administered to the farmers who are members of these cooperatives. Primary data were collected through face-to-face surveys conducted with farmers who are members of oilseed agricultural sales cooperatives operating in Samsun province, Türkiye (Figure 1). Ethical approval for this survey was obtained from the Ondokuz Mayıs University Social and Human Sciences Research Ethics Committee (Decision No. 2025-248).

A stratified sampling method was applied to determine the sample size, and proportional allocation was used across strata (Yamane, 2010). Farms were classified into four strata based on cultivated land size. The first stratum included farms with 1–25.9 decares, the second 26–66.9 decares, the third 67–164.9 decares, and the fourth stratum farms with 165 decares and above. The margin of error was set at 10% with a confidence level of 99%, resulting in a total sample size of 175 farmers (Formula 1).

$$n = \frac{N\sum(N_h S_h^2)}{N^2D^2+\sum(N_h S_h^2)} \quad (1)$$

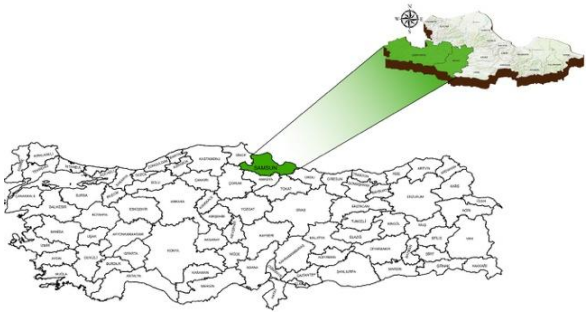
n: Sample size,
N: Number of units in the population (3,125),
N_h: Number of units in the h^{th} layer,
S_h^2: Variance of the h^{th} layer,
D^2: (d^2/Z^2),
d: The maximum allowable error or the difference between the sample mean and the population mean,
z: The z-value from the standard normal distribution table at the 99% confidence level (2.57).

The Proportional Allocation Method was used to allocate the sample size across strata (Yamane, 2010). In this method, the sample size (n_h) for each stratum is proportional to that stratum's share of the population (N_h/N); was calculated using the Formula 2.

$$n_h = \frac{N_h S_h}{\sum(N_h.S_h)}.n \quad (2)$$

The distribution of surveyed farmers across cooperatives shows a balanced structure. Approximately half of the respondents were members of the Havza Oilseed Agricultural Sales Cooperative, while the remaining respondents were members of the Vezirköprü Oilseed Agricultural Sales Cooperative. This distribution was designed to adequately represent the activity areas and member profiles of both cooperatives. The main data was obtained from the surveys conducted June-August 2025 with the members of AMC in Samsun province, Türkiye.

Figure 1
Research area



To evaluate the contribution of agricultural cooperatives to the Sustainable Development Goals (SDGs), a questionnaire consisting of 60 five-point Likert-scale statements covering all 17 SDGs was developed. Since there is no standardized measurement scale directly assessing cooperatives' contributions across all SDGs, the survey items were compiled and adapted from related literature examining cooperatives, sustainable development, environmental sustainability and rural livelihoods (Andrieu et al., 2023; Anigbogu & Uzondu, 2019; Biermann et al., 2017; Birchall, 2017; Díaz de León et al., 2021; González & Alonso, 2022; Heifer International, 2012; ICA, 2015, 2022; ILO, 2019; Lafont et al., 2023; Martinez-Leon et al., 2020; Neupane et al., 2023; Nkpoyen & Awusa, 2019; Osti, 2012; Pakawanich et al., 2022; Surendran Padmaja et

al., 2023; UN, 2024; Vu et al., 2023; Wu et al., 2023). In addition, the official SDG targets and indicators published by the United Nations were used as a guiding framework to ensure that each goal was adequately represented. The draft questionnaire was reviewed by experts in agricultural economics and cooperative studies to ensure content validity before the final survey implementation.

In the study, the 17 Sustainable Development Goals (SDGs) were broken down into sub-goals, using the classification developed by Lafont et al. (2023) (Table 1). Accordingly, SDG 8, SDG 9, SDG 10, and SDG 12 have been assigned to the 'Economic' category, SDGs 1, 2, 3, 4, 5, 7, 11, and 16 to the 'Social' category, and SDGs 6, 13, 14, and 15 to the 'Environmental' category. SDG 17 has been designated as a separate group under 'Partnerships for the Goals'.

Table 1
Classification of the Sustainable Development Goals

Categories	Description	Sustainable Development Goals	Authors
Economic	Objectives focused on economic and sustainable development	SDG 8-Decent work and economic growth SDG 9-Industry, innovation, and infrastructure SDG 10-Reduced inequalities SDG 12-Responsible consumption and production	Costanza et al. (2016) Halkos & Gkampoura (2021) van Zanten & van Tulder (2021)
Social	Objectives focused on promoting actions that respect society and its values, as well as on provision of access to actions linked to equal development on the global level	SDG 1-No poverty SDG 2-Zero hunger SDG 3-Good health and well-being SDG 4-Quality education SDG 5-Gender equality SDG 7-Affordable and clean energy SDG 11-Sustainable cities and communities SDG 16-Peace, justice, and strong institutions	Voola et al. (2022) Biermann et al. (2022) Di Pierro et al. (2023)
Environmental	Objectives focused on the environment and counteracting the adverse effects of climate change and unsustainable actions	SDG 6-Clean water and sanitation SDG 13-Climate action SDG 14-Life below water SDG 15-Life on land	Omisore (2018) Kopnina (2016) Manigandan et al. (2022) Parmentola et al. (2022)
Cross-cutting	Cross-cutting objectives linked to a multitude of areas	SDG 17-Partnership for the goals	Yu et al. (2022) Anwar et al. (2022)

Reference: Lafont et al. (2023).

Results and Discussion

Member Profile and Descriptive Statistics

The socio-economic characteristics of members presented in Table 2 provide an overview of the socio-demographic and economic characteristics of the members of agricultural sales cooperatives included in the survey. The findings indicate that cooperative members largely consist of older farmers with long-standing agricultural experience, for whom farming remains the main livelihood activity.

The average age of the members is 56.4 years, while the mean duration of agricultural experience reaches 39.18 years, reflecting a highly experienced farming population. The average household size of 4.26 persons suggests that traditional rural family structures are still prevalent. The relatively low average education level (6.63 years of schooling) highlights the importance of cooperatives as complementary institutions for improving access to information, knowledge dissemination, and advisory support.

From an economic perspective, the mean Gross Production Value (GPV) of cooperative members amounts to USD 21,485 per year, while the average farm size is 136.4 decares, indicating the predominance of medium-scale farming operations. At the same time, the average distance to cooperatives (20.6 km) points to potential physical accessibility constraints for some farmers, which may affect participation and engagement.

Indicators related to cooperative membership reveal a stable and long-term relationship between farmers and their cooperatives. The average membership duration of 18.9 years suggests that cooperatives are perceived as enduring and reliable institutional arrangements. The vast majority of members have paid entry capital and membership dues, indicating a high level of organisational commitment and institutional loyalty.

In terms of gender distribution, cooperative membership is overwhelmingly male, with female involvement remaining extremely limited. This finding points to persistent gender disparities in cooperative participation within the agricultural sector. In addition, most members report having social security coverage and identify farming as their main occupation, confirming that agriculture constitutes a long-term and central livelihood strategy for cooperative members.

The results regarding profit-sharing are particularly

noteworthy. While approximately half of the members report receiving dividends from their cooperatives, a substantial proportion indicate that they do not benefit from profit distribution. This suggests that the economic benefits generated by cooperatives are not perceived equally among members, and that the distribution of returns may vary across the membership base.

Overall, the findings presented in Table 2 demonstrate that agricultural sales cooperatives constitute an important institutional structure for experienced farmers who rely primarily on agriculture for their livelihoods. However, the low level of female participation, the physical distance to cooperatives, and differences in perceived economic benefits point to areas where the transformative role of cooperatives could be further strengthened.

Table 2

Socio-economic characteristics of agricultural marketing cooperatives members

Variables	Definition of variables		
		Mean	Std. Dev.
AGE	Age of the member (years)	56.4	12.13
HOUSEHOLD	Household number (person)	4.26	1.96
EDUCATION	Education level of the member (year)	6.63	2.63
EXPERIENCE	Agricultural experience of the member (years)	39.18	11.68
DISTANCE	Distance from agricultural cooperatives (km)	20.6	30.80
GPV	Gross Production Value ($/year)*	21,485	25,318
LAND	Agricultural land (decares)	136.4	202.77
MEMTIME	Membership duration (years)	18.9	10.7
		n	%
GENDER	Members who were female	2	1.1
	Members who were male	173	98.9
SOCSEC	Members who have not social security	9	5.1
	Members who have social security	166	94.9
MAINOCCUP	Members whose main occupation is farming	143	81.7
	Members whose main occupation is not farming	32	18.3
ENTRYCAP	No paid entry capital to the cooperative	6	3.4
	Paid entry capital to the cooperative	169	96.6
DUES	No paid dues to the cooperative	6	3.4
	Paid dues to the cooperative	169	96.6
PROFITSHARE	Members not receiving profit share from the cooperative	81	46.3
	Members receiving profit share from the cooperative	94	53.7

*Exchange rate based on September 2025 values; 1 USD = 41.5 Turkish Lira.

Overall Assessment of the SDGs

The overall assessment of the contribution of agricultural sales cooperatives to the Sustainable Development Goals (SDGs) is based on indicator scores calculated from the perceptions of cooperative member farmers (Table 3). The findings reveal that cooperatives are perceived as making substantial contributions to certain SDGs, while their impact is considered more limited for others.

According to the overall ranking, SDG 3: Good Health and Well-being emerges as the goal to which agricultural sales cooperatives contribute most strongly. The notably higher average score for this goal suggests that cooperatives play an important role in improving farmers' quality of life, social security, and overall well-being. Farmers perceive cooperatives as institutions that indirectly enhance living conditions related to health and welfare.

The second highest-ranked goal is SDG 2: Zero Hunger, indicating that cooperatives are viewed as mechanisms that support the continuity of food production, stability in agricultural activities, and farmers' ability to remain engaged in production. This finding highlights the critical role of agricultural sales cooperatives in ensuring food security and sustaining rural livelihoods.

SDG 10: Reduced Inequalities, which ranks third, reflects the perception that cooperatives contribute to creating a more balanced structure among farmers in terms of income, market access, and bargaining power. Cooperative membership provides farmers with a more collective and inclusive economic and social position compared to individual market participation.

In contrast, goals that are more directly related to environmental and institutional dimensions receive relatively lower scores. SDG 14: Life Below Water, SDG 15: Life on Land, SDG 6: Clean Water and Sanitation, and SDG 7: Affordable and Clean Energy indicate that cooperatives are perceived by farmers as having a more indirect or limited role in environmental sustainability. Similarly, the lower rankings of SDG 17: Partnerships for the Goals and SDG 16: Peace, Justice and Strong Institutions suggest that the role of cooperatives in multi-stakeholder governance and

institutional partnerships is not sufficiently visible at the farm level.

Overall, the findings show that agricultural sales cooperatives are primarily associated by farmers with economic security, well-being, and the continuity of production, while their perceived contribution to environmental sustainability, energy, water management, and global partnerships remains more limited. This pattern indicates that the transformative role of cooperatives is currently concentrated in economic and social dimensions, while there is considerable potential to strengthen their contribution in environmental and institutional domains. Nkpoyen & Awusa (2019) in their study conducted in the rural areas of Akwa Ibom State, Nigeria, the researchers focused solely on the SDG goals of 'No Poverty' (SDG 1) and 'Zero Hunger' (SDG 2) to examine the impact of cooperatives on these goals using a 5-point Likert scale. The study found that cooperatives have a significant impact on SDGs 1 and 2. Similarly, in a study conducted by Díaz de León et al. (2021) on 134 cooperatives in Mexico, the impacts of cooperatives on the SDG targets—No Poverty (SDG 1), Good Health and Well-being (SDG 3), Quality Education (SDG 4), Gender Equality (SDG 5), decent work and economic growth (SDG 8), and responsible consumption and production (SDG 12). The results indicated that cooperatives have significant impacts on the relevant SDGs. Andrieu et al. (2023) investigated the contribution of cooperatives in the beekeeping sector to the SDGs, focusing on SDGs 5, 8, 9, 12, and 17. The findings of the study indicate a positive alignment between cooperatives in the beekeeping sector and SDGs 5, 12, and 17; however, they also highlight the challenges the sector will face in the future, particularly regarding SDGs 8 and 9.

Table 3

Overall contribution of agricultural sales cooperatives to the Sustainable Development Goals (SDGs)

Total N:175 (%100)									
	Goals	Score	Mean	Rank		Goals	Score	Mean	Rank
	SDG 3 Good health and well-being	854	4.88	1		SDG 13 Climate action	271	1.55	9
	SDG 2 Zero hunger	750	4.29	2		SDG 11 Sustainable cities and communities	270	1.55	10
	SDG 10 Reduced inequalities	459	2.63	3		SDG 16 Peace, justice and strong institutions	257	1.47	11
	SDG 14 Life below water	343	1.96	4		SDG 12 Responsible consumption and production	236	1.35	12
	SDG 4 Quality education	324	1.87	5		SDG 15 Life on land	198	114	13
	SDG 1 No poverty	283	1.62	6		SDG 8 Decent work and economic growth	190	1.09	14
	SDG 9 Industry, innovation and infrastructure	277	1.58	7		SDG 17 Partnerships for the Goals	187	1.07	15
	SDG 5 Gender equality	274	1.57	8		SDG 6 Clean water and sanitation	185	1.06	16
						SDG 7 Affordable and clean energy	185	1.06	17

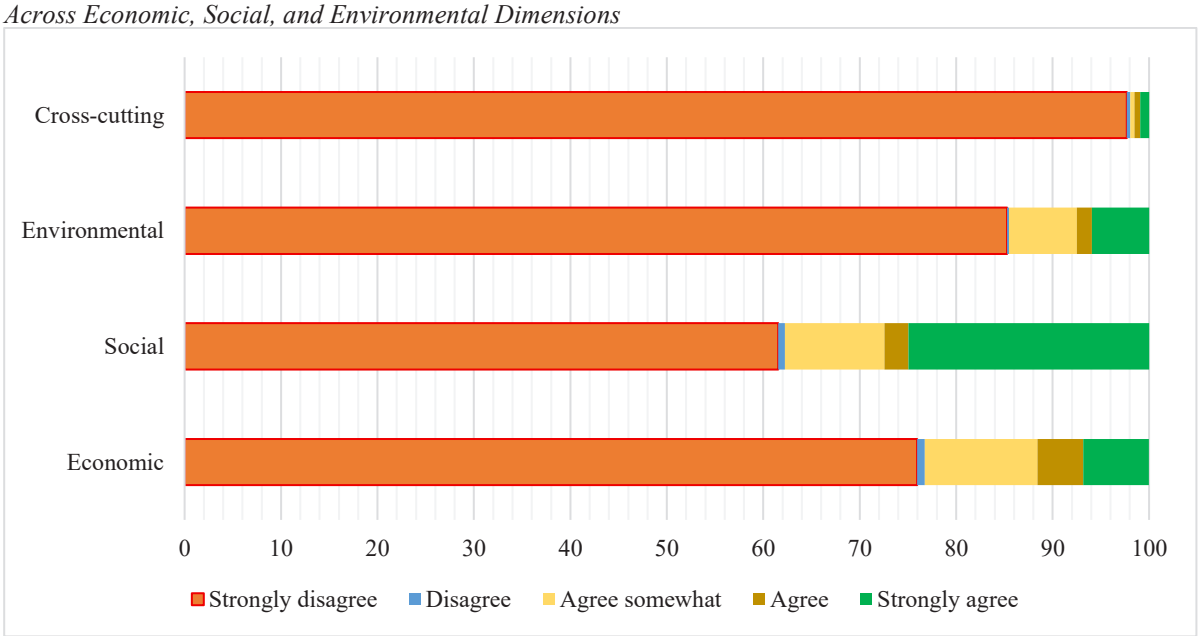
The findings indicate that the contribution of agricultural marketing cooperatives to the Sustainable Development Goals is particularly evident in the social dimension (score: 3,201; mean: 2.29). An examination of the results related to the social category reveals that a significant proportion of participants demonstrated a high level of engagement with the social impacts of cooperatives. Findings in the economic dimension also show that cooperatives make meaningful contributions through functions such as enhancing producers' income opportunities, facilitating market access, and ensuring economic stability (Table 4). This finding is consistent with studies in the literature. For example, According to Lafont et al. (2023), producer cooperatives are closely associated with the achievement of no poverty (SDG 1), zero hunger (SDG 2), responsible consumption and production (SDG 12) and life on land (SDG 15). The researchers emphasise that cooperatives can play significant roles in reducing poverty, supporting food security and protecting environmental resources.

Table 4
Results of classification of the Sustainable Development Goals

Categories	Score	Mean	Rank
Economic	1,163.38	1.66	2
Social	3,201.78	2.29	1
Environmental	998.08	1.42	3
Cross-cutting	187.00	1.07	4

The distribution of agricultural marketing cooperatives' contribution to the sustainable development goals across economic, social, and environmental dimensions is given in Figure 2. In particular, the proportion of 'agree' and 'strongly agree' responses are higher in the social and economic dimensions, indicating that members viewed the contributions of agricultural marketing cooperatives in these areas positively. In contrast, the relatively higher proportion of 'agree somewhat' and 'disagree' responses in the environmental dimension suggests that environmental contributions are perceived as more limited compared to other dimensions. Results regarding the environmental dimension, however, indicate that cooperatives are still assuming a developing role in this area, though there is a certain level of awareness and potential for contribution. Overall, it is evident that the contribution of agricultural marketing cooperatives to the Sustainable Development Goals is more pronounced in the social and economic dimensions, while the environmental dimension remains open to further development. These findings highlight that cooperatives are multifaceted structures that contribute significantly to the rural development process and play a critical role, particularly in strengthening social sustainability.

Figure 2
The Distribution of Agricultural Marketing Cooperatives' Contribution to the Sustainable Development Goals Across Economic, Social, and Environmental Dimensions



Conclusions

1. The findings of this study offer practical insights for policymakers, cooperative managers, and rural development practitioners.
2. The contribution of cooperatives to the SDGs has been concentrated on certain goals and limited in others.
3. In particular, their contribution is strong in production- and well-being-related goals but weak in environmental and institutional goals.
4. The SDGs to which agricultural marketing cooperatives contribute the most are SDG 3, SDG 2, and SDG 10. This finding strongly demonstrates that agricultural marketing cooperatives indirectly contribute to health and quality of life by improving farmers' incomes and living standards, and that they have a direct impact on food security. Additionally, agricultural marketing cooperatives play a balancing role in income distribution by facilitating small producers' access to markets.
5. The SDGs to which agricultural marketing cooperatives contribute at a moderate level are SDG 9, SDG 5, SDG 13, SDG 11, SDG 16, and SDG 12. The low level of contribution in areas such as innovation, gender equality, climate action, and institutional frameworks indicates that cooperatives are not sufficiently active in these areas.
6. The lower scores observed for environmental and institutional goals highlight the need for capacity-building measures and policy incentives to strengthen agricultural marketing cooperatives' roles beyond their traditional economic functions.
7. Agricultural marketing cooperatives make their greatest contribution to the Sustainable Development Goals in the social dimension. It is clear that cooperatives play a critical role in rural development, particularly in terms of fostering solidarity, cooperation, and strengthening social capital among producers.
8. To further strengthen cooperatives' existing social contributions and extend them to other dimensions of sustainability, socially focused activities should be supported; simultaneously, policies and educational programs that encourage the integration of economic and environmental practices into the cooperative structure should be developed.

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INTERREGIONAL TOURISM SPILLOVERS AND REGIONAL DEVELOPMENT: A SPATIAL NETWORK APPROACH

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Abstract
This study examines interregional tourism spillovers and their consequences for regional development using a spatial network framework. Treating 47 subnational regions as nodes in a weighted directed network of domestic tourism flows, the study investigates how network structural properties condition the magnitude, directionality, and spatial reach of tourism-induced development externalities. The theoretical framework integrates network science, spatial econometrics, and regional development theory, drawing on growth pole concepts, relational economic geography, and graph-theoretic methods. The study constructs interregional tourism flow networks and computes four centrality measures—degree, betweenness, closeness, and eigenvector—synthesised into a composite Network Position Index (NPI). Flow-derived and geographic contiguity spatial weight matrices are compared using Moran's I and LISA statistics; spillover magnitudes are estimated via Tourism Multiplier Spillover (TMS) and Spatial Growth Spillover (SGS) indicators disaggregated by NPI quartile. Findings reveal heterogeneous development outcomes: hub regions exhibit strong multiplier-driven growth diffusion; gateway regions serve as intermediaries in the two-hop transmission chain from core to periphery; and peripheral regions receive attenuated spillovers due to structural isolation. Network-derived weight matrices consistently outperform geographic contiguity matrices in explaining regional development clustering, validating the functional connectivity approach. These results provide actionable guidance for regional tourism planning and infrastructure investment strategies targeting peripheral integration.
Keywords: spatial network analysis, tourism spillovers, interregional flows, spatial autocorrelation, network centrality.

Introduction

Tourism ranks among the most geographically dispersive economic sectors, with flows of visitors, capital, knowledge, and labor crossing administrative boundaries in patterns that rarely correspond to the jurisdictional logic underpinning regional development policy (Hall & Page, 2014; Scott & Jafari, 2010). While the direct economic impacts of tourism at the destination level are extensively documented through input-output analysis, tourism satellite accounts, and employment multiplier studies (Fletcher, 1989; Dwyer et al., 2004), the secondary and tertiary ripple effects that propagate outward from primary destinations into structurally connected or geographically adjacent regions remain undertheorized and empirically underexplored (Yang & Fik, 2014; Urtasun & Gutierrez, 2006).

The dominant analytical tradition in tourism economics has framed regional impact assessment as a destination-level problem, deploying multiplier frameworks that treat the region of study as an isolated system (Williams & Shaw, 1998; Pearce, 1995). This framing systematically neglects the spatial interdependencies that arise when tourism activity generates interregional demand flows, cross-boundary supply chain integration, shared infrastructure investments, and competitive or complementary positioning dynamics between destinations. The recognition that regions function as nodes in relational systems – whose economic significance is shaped not merely by internal endowments but by position within webs of interaction – has progressively advanced from mainstream economic geography (Krugman, 1991; Fujita et al., 1999; Bathelt & Gluckler, 2003) into tourism research, though the integration remains methodologically fragmented and theoretically incomplete.

Spatial econometrics has made partial progress in addressing spatial interdependence in tourism systems by documenting positive spatial autocorrelation in regional tourism performance indicators (Yang & Wong, 2012; Romao et al., 2017; Patuelli et al., 2013). However, these contributions overwhelmingly rely on geographic contiguity or distance-based spatial weight matrices that impose an a priori spatial structure – one that may poorly reflect actual functional connectivity when tourism flows are shaped by transport corridors, institutional arrangements, or cultural linkages that diverge from physical proximity.

This article develops and applies a spatial network framework to the analysis of interregional tourism spillovers and their regional development consequences. The study makes three principal contributions. First, it formalises the concept of spatial network position as a primary determinant of tourism spillover exposure, shifting the analytical frame from geographic proximity to functional connectivity. Second, it identifies the structural conditions – hub concentration, gateway brokerage, peripheral isolation – under which tourism spillovers are likely to reduce versus reinforce spatial inequality. Third, it demonstrates empirically that network-derived spatial weight matrices outperform geographic contiguity matrices in explaining regional development clustering.

Theoretical framework

Tourism as a relational spatial system

Conventional models of tourism's regional impact derive from location theory and agglomeration economics, emphasising the concentration of tourism activities at destination nodes endowed with

natural, cultural, or infrastructural assets (Pearce, 1995; Williams & Shaw, 1998). These models conceptualise space primarily as a container for economic activity rather than as a relational medium through which flows, interactions, and dependencies are organised. The spatial turn in economic geography (Sheppard, 2002; Bathelt & Gluckler, 2003) introduced a relational ontology in which the economic significance of a place is defined by its position within webs of interaction: flows of people, goods, knowledge, and investment that constitute the functional geography of economic life.

Leiper's (1979) foundational model of the tourism system – comprising origin regions, transit routes, and destination regions linked by tourist flows – already contains an implicit network logic, positioning tourism as a flow system rather than a site-based phenomenon. Oppermann (1995) extended this framework through multi-destination itinerary structures. Dredge (1999) proposed a nodes-and-links model of destination structure emphasising connectivity as a structural determinant of competitive positioning. Shih (2006) explicitly applied graph-theoretic methods to characterise the topology of a regional tourism network, demonstrating that network structure systematically shaped destination attractiveness and visitor flow patterns.

Spillover mechanisms in regional tourism systems

Economic spillovers refer to the transmission of economic impulses from one regional unit to others through channels not fully captured by market prices (Capello, 2009; Audretsch & Feldman, 1996). In the tourism context, several distinct transmission mechanisms operate. Supply chain spillovers arise when a tourism-receiving region sources inputs from neighbouring or connected regions, generating backward linkage effects that propagate demand through interregional input-output relationships (Yang & Fik, 2014; Fletcher, 1989). Corridor spillovers emerge when tourism flows traverse transit regions en route between origin and primary destination, generating expenditure in intermediate nodes. Infrastructure spillovers arise when investments in gateway infrastructure – airports, motorway junctions, railway hubs – improve accessibility for a regional catchment extending well beyond the primary investment site (Vickerman, 1991). Against these positive channels, substitution effects may generate negative externalities: concentration of visitor flows at primary hubs may divert demand from peripheral alternatives (Ma & Hassink, 2013).

Spatial network analysis: analytical framework

A spatial network G = (V, E, W) consists of a node set V (regions), an edge set E (interregional flow linkages), and a weight matrix W with entries w_{ij} representing directional flow intensity from region i to region j. Four centrality measures are employed at the node level. Degree centrality (DC_i) counts the number and strength of a region's direct connections. Betweenness centrality (BC_i) counts how frequently a region lies on the shortest path between all other pairs of regions – identifying 'gateway' regions that tourists must pass through to travel between distant parts of the system. Closeness centrality (CC_i) measures how quickly a region can be reached from all others. Eigenvector centrality (EC_i) weights a region's connections by the centrality of its neighbours. A composite Network Position Index (NPI) synthesises these four measures via principal component analysis. Networks combining high clustering coefficient with low average path length exhibit small-world properties (Watts & Strogatz, 1998). Scale-free degree distributions (Barabasi & Albert, 1999) concentrate spillover generation in hub regions.

Literature review

Spatial econometric studies of tourism spillovers

The application of spatial econometrics to tourism research has advanced substantially since the early 2000s (Anselin, 1988; LeSage & Pace, 2009). Yang and Wong (2012) applied spatial lag and spatial error models to provincial tourism data in China, finding significant positive spatial dependence consistent with demand-driven spillover mechanisms. Romao et al. (2017) deployed geographically weighted regression to reveal spatial heterogeneity in drivers of tourism performance across European regions. Patuelli et al. (2013) documented persistent spatial autocorrelation in regional tourism demand using gravity model specifications. A consistent limitation of this literature is reliance on geographic contiguity or inverse-distance spatial weight matrices that impose a priori spatial structures independent of actual functional connectivity.

Network analysis in tourism geography

Formal network analysis has been applied across several tourism research domains. Scott et al. (2008) applied social network analysis to destination stakeholder collaboration networks, identifying bridging actors whose removal would fragment cooperative governance. Shih (2006) demonstrated that graph-theoretic centrality measures predict visitor flow volumes in Taiwan's drive tourism network. Hwang et al. (2006) revealed hierarchical gateway structures in multi-city itinerary patterns. Mou et al. (2020) used geotagging data to construct a province-level tourism flow network for China, finding coastal provinces dominate eigenvector centrality. Guo et al. (2019) applied community detection to identify tourism regions diverging substantially from administrative provinces.

Research gaps and study positioning

Three primary gaps motivate this study. First, spatial econometric research has documented tourism spillovers without linking magnitude to network position – treating spatial dependence as a nuisance rather than a structural property. Second, network analysis has characterised flow system topology

without connecting structural properties to development consequences within a theoretically motivated framework. Third, the identification of structurally distinct regional types – hubs, gateways, peripheral nodes – and their differential spillover profiles has not been empirically investigated at scale. The present study bridges all three gaps through an integrated spatial network methodology.

Study area and data

Study area

The empirical analysis is conducted at the subnational provincial/NUTS-2 equivalent regional level across 47 administrative regions. The study area encompasses a contiguous national territory with well-documented interregional tourism flows and publicly available regional economic statistics, enabling full coverage of the origin-destination matrix without significant data gaps. The spatial scope captures meaningful variation in tourism development trajectories: the sample includes coastal and inland regions, metropolitan and rural areas, internationally recognised destination zones, and transit regions whose tourism role is primarily defined by corridor function rather than terminal attraction.

Data sources and temporal coverage

Six data series are employed: (1) interregional domestic tourism flow matrices from the national tourism statistics authority's household travel survey (~80,000 households per wave); (2) regional GDP per capita and growth rates at constant 2015 prices; (3) regional employment shares in tourism-adjacent sectors; (4) regional accommodation stock and capacity growth from establishment-level registry data; (5) regional infrastructure accessibility indices from transport network databases; and (6) regional population and urbanisation rates from decennial census. The panel covers ten years of consistent data (2012–2021). All flow matrices are normalised by origin-region population to control for scale effects prior to network construction.

Materials and Methods

Analytical units and variable operationalisation

The empirical analysis is conducted at the subnational provincial/NUTS-2 equivalent regional level, with n = 47 regions constituting network nodes. Regional GDP per capita growth serves as the primary development outcome variable. Flow matrices are log-transformed and normalised by origin-region population prior to network construction to control for scale differences. Temporal analysis covers the 2012–2021 panel.

Network construction

The interregional tourism network is formalised as a directed weighted graph G = (V, E, W), where W is the n×n asymmetric weight matrix with entries w_{ij} representing normalised tourist-night flows from origin i to destination j. Edge weights are log-transformed for centrality computation ($w^*_{ij} = \log(1 + w_{ij})$) to address right-skewness. Threshold filtering removes edges below the 10th percentile of the nonzero flow distribution. Global network statistics – density, reciprocity, clustering coefficient, average path length, small-world index, degree assortativity, and degree distribution power-law exponent – are computed and benchmarked against equivalent random graphs (Erdős-Rényi, 1,000 simulations).

Centrality analysis and Network Position Index

Four centrality measures are computed: (i) Degree centrality (DC_i) as weighted strength aggregating inbound and outbound flows; (ii) Betweenness centrality (BC_i) using Brandes' (2001) algorithm on weighted shortest paths; (iii) Closeness centrality (CC_i) as the inverse mean weighted geodesic distance; (iv) Eigenvector centrality (EC_i) as the leading eigenvector of W*. All measures are normalised to [0,1]. A composite NPI is extracted as the first principal component of the four normalised measures, standardised to mean = 0, SD = 1.

Spatial weight matrices and autocorrelation analysis

Two spatial weight matrices are constructed. W^c is a row-standardised first-order geographic contiguity matrix. W^f is a row-standardised matrix derived from the log-transformed tourism flow network W*, representing functional connectivity. The Mantel test quantifies divergence between W^c and W^f. Global Moran's I statistics are computed under both matrices (9,999 Monte Carlo permutations). Local Indicators of Spatial Association (LISA; Anselin, 1995) identify High-High and Low-Low development clusters with false discovery rate correction applied.

Spillover magnitude estimation

Two complementary spillover indicators are operationalised. The Tourism Multiplier Spillover (TMS_i) captures supply-chain-driven spillovers and is defined as: $TMS_i = (II_i + IND_i) / DVA_i$, where II_i denotes indirect economic impacts, IND_i denotes induced impacts, and DVA_i is direct tourism value added in region i. Indirect and induced effects are estimated from regional input-output coefficients via the Leontief inverse approach (Fletcher, 1989). The Spatial Growth Spillover (SGS_i) is estimated from a fixed-effects panel growth regression: $\Delta\ln(GDP_{it}) = \alpha_i + \lambda_t + \beta \cdot W^f \Delta\ln(GDP_{jt}) + \gamma X_{it} + \varepsilon_{it}$, where X_{it} is a vector of regional controls. The estimated coefficient β represents the average network-mediated growth spillover.

Robustness checks

Three robustness exercises confirm the stability of the main findings. First, network threshold sensitivity is evaluated using 5th and 15th percentile thresholds; Spearman rank correlations between NPI rankings across specifications exceed 0.94 ($p < 0.001$). Second, alternative spatial weight matrix specifications are tested; W^f outperforms all alternative geographic matrices in Moran's I

comparisons. Third, the SGS regression is re-estimated using spatial Durbin and spatial error model specifications; the sign and significance of β are maintained throughout.

Results and Discussion

Network topology

Table 1 presents the global topological statistics. The network exhibits moderate density (ρ = 0.342), with reciprocity r = 0.612 confirming that a majority of corridor dyads sustain bidirectional flows. The mean clustering coefficient (CC = 0.481) substantially exceeds the random benchmark ($p < 0.001$), confirming strong local clustering. The small-world index σ = 1.68 ($p < 0.001$) is consistent with rapid within-cluster diffusion dynamics. The negative degree assortativity (r = −0.18, p = 0.008) indicates a disassortative hub-and-spoke pattern with direct implications for spillover asymmetry. The power-law exponent γ = 2.31 ($p < 0.05$) confirms a scale-free degree distribution with a small number of hub regions dominating the system.

Table 1

Global topological statistics of the interregional tourism network

Benchmarks from 1,000 Erdős-Rényi random graphs (Monte Carlo, 9,999 iterations)

Network property	Observed	Benchmark	p-value
Node count (n)	47	—	—
Network density (ρ)	0.342	—	—
Reciprocity (r)	0.612	0.342	<0.001
Mean clustering coeff.	0.481	0.340	<0.001
Mean path length (L)	2.73	2.89	0.031
Small-world index (σ)	1.68	1.00	<0.001
Degree assortativity	−0.18	0.00	0.008
Power-law exponent (γ)	2.31	—	<0.05

Regional network centrality and geographic distribution

Table 2 reports summary statistics for the centrality measures and composite NPI. Pronounced heterogeneity is evident: top-quartile regions by DC exhibit weighted strength 4.8 times the median, while Q1 regions command less than 22% of median strength. The high inter-measure correlation (mean r = 0.74) confirms convergent validity; the lower BC correlations (mean $r^{Bc} = 0.61$) indicate that gateway brokerage is held by intermediate-connectivity regions strategically positioned on inter-cluster paths. The first principal component explains 71.3% of total variance, confirming a coherent underlying embeddedness dimension.

Table 2

Network centrality descriptive statistics

Centrality Measure	Mean	SD	Q1 (25th)	Q4 (75th)
Degree Centrality (DC_i)	0.412	0.198	0.251	0.573
Betweenness Centrality (BC_i)	0.187	0.143	0.071	0.284
Closeness Centrality (CC_i)	0.553	0.141	0.449	0.657
Eigenvector Centrality (EC_i)	0.389	0.221	0.204	0.571
Network Position Index (NPI)	0.000	1.000	−0.681	0.705

All centrality measures normalised [0,1]. NPI = first principal component (71.3% variance explained), standardised mean = 0, SD = 1.

Spatial autocorrelation: network vs. geographic weight matrices

Table 3 reports Moran's I statistics under geographic contiguity (W^c) and tourism flow network (W^f) weight matrices. W^f consistently produces higher Moran's I values across all tested development indicators, with differences most pronounced for tourism employment share ($I^f = 0.531$ vs. $I^c = 0.374$; z-diff = 5.21, $p < 0.001$). This systematic superiority confirms that regional development indicators are more strongly structured by tourism network connectivity than geographic adjacency – directly vindicating the use of flow-derived rather than proximity-based weight matrices. Notably, geographically peripheral but network-central regions shift from spatial outliers under W^c to High-High cluster members under W^f.

Table 3
Moran's I under geographic contiguity (W^c) and network flow (W^f) weight matrices

Indicator	Moran's I (W^c)	Moran's I (W^f)	z-diff	p (diff.)
GDP per capita (level)	0.341**	0.396**	2.14	0.032
GDP per capita (growth)	0.287**	0.412***	3.78	<0.001
Tourism employment share	0.374***	0.531***	5.21	<0.001
Accommodation capacity growth	0.321***	0.488***	4.63	<0.001
Regional wage level	0.298**	0.341**	1.47	0.141

*** $p < 0.001$; ** $p < 0.01$ (Monte Carlo, 9,999 iterations). Mantel $r(W^c, W^f) = 0.43$ ($p < 0.001$).

Tourism spillover magnitude by network position
Table 4 presents the quartile analysis of TMS and SGS by NPI quartile. A monotonically increasing relationship is confirmed: Q4 regions exhibit TMS 3.2 times higher and SGS 2.8 times higher than Q1 regions (Kruskal-Wallis H = 18.4, $p < 0.001$ for TMS; H = 14.7, $p = 0.002$ for SGS). The bivariate relationships reveal approximately linear increases from Q1 through Q3 with concavity at the upper Q4 tail – consistent with hub saturation effects whereby the marginal spillover return per unit of additional centrality declines as hub regions accumulate disproportionate flow volumes.

Table 4
Tourism spillover measures by NPI quartile

NPI Quartile	n	Mean TMS	Mean SGS	TMS (CV)	SGS (CV)
Q1 — Lowest NPI	12	1.24	0.031	0.21	0.38
Q2	12	1.67	0.048	0.19	0.33
Q3	11	2.41	0.072	0.34	0.41
Q4 — Highest NPI	12	3.96	0.087	0.24	0.29
Full sample	47	2.30	0.060	0.47	0.46

TMS = Tourism Multiplier Spillover; SGS = Spatial Growth Spillover. CV = coefficient of variation. Kruskal-Wallis test confirms significant quartile differentiation.

Regional type differentiation
K-means clustering on the four centrality profiles identifies three structurally distinct regional types (Table 5). Type I Hub regions (n = 9): high DC, EC, and BC – primary flow attractors and growth redistributors with highest TMS and SGS values. Type II Gateway regions (n = 14): high BC relative to DC and EC – structural brokers with disproportionately high SGS relative to direct tourism volume, confirming efficient flow-through spillover transmission. Type III Peripheral regions (n = 24): low scores across all measures – lowest TMS and SGS, with network isolation (not geographic remoteness) as the primary predictor of peripheral status. Proximity to Type II gateway regions predicts modest spillover reception ($\beta = 0.31$, $p = 0.017$), confirming the two-hop diffusion mechanism.

Table 5
Regional type profiles from k-means clustering

Regional Type	n	Mean NPI	Mean TMS	Mean SGS	Structural Role
Type I: Hub	9	+1.82	3.91	0.086	Primary attractor & growth pole
Type II: Gateway	14	+0.44	2.18	0.074	Inter-cluster broker & relay
Type III: Peripheral	24	−0.81	1.31	0.033	Dependent receiver node

Silhouette coefficient s = 0.58 ($p < 0.001$).

Theoretical contributions
The empirical findings yield several theoretically consequential insights. The most fundamental is the demonstration that network connectivity – captured by the flow-derived weight matrix W^f – outperforms geographic proximity (W^c) as an explanatory structure for regional development clustering across all key indicators. This finding aligns with the relational turn in economic geography (Bathelt & Gluckler, 2003; Yeung, 2005) and extends it to the tourism context, providing the first systematic empirical validation that functional connectivity is the primary organising

principle of tourism spillover geography.

The identification of three structurally differentiated regional types advances theoretical resolution of the longstanding ambiguity about tourism's distributional consequences. The findings support a modified growth pole framework in which growth diffusion from hub regions is real but geographically selective, mediated by gateway regions' structural brokerage capacity. This two-hop mechanism – hub-to-gateway followed by gateway-to-periphery – implies that extending tourism-driven development to peripheral zones requires strengthening hub-gateway integration and developing gateway-periphery accessibility.

The concavity of the NPI-spillover relationship at high centrality values introduces the concept of hub saturation effects. As hub regions accumulate disproportionate flow volumes, marginal spillover returns per unit of additional centrality decline, potentially reflecting increasing import leakage, congestion diseconomies, or flow redistribution. This provides empirical grounding for the spatial Kuznets curve hypothesis in tourism contexts (Sequeira & Nunes, 2008) – suggesting that tourism development trajectories may produce first increasing, then decreasing spatial inequality as the hub network densifies.

Policy implications

For regional tourism authorities, the spatial network framework provides a diagnostic infrastructure for identifying structurally underperforming regions – nodes with moderate-to-high NPI whose observed spillover generation falls below expectation. These represent candidates for targeted supply-side intervention: investments in hospitality capacity, workforce skill development, and product diversification that convert network position into realised economic outcomes.

For spatial planners and transport authorities, the identification of gateway regions as the most efficient transmitters of growth impulses to peripheral zones suggests reorienting infrastructure investment strategy. Corridor-based regional development strategies investing in transport and service infrastructure along gateway-to-periphery pathways are grounded in the structural logic of the tourism flow network, yielding disproportionate regional development dividends not through direct tourist attraction but through structural network integration.

Limitations

Several limitations merit acknowledgement. Reliance on survey-based secondary flow data introduces sampling error for low-volume dyads and likely undercounts sharing-economy accommodation. Integration of mobile device location data and digital platform transaction records would substantially increase flow measurement resolution. The cross-sectional characterisation of network structure cannot fully capture temporal dynamics. Causal identification faces unresolved omitted variable concerns despite regional fixed effects; instrumental variable strategies exploiting historical infrastructure endowments would strengthen identification. The analysis is restricted to domestic tourism flows.

Conclusions

1. This study has advanced the analysis of interregional tourism spillovers and their regional development consequences through a spatial network framework integrating network science, spatial econometrics, and regional development theory. By formalising the interregional tourism system as a directed weighted graph and deploying a battery of centrality measures, spatial autocorrelation statistics, and descriptive spatial techniques, the study demonstrates that the structural topology of the tourism flow network is a primary determinant of spillover magnitude, directionality, and geographic reach.

2. Three core empirical contributions stand out. Topologically, the interregional tourism network exhibits small-world properties with disassortative hub-and-spoke structure and a scale-free degree distribution concentrating spillover generation in hub nodes and constraining peripheral region integration to indirect two-hop pathways through gateway intermediaries. Methodologically, network-derived spatial weight matrices explain regional development clustering better than geographic contiguity matrices across all tested indicators. Empirically, a monotonically increasing NPI-spillover relationship is confirmed with hub saturation effects, and three structurally distinct regional types are identified with differentiated spillover profiles.

3. Future research priorities include: dynamic network analysis tracking temporal topology evolution; instrumental variable identification strategies using historical transport endowments; extension to international tourism flow networks; micro-level supply chain analysis of multiplier transmission mechanisms; and integration of digital trace data for higher-resolution flow network construction. The spatial network lens transforms the analysis of tourism spillovers from a problem of proximity to a problem of position opening new theoretical and policy horizons for the governance of tourism-led regional development.

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FROM GLOBAL ISSUES TO LOCAL AGENCY: SOCIAL WORK FOR COMMUNITY RESILIENCE IN RURAL MUNICIPALITIES IN LATVIA

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Abstract
In the 21st century, society faces interconnected global issues that transcend national boundaries and require urgent attention and action. Although global issues increasingly affect local communities worldwide, there remains a lack of knowledge about how these challenges manifest locally and how community resilience can be effectively strengthened. Social work can be seen as an essential but underutilised resource for strengthening the resilience and security of communities. The aim of this paper is to examine the role and potential of social work in promoting community resilience in the context of complex and multidimensional global challenges. This study has been conducted within the framework of the Latvian Council of Science research project 'How can social work make communities more resilient? Social work for community resilience between global issues and local agency'. The study uses an explanatory multiple-case study design and the units of analysis are four rural municipalities. The findings indicate that perceptions of community challenges are strongly shaped by stakeholders' professional roles and everyday experiences, with depopulation, low birth rates, and population ageing emerging as the main shared concerns across municipalities and stakeholder groups. The study further reveals a disconnect between academic and policy constructions of 'global challenges' and the ways local stakeholders interpret social problems. In the context of military threat risks, the findings demonstrate limited crisis preparedness and the structural under-recognition of social work within civil protection systems at both municipal and national levels, highlighting the need for stronger integration of social work into disaster preparedness and civil protection frameworks in order to strengthen community resilience.
Keywords: community social work, community resilience, disaster preparedness, global challenges.

Introduction

In contemporary society, we live in an increasingly interconnected world. In the twenty-first century, societies are confronted with a range of interrelated global challenges that transcend national borders and demand urgent attention and collective action. From climate change and environmental degradation to economic insecurity and inequality; from armed conflicts to rapid technological transformations; and from population ageing to public health crises, these issues threaten the well-being of both present and future generations (World Economic Forum, 2024; United Nations, n.d.).

The most recent Global Risks Report published by the World Economic Forum identifies geoeconomic confrontation, interstate armed conflicts, and natural disasters as three of the most significant global risks (World Economic Forum, 2026). Similarly, social work scholars emphasise that we are living in 'unprecedented times as we face economic pressures, growing inequalities, climatic changes, natural disasters, armed conflict and geo-political divisions' (O'Leary & Tsui, 2023).

These global processes also shape local development and the resilience of communities. This raises the question of how global processes, and particularly global challenges, affect small places and rural communities, and to what extent these communities are resilient in the face of crises. Within the European context, this issue has received relatively limited scholarly attention; however, in Latvia it is particularly significant due to both pronounced regional development disparities and the country's geographical proximity to the aggressor state, Russia. Within the framework of the United Nations Sustainable Development Goals, inequality and poverty are recognised as major global challenges that must be addressed at all levels of governance (United Nations, 2015). In this context, regional development disparities and the associated income inequalities in Latvia should not be understood solely as a national issue; rather, they also reflect broader global patterns of inequality. At the same time, Latvia's geographical location next to Russia, the war initiated by Russia in Ukraine, and the aggressor state's imperial ambitions to restore the borders of the former Soviet Union place the country in a pre-conflict situation (Tudor & Boetto, 2024).

Social work may represent an underutilised resource for strengthening community resilience and societal resilience in Latvia. Social work is more widely recognised at the micro level, primarily as support for individuals and families facing various difficulties. This form of practice helps people understand the causes of problems in their lives, provides support in times of crisis, and encourages individuals to participate actively in resolving their own challenges (Bela & Rasnača, 2023; Ministry of Welfare, 2023). However, many social problems cannot be effectively addressed at the individual level alone. Therefore, community social work is equally important. Although this approach is only beginning to gain wider recognition in Latvia, it has already assumed a significant role in many other contexts. Community social work is understood as a form of social work that 'helps community members achieve a higher level of well-being, enhance their capacity for self-organisation, and assume responsibility for their own actions and the surrounding environment' (Bela & Rasnača, 2023).

The aim of this paper is to examine the role and potential of social work in promoting community resilience in the context of complex and multidimensional global challenges.

The paper first introduces research design and methods. It then discusses the rationale for focusing on the impact of global challenges on local communities and, more specifically, on the role of social work in strengthening community resilience. The subsequent section presents the findings through a cross-case comparison of how different stakeholders – community activists, local government representatives, and social workers – perceive major contemporary challenges and assess them as local, national, European or global in scope. It further explores perceptions of the role and potential of social work in fostering community resilience in the context of military threat risks, with particular attention to civil protection planning and disaster preparedness across municipalities. Given the scope of the paper, this issue was selected as it represents one of the most pressing contemporary challenges affecting community resilience in the current geopolitical context.

Materials and Methods

This study has been conducted within the framework of the Latvian Council of Science research project 'How can social work make communities more resilient? Social work for community resilience between global issues and local agency'. The study employs an explanatory multiple-case study design, with four municipalities serving as the units of analysis. The selected municipalities are rural localities with small towns as their centres, with one municipality representing each of Latvia's cultural and administrative planning regions.

A qualitative research strategy was chosen because the topic remains relatively underexplored and because the study seeks to gain a deeper understanding of how research participants interpret the problems and challenges faced by their communities. In particular, the study explores how participants understand the role and potential of social work in addressing these challenges and provides a detailed insight into the interaction among key stakeholders.

Empirical data collection has been planned in two stages. In the first stage, semi-structured interviews are used to explore the challenges faced by local communities, stakeholder interaction, and issues related to civil protection planning and disaster preparedness within the selected units of analysis. In the second stage, participatory action research methods – specifically workshops – are planned in order to explore in greater depth potential solutions to the most significant problems identified by the communities and to discuss the possibilities of community social work in strengthening community resilience.

During the first stage of fieldwork (October 2025–February 2026), 50 semi-structured interviews were conducted, each lasting approximately one hour. In each municipality, it was planned to interview five participants from each stakeholder group: social service managers and social workers, municipal employees and council members, as well as community activists. Informed consent was obtained from all participants. Each interview was assigned a code, and any identifying details have been pseudonymised when interview excerpts are cited in the publication.

The initial analysis of the interview data was conducted using thematic analysis. The interview transcripts were systematically coded in order to identify recurring themes and patterns across the data. This process allowed to explore how different stakeholders interpret problems faced by local communities, how they perceive the role of social work in addressing these problems, and how interaction dynamics among stakeholders shape community resilience practices.

Community Social Work and Its Role in Times of Global Challenges

In recent years, the interaction between global problems and their local significance has intensified, and consequently the impact of global processes, transformations, and challenges on social work has increased. In contemporary society, the global and the local have become increasingly interlinked, and social work needs to be globally informed as well as locally grounded (Pentaris & Walker, 2026). In this context, there is a need for a deeper understanding of the interplay between global phenomena and their local impacts, offering a nuanced perspective on how social work can respond to some of the most pressing global challenges while remaining rooted in the practical realities of local communities (Lombard, 2026).

Recent global challenges have highlighted the importance of community-based social work. Community resilience, social innovation, and collaborative networks have increasingly been recognised as essential strategies for addressing complex social problems during times of crisis (Khazaee-Pool et al., 2023). Although community practice has been a significant component of social work since the profession's early development, its centrality among social work methods has diminished over the past century (Gutiérrez & Gant, 2018). Social services have increasingly shifted towards more individualised and procedural forms of intervention. Rather than collective or community-based approaches, many services have focused on case-by-case solutions and standardised procedures, which has weakened the role of community empowerment and collective action in social work practice (Harrison, 2009). In recent years, however, interest in community-based social work practices has been renewed. Scholars emphasise the importance of strengthening community engagement, collective action, and participatory approaches as central elements of the profession's future (Gutiérrez & Gant, 2018). They also highlight the significance of social capital, community solidarity, and participatory decision-making in strengthening communities. Many researchers argue that the profession must reconnect with its historical roots in activism, community

organising, and social justice advocacy in order to effectively address contemporary global challenges (Tan & Shajahan, 2022).

Attention to communities is also supported by the view that contemporary societies are experiencing the disintegration of traditional communities in modern and postmodern contexts. Urbanisation and depopulation are causing communities in rural areas to shrink, thereby creating a need for new local responses to the global challenges of the twenty-first century (Deng, 2019).

At the same time, scientific research on the role of social work in developing local responses to global challenges and in strengthening community resilience remains relatively limited. Scholars have, however, drawn attention to how climate change and environmental disasters are destabilising communities worldwide. For example, Margaret Alston outlines the reconceptualisation of the ecological space as a domain of social work practice and discusses ways in which social work can address these significant global challenges at the local community level (Alston, 2015). Considerable attention has also been devoted to the development of global and cross-border communities in response to environmental crises (Beck et al., 2013). Meanwhile, research on local territorial communities has primarily focused on community resilience in the context of emergencies and disasters (Cox & Hamlen, 2015; Finucane et al., 2020), food crises (Blay-Palmer et al., 2016), health crises (Pan et al., 2020), or human-induced crises (Migliorini et al., 2023). These studies, however, have largely concentrated on contexts in developing countries. Comparatively less attention has been paid to how communities in small towns and rural areas in Europe mobilise resources in response to complex global challenges, and in particular to the role that social work – more specifically community social work – can play in strengthening community resilience in such contexts. Within this study, community resilience is understood as being grounded in several interrelated elements: people-centred approaches, systems thinking, adaptability, transformability, sustainability, and courage (Nanditha & Karibeeran, 2022). This conceptualisation highlights the importance of collective capacities, participatory processes, and collaborative governance, all of which are central to community social work practice.

Results and Discussion

The analysis first examines how research participants perceive the most significant challenges faced by local communities and whether these are interpreted as local, national, European, or global in scope. It then focuses in greater depth on one global challenge – the risk of military threat – by comparing similarities and differences in the perceived role and potential of social work in fostering community resilience in relation to civil protection planning and disaster preparedness at the local level.

When describing the challenges faced by local communities, each stakeholder group (municipal employees, social workers, and community activists) tended to interpret these issues primarily from their own professional or experiential perspective. Only a limited number of challenges were consistently identified across interviews in all selected municipalities and across stakeholder groups. These included rural depopulation, low birth rates, and, in many cases, population ageing. In several interviews across different municipalities and stakeholder groups, issues related to substance use among young people (including electronic cigarettes, alcohol, and drugs) were also highlighted. These problems were generally described as significant at the national and European levels, and less frequently as global challenges.

Participants also frequently referred to problems related to road infrastructure and the limited availability of public transport in rural areas, which restricts access to employment, healthcare services, and other essential services. These issues were typically framed as national-level problems.

At the same time, a number of challenges were more specific to particular stakeholder groups, reflecting their everyday professional responsibilities. Social workers and municipal employees, in particular, emphasised the limited availability or accessibility of services in rural areas, including transport, healthcare, education, social services, and banking services. Social workers also identified social problems such as poverty (often described in terms of ‘insufficient financial resources’), substance dependency among adults, and mental health problems among young people, unemployment and limited digital literacy among socially vulnerable individuals.

Participants noted that low levels of digital literacy, combined with the increasing digitalisation of services, further exacerbate barriers to accessibility of services. For example, tasks such as booking medical appointments, paying bills, or obtaining bank statements become difficult or impossible for individuals who do not use smartphones or computers. However, neither poverty nor the digital divide were commonly interpreted by participants as broader global challenges, despite being widely recognised as such in academic literature and expert discourse (United Nations Development…, 2019). For example, the digital divide is increasingly conceptualised as a new form of social inequality in the twenty-first century, which both reflects and reinforces existing disparities within and between countries (Ragnedda & Muschert, 2013). This points to a discrepancy between academic and theoretical understandings of global issues and the ways in which individuals perceive and interpret them in everyday life. As noted by Pentaris & Walker (2026), even in relation to poverty, there is limited clarity regarding the extent to which it is shaped by local contextual factors as opposed to broader structural forces such as policy frameworks and neoliberal economic systems. The findings

indicate that broader global narratives appeared to have limited influence on how participants understood and prioritised community issues, which were framed primarily through local experiences and immediate practical concerns.

Of the global challenges outlined in the introduction, also the risk of military threat was not identified by participants as a major problem when discussing the key challenges facing their municipalities. Only when specifically asked about their personal sense of security and the civil protection system did participants reflect on these issues. Social workers and community activists generally perceived the risk of military threat in rural areas as low and reported feeling relatively safe, while municipal employees primarily emphasised the progress made in strengthening civil protection systems and developing new preparedness plans. On the one hand, this sense of subjective security may be viewed positively, as it indicates the absence of widespread fear or anxiety despite geographical proximity to an aggressor state. On the other hand, level of crisis preparedness remains low, and the development of civil protection systems is progressing slowly. Also, this finding suggests a disconnect between the prominence of military threat risk in policy discourse and its limited salience in everyday community perceptions.

The following section therefore examines in greater depth how such a risk is understood within civil protection planning and crisis preparedness frameworks, with particular attention to the role and potential of social work across municipalities.

The military threat has been a sustained reality in the region for several years and significant national resources have been invested in strengthening military preparedness. However, comparatively less attention appears to have been paid to societal preparedness and the role of local communities in crisis situations. For these reasons, the subsequent analysis focuses specifically on preparedness for military threat, with particular attention to civil protection systems and the role of social work within them at the local level.

Municipal employees generally emphasised progress in the development of civil protection systems, referring to various training activities, simulation exercises, and effective cooperation between state and municipal institutions. Some participants indicated that they were not directly involved in civil protection matters and therefore preferred not to comment on them. Only one participant noted that more detailed, institution-level action plans for different crisis situations would be necessary, arguing that a single, general civil protection plan is insufficient.

In contrast, social workers – particularly those in managerial positions – expressed a more critical perspective although some acknowledged that certain activities and improvements are taking place in the field of civil protection. Participants highlighted the absence of clear protocols or algorithms for action within social services in situations of crisis or threat, despite recognising the need for such guidance. Civil protection commissions were described as providing limited information, even to social service managers. As a result, social workers reported uncertainty regarding their roles and responsibilities in the event of a disaster.

Collaboration with civil protection commissions or municipal civil protection specialists was generally described as insufficient or weak. This can be partly explained by the fact that social work is not explicitly included within the framework of the Civil Protection and Disaster Management Law and is therefore also not sufficiently integrated into municipal civil protection plans. Social services are often not integrated in municipal civil protection commissions although the regulatory framework formally allows for their inclusion. For example, in one of the municipalities included in the study, the head of the social service had participated in only one commission meeting, held specifically to address the evacuation of residents from a long-term care institution, where her professional expertise was required. In some municipalities, limited forms of cooperation between the municipal civil protection commission and the social service were reported, such as compiling lists of individuals who would require priority assistance in crisis situations.

It can be concluded that social services remain an under-recognised and insufficiently integrated resource in this policy field. This stands in notable contrast to the disaster social work literature, which emphasises the crucial role of social work in disaster preparedness, response, and recovery (Hay & Pascoe, 2022).

There was a relatively high level of agreement among participants regarding the groups most at risk in crisis situations. These were identified as older people (particularly those who are bedridden and seniors living alone), individuals with mobility impairments, and people with intellectual disabilities. However, none of the social services included in the study reported having clear guidance on how to support individuals with limited cognitive capacities or restricted mobility in situations of crisis or threat. These findings are consistent with evidence presented in February at the Latvian Parliamentary Human Rights Committee by the Latvian Disability Alliance Sustento. Their 2025 study, involving 1,060 people with disabilities and functional impairments, examined preparedness for emergency situations and found that the majority of respondents had not seen or did not understand their municipality's civil protection plan, were unaware of how to act in the event of a threat, and did not know the location of the nearest accessible shelter (Dzērve, 2026). Some social workers highlighted community solidarity as a significant resource, suggesting that mutual support among neighbours and local community members could play a crucial role in crisis situations, especially for vulnerable individuals. Social workers themselves are

well positioned to assume a coordinator's role, as they act as intermediaries between communities, institutions, and available support resources.

In municipalities located along the border with an aggressor state, the need for rapid response in the event of a crisis is particularly acute. This requires clarity regarding population evacuation procedures and other highly practical aspects, such as the provision of shelter, food, water, and social care in case of emergency or disaster. As one participant explained: 'We clearly understand these situations and who would most likely need assistance. We have thought about this carefully, but we are also waiting for stronger cooperation with civil protection. More involvement in civil protection planning, training, general awareness, and the development of clear action protocols is essential. This is very important' (SD17L). The findings suggest that awareness and preparedness regarding action in situations of military threat or other emergencies remain limited not only among the wider population, but also within social services. Across all municipalities included in the study, social service staff had not participated in training related to crisis or threat response, with the exception of standard fire safety drills. At the same time, many interviewees expressed a willingness to engage in such training opportunities and emphasised the need for clear operational guidelines for action in crisis situations. Insufficient knowledge and preparedness may lead to confusion and disorder in crisis situations, particularly in the absence of prior experience or practical knowledge of how to respond.

In Latvia, social work remains an underutilised resource for strengthening community resilience in the context of military threats and other disasters. The integration of social workers into civil protection systems is essential for comprehensive disaster management. Disaster social work plays a significant role across all phases of disaster management, including risk assessment, prevention, preparedness, response, and recovery (Guddo, 2023; Hay & Pascoe, 2022; Sim & He, 2024; Tudor & Boetto, 2024).

In the context of risk reduction and preparedness, social workers contribute to risk assessments, support early warning systems, and assist in the development of emergency response plans (Guddo, 2023; Sim & He, 2024). They are also involved in informing and educating the public about disaster risks, which is essential for strengthening community preparedness (Özkan & Kiyak, 2025). Consistent with these insights, participants in this study emphasised that social services should have their own emergency action plans and that municipal-level plans should be more detailed. They also expressed willingness to be involved in the development of such plans.

At present, there are population groups for whom existing civil protection information is either inaccessible (e.g. due to limited digital skills) or not comprehensible (e.g. for individuals with intellectual disabilities). Social workers could play a key role in ensuring that such information is accessible and understandable to these groups.

Although emergency response is rightly led by rescue services, social work can play a significant role in the immediate aftermath of disasters by providing practical assistance, including support in securing safety, food, water, and shelter (Cunningham et al., 2026). Social workers may also offer emotional and psychological support, helping individuals cope with trauma and loss (Rowlands, 2013). However, the interview data suggest that emergency shelters are largely unequipped, and there is limited clarity regarding the provision of basic needs such as temporary accommodation and food. While legislation minimally acknowledges the need for emotional and psychological support, this aspect was not mentioned also by participants, indicating a limited understanding of the full scope of response activities.

The least developed phase of disaster management in Latvia appears to be recovery. Social workers can play a crucial role in supporting communities to rebuild everyday life after crises (Guddo, 2023). At the policy level, they may also advocate for inclusive and equitable decision-making processes, ensuring that disaster policies take into account the needs of socially vulnerable groups (Tudor & Boetto, 2024). However, the legal framework reflects a rather narrow understanding of recovery, primarily focusing on the provision of basic needs such as food, housing, healthcare, electricity, water, heating, waste management, communication, and environmental restoration. Notably, environmental restoration is one of the few explicitly recognised recovery dimensions beyond immediate survival needs.

The literature suggests that integrating social work into civil protection systems can also strengthen coordination and collaboration processes. Social workers can act as mediators between affected communities and disaster management institutions (Hay & Pascoe, 2022). Strengthening collaborative ties between social service providers and civil protection institutions may significantly improve both response effectiveness and recovery processes (Hay & Pascoe, 2022). Furthermore, social workers can contribute to the development of disaster policies by promoting inclusive approaches that take into account the needs of all members of society (Tan, 2013; Tudor & Boetto, 2024).

Conclusions

1. The findings suggest that perceptions of community challenges are strongly shaped by stakeholders' professional roles and everyday experiences. Only a limited number of issues – particularly depopulation, low birth rates, and population ageing – emerged as common concerns across municipalities and stakeholder groups. This indicates that shared understandings of local challenges remain relatively narrow, while many other issues are perceived in fragmented and sector-specific ways.

2. The findings further reveal a significant discrepancy between academic and expert-driven conceptualisations of global challenges and the ways these issues are perceived in everyday community contexts. Problems such as poverty, digital exclusion, and social inequality – widely recognised in academic and policy discourse as structural global challenges – were rarely interpreted by participants in these terms. Instead, they were understood primarily as immediate practical or localised problems. The study highlights a disconnect between expert-driven constructions of 'global challenges' and the ways local populations interpret social problems in everyday life. In the studied municipalities, broader global narratives appeared to have limited influence on how participants understood and prioritised community issues, which were instead framed primarily through local experiences and immediate practical concerns.
3. The findings indicate that the risk of military threat – despite Latvia's geographical proximity to Russia and the growing prominence of this issue in academic, policy, and public security discourse – was not perceived by local stakeholders as a primary community challenge. Participants generally reported feeling relatively safe, with the war largely perceived as a distant external reality rather than an immediate local threat. This is reflected in limited crisis preparedness at the community level.
4. The findings demonstrate that social work remains structurally under-recognised and insufficiently integrated within civil protection and crisis preparedness systems at both municipal and national levels. The limited involvement of social services in preparedness planning and coordination appears to be linked not only to local institutional practices but also to the broader policy framework, as social work is not explicitly incorporated into the Civil Protection and Disaster Management Law. As a result, the role of social services within civil protection systems remains fragmented, reactive, and largely limited to specific situations requiring immediate social care expertise.
5. There is a lack of clear procedures, training, and role definition for social workers in disaster contexts. The absence of operational protocols, limited access to information, and a lack of targeted training indicate significant gaps in institutional preparedness.
6. Vulnerable groups face heightened risks due to limited accessibility and inclusivity of civil protection measures. Older people, individuals with mobility impairments, and those with intellectual disabilities are recognised as the most at-risk groups. However, existing civil protection information and planning mechanisms are often inaccessible or inadequate for their needs, further deepening inequality in crisis situations.
7. Strengthening community and societal resilience requires a more prominent role for social work across all phases of disaster management. The findings, supported by existing literature on disaster social work, suggest that social workers can play a critical role in risk assessment, preparedness, response, and recovery. Enhancing their integration into civil protection systems, improving collaboration among stakeholders, and investing in community-based approaches are essential steps towards building more resilient communities.

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EMBEDDING CULTURE IN SUSTAINABLE RURAL PLACEMAKING: EVIDENCE FROM REGIONAL PLANNING STRATEGIES IN LATVIA

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Abstract
This article investigates how cultural resources are conceptualized and operationalized in regional and municipal planning strategies in Latvia, with a focus on their role in sustainable place-making. Despite policy recognition of culture as a driver of regional development, social cohesion, and local identity, its strategic integration into planning remains uneven. To examine this, the study conducts a qualitative content analysis of eighteen planning and cultural policy documents, including NUTS III-level regional development strategies and municipal and city-level cultural development strategies. Cultural resources are treated as both tangible and intangible assets, encompassing heritage, cultural infrastructure, traditions, and community practices. The analysis reveals that sustainability is predominantly framed in terms of preservation of heritage and continuity of cultural traditions, particularly Song and Dance Festival practices, with less attention to innovation, adaptive reuse, and participatory governance. Regional and municipal strategies selectively adapt national cultural policy priorities according to local territorial profiles and perceived needs, resulting in fragmented approaches that emphasise protection over strategic development. Economic, social, and environmental dimensions of sustainability are inconsistently articulated, and the term 'sustainable' is often operational rather than guiding long-term planning. The findings highlight that, while cultural resources are acknowledged as foundational to sustainable place-making, their use in planning is limited by fragmented understanding and weak integration into participatory and adaptive frameworks. The study concludes that more coherent, locally grounded, and strategic approaches are needed to embed culture effectively in sustainable place-making across Latvian regions.
Keywords: cultural resources, cultural policy, rural place-making, sustainable development.

Introduction

In recent years, scholarly literature has increasingly sought to define measurable criteria for assessing the impact of culture on regional development, the integration of the cultural sector into the concept of sustainable development, and its role within cross-sectoral policymaking. Cultural activities at the local and regional levels are gaining increasingly convincing evidence of their economic and social benefits, both at the individual and collective levels (Ćwikła et al., 2023). Recent theoretical trends emphasize community and regional development grounded in horizontal networks, interdisciplinary cooperation, and the pursuit of synergies, as well as in the purposeful maintenance and use of cultural resources. Theorists of sustainable development emphasize that, alongside global and national objectives, local-scale resources and capacities must also be considered in promoting sustainable development. These resources are embedded in interconnected networks linking civic engagement, cultural heritage, housing, inclusion, mobility, culture, nature, resilience, and governance (Duxbury et al., 2016).

In Latvia, due to intensive depopulation processes in Latvian rural territories over recent decades (Dahs et al., 2021), it has led to an extensive search for new ways of living and remaining in place. Tangible and intangible cultural resources have emerged as significant drivers for sustaining rural life and supporting its ongoing development. During depopulation processes, rural communities mobilize their cultural resources to establish new economic structures and develop place-branding strategies. Rural branding typically emphasises communal identity, food and drink, arts and crafts, music, and the aesthetic qualities of the surrounding natural environment rather than architectural design (Jafarli & Canavari, 2025).

Cultural resources are interpreted and defined broadly; however, in the context of sustainable place development, they can be understood as a set of tangible and intangible resources – such as architecture, landscapes, traditions, values, and communication practices – that are actively used in place-making processes (Erfani, 2022). Culture is seen as an interplay between environment and people as people have to find creative ways to adapt to the environment and make it familiar (Pillai, 2020). Consequently, the concept of a 'cultural ecosystem' becomes particularly relevant, encompassing both cultural life and the cultural community (Einarsson, 2016). Cultural resources can be conceptualized as comprising two interrelated dimensions: first, the tangible and intangible elements of local culture; and second, the modes through which local communities collectively organize, interpret, and deploy existing resources. However, the organization and cooperation practices of a given community or society are often crucial for the maintenance and effective use of cultural resources. In a broader sense, both the 'territorially embedded modus operandi' and the 'local habitus' constitute key factors that shape, and at times limit, the dynamics of placemaking (Weck, 2023). Local culture is considered as a key factor in creating 'environments in which people have invested meaning over time. A place has its own history – a unique cultural and social identity that is defined by the way it is used and the people who use it' (Katz et al., 2015) as well as in place-based innovations where four elements of sustainable development are identified: (1) who? (social axis); (2) what? (cultural axis) (3) where?

(spatial axis); (4) how? (the catalyst) (Devaney, 2017). Both aspects of cultural resources are considered foundational to sustainable place development, which is understood as an interplay between emotional attachment and beliefs, knowledge, behaviours, and actions in relation to place (Domingues et al., 2021). In some cases, the significance lies not in cultural heritage per se, but in the ways it is mobilized, especially when tangible heritage is meaningfully integrated with intangible cultural assets (Capello et al., 2020).

Considering above mentioned, the aim of this article is to examine how cultural resources are conceptualized and integrated into regional and municipal planning strategies in Latvia, and to assess their role in supporting sustainable placemaking. The central research question addresses whether, and in what ways, Latvian planning documents reflect the use of cultural resources in the context of sustainable rural placemaking. More specifically, the study explores the extent to which a connection between sustainable development and cultural resources is articulated within these documents.

The introduction of a cultural perspective has transformed both the discourse and the dominant paradigms of placemaking and sustainable development, as well as the range of social actors involved in shaping it. This shift has also altered how sustainable development is understood and pursued. Territorial development can no longer be conceptualized as a linear process defined solely by continuous economic growth (Della Spina, 2025) or top-down process which marginalises regions and countries (Vasta et al., 2019). Moreover, assessing the impact of culture remains challenging, as many processes generated by cultural activities are not immediately observable or easily measurable. At the same time, the integration of culture into the sustainable development framework is inherently organic, since culture – alongside the physical and emotionally perceived dimensions of the environment – constitutes the so-called conceptual environment that influences both individuals and society (Fikfak et al., 2018). Therefore, researchers and project implementers emphasize the importance of prioritizing local initiatives and development strategies, including the integration of cultural aspects into agricultural policy and related fields (Akbar et al., 2021).

In the context of cultural resources, particular emphasis must be placed on cultural heritage. On the one hand, there is a growing recognition of the fragility of individual elements of cultural heritage and the need to protect and preserve them. On the other hand, cultural heritage represents a significant resource for meeting community needs and should therefore be appropriately utilized. Through the processes of identifying, researching, interpreting, safeguarding, preserving, and presenting cultural heritage, the essence of communities becomes visible, along with their cohesive and collective strength (Cerreta & Giovene di Girasole, 2020). The preservation of cultural heritage is also regarded as a counterforce to cultural homogenization resulting from modernization, industrialization, urbanization, and globalization (Nagy-Sándor & Berkers, 2018).

At a broader scale, the dissemination of good practice examples – also through digital and virtual means – is strongly recommended (Arts & Culture…, 2016). The formation of broad social networks and the promotion of synergy become possible when previously hierarchical power structures within a given territory are transformed into more horizontal arrangements, in which social actors participate on relatively equal terms and with comparable levels of influence. Place-based development also requires the simultaneous consideration of both exogenous and endogenous factors. Regarding exogenous influences, scholarly literature particularly highlights the importance of adequate infrastructure to support the development of local creative economies, including transport infrastructure, communication opportunities, and spaces for work and business support (Munro, 2016). Recent developments in governance and decision-making, including mechanisms such as participatory budgeting, reflect a shift toward more inclusive, transparent, and community-driven approaches to resource allocation and local development (Anders-Morawska & Hereźniak, 2019). Community-oriented governance and participatory decision-making are frequently embedded within the cultural fabric of local communities, reflecting longstanding social norms and collective practices (Kádár & Reicher, 2025).

Cultural heritage, creativity, and diversity provide a foundation for promoting humane, inclusive, and holistic long-term development (Duxbury et al., 2016). In other words, culture expands opportunities for individuals, extending beyond mere economic growth to enhance intellectual, emotional, moral, and spiritual well-being (UNESCO, 2001). Through interactions with other economic sectors, cultural capital generates a multiplier effect, particularly in terms of employment and income growth (Keser, 2016; Kuliš & Šimundić, 2023). Regarding the environment, cultural activities help to restore abandoned buildings and public spaces, enhance safety in public areas and reduce vandalism, stimulate environmental regeneration and health-promoting activities, and contribute to the creation of attractive living environments, among other benefits (Tjarve & Zemīte, 2016).

The literature identifies various ways in which culture contributes, both directly and indirectly, to the development of territories and regions (Centre for Strategy…, 2010). In addition to the commercial benefits derived from the use of cultural resources, culture also provides intellectual resources for the design industries (e.g. fashion and furniture) and helps create an attractive environment for attracting tourists, among other contributions (Benner, 2017). Cultural aspects are incorporated into regional and national policies not only as components of sustainable

development but also through targeted cultural strategies. Cultural activities are characterized as diverse, dynamic, and intertwined with daily mobility and lifestyle practices (Talvitie, 2011).

Economic and social processes in rural areas differ from those in urban contexts. Research indicates that factors such as quality of life, access to creative inspiration, and strong social networks in the cultural field more effectively support the creative economy in rural areas than in cities (Roberts & Townsend, 2016). Culture-based development fosters social inclusion, rootedness, flexibility, innovation, creativity, and entrepreneurship, making cultural resources a key driver of sustainable territorial development (Keser, 2016).

Theoretical literature emphasizes that culture should not be understood narrowly as a set of discrete activities; rather, it is embedded in sustainable development processes, shaping economic, social, and environmental relations. The context of cultural resource identification and use introduces specific adjustments. It is possible that the nearest prospects for the use of cultural resources are directly related to the involvement of the local community and the alignment of its interests with the demands of the external environment. As recent studies show, social sustainability is based on the emotional attachment of the inhabitants of a certain place/territory to the place. New trends to some extent confirm the transition from obtaining economic benefits to obtaining social benefits. For example, local communities and municipalities are advised to primarily focus on creating an attractive and safe environment for the needs of residents rather than on marketing and attracting tourists. Within the context of climate change and sustainable place development, it is essential to prevent the overexploitation of cultural heritage and to integrate the principles of the circular economy into planning and management practices. Over time, local stakeholders assume the role of custodians of natural and cultural resources, contributing to their sustainable stewardship and long-term resilience (Ćwikła et al., 2023).

To sum up, the literature highlights cultural resources as central to sustainable placemaking and regional development, extending beyond economic or heritage value to shape social cohesion, local identity, and environmental stewardship. Their effective use relies on both tangible and intangible elements and on the collective practices through which communities mobilize them. In countries and regions with high depopulation, cultural resources are especially important for sustaining local economies, social networks, and place-based innovation. Sustainable development requires balancing preservation with adaptive use, integrating social, economic, and environmental considerations, and fostering participatory, community-driven governance. Overall, culture emerges as a foundational driver of sustainable development, demanding strategic, inclusive, and locally grounded approaches to ensure long-term impact.

Materials and Methods

According to the common classification of territorial units for statistics (NUTS) in Latvia, the application of NUTS III corresponds to the administrative territorial division of Latvia, which includes five statistical regions: Kurzeme, Latgale, Zemgale, Vidzeme and Riga. They include 7 national cities and 35 counties (Latvijas Republikas tiesību akti, 2024).

A qualitative content analysis was conducted on the planning documents of Latvian regions to identify cultural resources and assess how they are prescribed to support sustainable placemaking. The analysis focused on both tangible and intangible cultural elements, as well as the ways in which planning frameworks guide their utilisation in fostering sustainable territorial development. The main object of the deductive content analysis was the full goal, objective (s), priority directions or similar strategic components of the culture strategies and their correspondence to five priorities of a Cultural Policy Guidelines 2022-2027. The color-coded categorization was used as a visual analytic tool to systematically categorize the strategic elements of the cultural strategies enabling clearer identification of priorities. This assessment was based on conceptual similarity and contextual meaning, rather than solely on the presence of specific keywords. In addition, a keyword-based analysis was conducted focusing on the word stem ‘sustain[…].’ in Latvian ‘ilgtsp[…]’ and the instances derived. The results were interpreted according to the context and meaning the word was applied to. This approach allowed for an initial understanding of the role of cultural resources within policy and planning discourse, highlighting both explicit and implicit references to culture in regional development strategies. To assess the significance of cultural resources across the regions of Latvia, a total of 18 current policy and planning documents were analysed. These included five development strategies of all planning regions and thirteen cultural development strategies, of which eight pertained to municipalities and five to national cities. Within the scope of this article, the analysis of planning documents includes only those municipalities that have developed specific cultural development strategies. For two municipalities, the strategy has expired (Talsi and Tukums counties), and for two municipalities they are being developed (Gulbene county 2026-2031 and Balvi county 2026-2023). The remaining counties and cities (i.e., 25) do not have separate strategies for the cultural sector, but cultural development is integrated into the sustainable development strategy or development program. National cities were included as (1) they are as a part of statistical regions analysed, (2) statistics approve that 35 % of inhabitants travel within their own region, including cities, for cultural life and 27% go to regions further away (Kultūras ministrija, 2025), (3) territorial reform (Latvijas Republikas tiesību akti, 2024) foresees to merge all national cities with the counties

until 2029. The strategies were examined to identify differences in thematic priorities and in the application of the concept of sustainability within cultural planning documents.

Results and Discussion

The framework for defining cultural resources in Latvia is formed by several policy documents, such as the Intangible Cultural Heritage Law, Cultural Policy Guidelines for 2022-2027 'Cultural State', the European Cultural Heritage Strategy for the 21st Century, etc. The Cultural Policy Guidelines for 2022-2027 aim to 'sustainable and publicly accessible culture for human growth and national state development', including access to cultural resources for all, public participation in cultural processes, sustainable development of cultural sectors, preservation of cultural heritage, talent development and professional growth of cultural workers (Kultūras ministrija, 2022).

Development strategies from the Zemgale, Kurzeme, Latgale, Vidzeme, and Riga planning regions were included in the analysis. Culture is explicitly identified as a development priority in the strategies of the Kurzeme, Vidzeme, and Zemgale regions, which indicates that cultural resources are considered important assets for regional development and sustainable placemaking. Within these strategies, the principal directions of cultural development include the protection and promotion of cultural heritage, development of cultural infrastructure, advancement of the cultural and creative industries, as well as the preservation of traditions and the diversification of cultural events. This demonstrates that the strategies aim to balance long-term cultural development with economic, social, and environmental sustainability. Strategies encourage diversification of cultural events and preservation of traditions, which supports social cohesion, community engagement, and the vitality of local culture key components of sustainable placemaking. Investments in cultural infrastructure are highlighted, showing that tangible cultural resources are considered essential for facilitating public participation, enhancing quality of life, and creating distinctive local identities that contribute to sustainable regional development. In contrast, in the Latgale planning region, culture is not defined as a distinct development priority; instead, it is incorporated horizontally across broader strategic priorities such as municipal development, innovation, and excellence. Each city and municipality within the Latgale planning region pursues a context-specific approach to cultural development. The strategies identify cultural resources both as tangible (heritage, infrastructure) and intangible (traditions, cultural knowledge) assets. They prescribe their development and preservation in ways that integrate sustainability principles economically, socially, and environmentally thereby positioning culture as a central instrument for sustainable placemaking, regional identity, and community vitality. In the Riga Planning Region, multiculturalism and cultural diversity are frequently highlighted as key values, and Riga has developed a cultural development strategy outlining concrete measures to advance its cultural sector.

An analysis of cultural strategies in Riga, Jekabpils, Liepaja, Jelgava, and Daugavpils covering periods from three to ten years reveals that, despite some local distinctions, common priorities include improving accessibility to cultural services, fostering cultural events, and encouraging public participation. Liepaja's strategy is notably distinct, as it is specifically tailored to support the city's candidacy for the European Capital of Culture. Across the cities, additional objectives focus on preserving cultural resources, developing infrastructure, promoting local and international cooperation, ensuring funding for cultural projects, supporting cultural education, enhancing city recognition, attracting talent, and fostering professional growth among cultural practitioners. The cultural development strategies of the municipalities (counties) of Cesis, Sigulda, Limbazi, Ropazi, Valmiera, Kuldiga, Bauska and Saldus were analysed. Across all municipalities, the strategies identify a set of shared priorities, including the strengthening of cultural governance and management, ensuring access to cultural services, diversification of cultural events, promotion of interinstitutional cooperation, professional development of cultural workers, and active participation of residents in cultural life. In addition, the strategies emphasize international cooperation, place recognition and image-building, preservation of cultural values, balanced development of cultural activities, and equitable accessibility of culture across the entire municipal territory. In contrast to national cities, municipal strategies place greater emphasis on the reinforcement of traditional values and local identity, territorial cohesion in cultural provision, and the central role of community engagement. These elements are given significantly greater importance in cultural development at the municipal level. In several regional strategies, the digital dimension of culture is highlighted to promote accessibility and to emphasize the role of culture in the sustainable development of a place.

The integration of the priorities from Cultural Policy Guidelines 2022-2027 into lower- level documents is presented in Table 1. The table reveals the extent to which the national level priorities are evidenced across different levels of governance. Some priorities are widely integrated as access to cultural resources for all, public participation and preservation of cultural resources. Meanwhile, the priority that covers professional development of employees in the sector and talent development is integrated only in part of the documents analysed. The priority of a sustainable development of the cultural sector is indirectly and vaguely referenced and tends to lack clear or explicit integration in the documents.

Table 1
Priorities from Cultural Policy Guidelines 2022-2027 incorporated into lower-level documents

Priority	City level culture strategy	County level culture strategy	Planning Region strategy
Access to cultural resources for all	Riga, Jekabpils, Jelgava, Daugavpils	Bauskas, Cesu, Siguldas, Limbazu, Ropazu, Kuldigas, Saldus, Valmiera,	Zemgale, Kurzeme, Vidzeme
Public participation	Riga, Jekabpils, Liepaja, Jelgava, Daugavpils	Bauskas, Cesu, Siguldas, Limbazu, Ropazu, Kuldigas	Zemgale, Kurzeme, Riga
Preservation of cultural resources	Riga, Jekabpils, Jelgava, Daugavpils	Bauskas, Cesu, Siguldas, Limbazu, Ropazu, Kuldigas, Saldus	Zemgale, Kurzeme, Vidzeme, Latgale
Professional development of employees in the sector, talent development	Daugavpils, Jelgava	Siguldas, Limbazu, Kuldigas, Valmieras, Saldus	Kurzeme, Vidzeme, Zemgale
Sustainable development of the cultural sector	n/a	Bauskas, Siguldas, Limbazu, Kuldigas	Zemgale, Vidzeme

An analysis of the use of the word stem 'sustain[…]' across cultural development strategies reveals that in regional and municipal strategies sustainability is emphasized in environmental and territorial management (Cēsu novada pašvaldība, 2022), the sustainable development of cultural and creative sectors including the use of Song and Dance Festival traditions, cultural events, monuments, and cultural spaces (Siguldas novada pašvaldība, 2023; Limbažu novada pašvaldība, 2025; Valmieras novada pašvaldība 2021; Bauskas novada pašvaldība, 2025), sustainability of historical territories and intangible heritage (Ropažu novada pašvaldība, 2024), economic and social sustainability of cultural operators and sustainable management of the Suiti cultural space (Kuldīgas novada pašvaldība, 2021), as well as the preservation and sustainable development of cultural heritage, sustainable data management, and public accessibility (Saldus novada pašvaldība, 2023). In regional strategies, sustainable aspects are similarly categorized as economic, through maintenance of infrastructure, institutions, and personnel; social, through promotion of social sustainability of cultural operators, preservation of intangible heritage, development of the Suiti cultural space, and maintenance of Song and Dance Festival traditions; and environmental, through sustainable environmental and historical territory management and preservation of cultural heritage and monuments. Within the sustainability context, urban strategies stress long-term financing for new initiatives (Rīgas valstspilsētas pašvaldība, 2024), sustainable cultural events, institutions, and the environment (Jēkabpils pilsētas pašvaldība, 2021), development of sustainable lifestyles and volunteerism (Nodibinājums Liepāja, 2025), investments in cultural sustainability and heritage preservation (Jelgavas valstspilsētas pašvaldība, 2023), and the sustainable integration of cultural-historical and natural heritage into tourism, city branding, and governance (Daugavpils valstspilsētas pašvaldība, 2021). In cities strategies, sustainable aspects are similarly categorised as economic as long-term financing and strategic investments in culture and heritage, positioning them as assets for resilient development and tourism. Social in the preservation of cultural traditions, support for cultural institutions, and the promotion of sustainable lifestyles and volunteerism, which together strengthen social cohesion, identity, and civic engagement. Environmental sustainability is reflected in the responsible use and integration of cultural and natural heritage into urban development, ensuring that cultural growth aligns with environmental protection. Consequently, the analysis reveals a broad but fragmented understanding of sustainability within the cultural sector, where the preservation of cultural heritage remains the dominant paradigm. The understanding of a sustainable use of cultural resources is aligned with all the sustainability areas: social, economic and environment. The use of a term 'sustainable' is more operational than strategic, more being descriptive label for activities (management, preservation, development etc.). While the Cultural Policy Guidelines for 2022–2027 ('Cultural State') ensure alignment with regional planning documents, national cities and municipalities integrate only those priorities from the national-level guidelines that most closely correspond to the profile and specific needs of each city or region. The greatest deviation from Cultural Policy Guidelines 2022-2027 was under the priority sustainable development of the cultural sector. Analysis of the word stem 'sustain[…] highlights that the term's usage and contextual meaning vary substantially across strategies. While some documents employ it broadly to outline the development of the entire cultural sector, others confine it to highly specific contexts, such as the operational sustainability of localized events.

Conclusions

1. The findings indicate that Latvian planning documents generally recognize cultural resources as important assets for regional and local development and explicitly link them to key elements of sustainable

placemaking. Across regions and municipalities, cultural resources are conceptualized broadly, encompassing both tangible assets (heritage, infrastructure, cultural spaces) and intangible elements (traditions, cultural practices, local knowledge). Strategies consistently emphasize accessibility to culture, public participation, preservation of cultural heritage, and the strengthening of local identity and community cohesion, confirming that culture is understood as a contributor to social sustainability and territorial vitality.

2. Simultaneously, the scope and depth of integration vary significantly across territories. In several regions culture is positioned as a strategic development priority, while in others it is incorporated horizontally within broader development frameworks. Although planning documents refer to economic, social, and environmental dimensions of sustainability, the connection between sustainable development and cultural resources is most often articulated through heritage preservation, maintenance of cultural infrastructure, and support for cultural activities. While the use of the sustainability concept is largely operational and descriptive rather than strategic, forward-looking and integrative approaches to the long-term, adaptive use of cultural resources remain underdeveloped.

3. Cultural resources are consistently mobilized to support social cohesion, identity-building, and heritage preservation, and to a lesser extent local economic development; however, they are rarely embedded within comprehensive, forward-looking sustainability frameworks that integrate environmental, economic, and cultural dimensions in a systemic way. Thus, while culture is institutionally recognized and operationally applied in rural development planning, its potential as a strategic and transformative driver of sustainable placemaking remains only partially realized.

4. Overall, the analysis suggests that Latvian planning documents do reflect the role of cultural resources in sustainable rural placemaking; however, this relationship is unevenly articulated and primarily framed through preservation and community-oriented functions, with national priorities selectively adapted to local contexts and development needs. These findings could be shared with the Latvian Association of Local Governments' (1) to highlight the necessity to pay more focused attention to the use of the term 'sustainable' and its meaning in a placemaking for future planning documents and (2) help to improve the quality of the content of the future strategies.

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REGULATORY FRAMEWORK OF PUBLIC ADMINISTRATION SERVICES GOVERNANCE IN LATVIA: TOWARDS GOOD GOVERNANCE

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Abstract
Public administration ensures the implementation of state functions and meets societal needs based on regulatory and policy objectives. Many countries emphasise that public administration shall adhere to the principles of good governance while simultaneously promoting accountability, public trust and the sustainable implementation of policies. Good governance is widely recognised as a cornerstone of modern public administration, because it contributes to more effective provision of public administration services, enhances the welfare of citizens and supports national economic development. The assessment of the conformity of regulatory frameworks with the principles of good governance is therefore essential, given that the quality of public services is a key criterion by which citizens evaluate governmental performance. This study aims to evaluate Latvia's regulatory framework for governing public administration services in the context of good governance principles. A qualitative content analysis of the regulatory framework was conducted to assess its compliance with the following good governance principles: accountability, rule of law, openness, fair procedures, efficiency and effectiveness, service accessibility, user-centricity, public participation, monitoring and improvement of services, data protection. The findings suggest that while Latvia has established a relatively robust legal foundation for governing public services, further improvements are needed to ensure the comprehensive and consistent application of all good governance principles across relevant legal acts. The study also recommends methodological enhancements for further studies, involving multiple experts and the use of statistical analysis to reduce subjectivity in evaluating regulatory compliance.
Keywords: good governance, public administration, services, regulatory framework, Latvia.

Introduction

The public sector constitutes a fundamental pillar of society, given a substantial share of public expenditures in GDP, role as a major employer and influence in the capital market. Political processes define the strategic and developmental priorities of the state, regions and sectors, which are implemented through legislation, public administration services and income redistribution (International Framework…, 2014). Consequently, the delivery of efficient public services is essential to global governance because it secures social stability and provides the necessary conditions for sustained economic growth and long-term prosperity (Gurnasa & Mazure, 2025).

The World Bank's report 'Business Ready' (B-READY) highlights a persistent discrepancy between high-quality regulatory frameworks and the practical provision of public services. While robust regulations on property rights and fair competition are intended to stimulate investment, the lack of functional public services (such as digital tax platforms and efficient border infrastructure) hinders business compliance and expansion. B-READY data reveal a significant 23% 'public services gap', particularly in demographically young economies. This divergence between 'de jure' regulation and 'de facto' public administration service de livery undermines economic performance, suggesting that sustainable development requires a dual focus on both regulatory quality and operational efficiency (The World Bank, 2025a).

The success of public administration services relies on the role of good governance, which ensures that the legal framework and administrative processes are coherent and contribute to the wider achievement of the national development priorities. The Asian Development Bank (2013) notes that the principle of good governance has become a core concept in development policy and public administration discourses. Governance encompasses the functioning of the political system, executive decision-making processes, the regulatory framework, including the drafting, amendment and implementation of legislation. Furthermore, it includes the institutional mechanisms through which public services are delivered and citizens interact with political and judicial institutions. Insufficient adherence to the principles of good governance may impede economic growth even where structural conditions are favourable. Strengthening public services remains one of the most visible means of achieving the gradual, overall improvement of governance, but the quality of public services is the primary criterion by which citizens judge governmental performance (Shikha et al., 2013). Similarly, the World Bank emphasises that inclusive and accountable institutions foster stronger economic growth, superior public services and greater opportunities for citizens (The World Bank, 2025b).

Assessing whether the regulatory framework conforms to good governance principles is therefore essential. The regulatory framework determines institutional capacity and provides the mechanisms through which abstract norms are transformed into accessible and high-quality public services. While much of the existing literature links good governance with economic performance, trust in government and administrative effectiveness, considerably less attention has been devoted to how these principles are operationalised through concrete legal instruments. Existing studies tend to focus either on governance indicators and macro-level institutional quality or the practical implementation of public services, leaving a gap in the analysis of the legal architecture connecting good governance principles to everyday service provision.

Good governance is widely acknowledged as a cornerstone of modern public administration. Sari (2023) highlights that its implementation generates numerous positive outcomes, such as greater transparency, more active citizen involvement, more efficient administrative processes, improved public services, support for economic development and the promotion of social stability. In turn, Jarvis et al. (2021) argue that good governance underpins more effective policymaking, enabling swifter responses to crises and fostering public trust in government – an essential factor when difficult policy decisions must be made. These differing perspectives underscore the importance of examining not only the abstract principles of good governance but also their concrete legal implementation.

Latvia follows a similar approach. The State Chancellery of Latvia emphasises that good governance is a fundamental precondition for responsible conduct and sound decision-making, placing the human at the centre of good governance (Cabinet of Ministers, 2020). Accordingly, good governance integrates transparency and public involvement, responsibility to society for results achieved, underpinned by ethical standards and a framework for fair, legal and well-deliberated decisions. Taken together, these elements enable public administration to perform its core function more effectively – namely, to act in the public interest – while simultaneously fostering public trust in public administration and ensuring the efficient delivery of public administration services that are responsive to the needs of the citizens.

In Latvia, the principle of good governance is embedded in the State Administration Structure Law, which provides that public administration is required to follow the principles of good governance, such as openness to the public, data protection, fair and timely procedures and measures safeguarding individuals' rights and legitimate interests (State Administration…, 2002). This legal act constitutes the central legal framework governing public administration and grants the Cabinet of Ministers the right to issue regulations defining unified rules for governance of public services.

From the perspective of public administration, good governance is realised not only through sound institutions and policymaking but also through the quality, accessibility and legal certainty of the public administration services delivered to individuals and businesses. Ensuring this requires a stable and transparent regulatory framework at both international and national levels. Latvia has been a member of the European Union since 2004, which implies that Latvia is bound by the legal framework regarding, inter alia, the cross-border provision of public services. The European Union regulations increasingly promote user-centric, digital and interoperable public services, imposing additional expectations and constraints for national legal frameworks.

In 2021, the Ministry of Smart Administration and Regional Development of the Republic of Latvia initiated an in-depth expert study to evaluate the implementation of existing policies and regulatory frameworks and to assess the outcomes achieved in the governance of public administration services, to develop evidence-based recommendations for improving the public services governance system. The findings of this study provided the basis for the subsequent implementation of the objectives set out in the Digital Transformation Guidelines for 2021–2027, including the establishment and implementation of a public services governance policy and the development of an appropriate regulatory framework (CETERA, 2021). As a result, the Public Service Environment Improvement Plan 2024–2027 was adopted in Latvia in 2024. This plan serves as the main policy instrument for governing public services in Latvia. It establishes a framework for full-scale governance of public administration services, ensuring a consistent approach to the design, provision and development of public administration services.

Against this background, the novelty of this research lies in providing one of the first legal analyses of Latvia's regulatory framework for governing public administration services, explicitly assessing it through the lens of good governance principles. By bridging the gap between abstract governance standards and the concrete regulatory framework guiding delivery of public services, this research contributes to the broader discussions on how good governance can be translated into enforceable rules and institutional practices.

The study aims to evaluate Latvia's regulatory framework for governing public administration services in the context of good governance principles. The research aim is achieved through the following tasks:

1) assessing the extent to which the current regulatory framework ensures governance of public administration services in accordance with good governance principles;
2) identifying the primary challenges, gaps and potential inconsistencies within this framework;
3) providing a justified assessment of Latvia's regulatory framework based on principles of good governance.

Materials and Methods

For this research, the term 'legal act' refers to legally binding normative acts, including laws and Cabinet Regulations. This study explores existing articles on good governance and public services using theoretical research methods: the monographic, synthesis-analysis and descriptive methods. A qualitative content analysis of Latvia's legal acts was conducted to assess the compliance of the regulatory framework for governing public administration services with the principles of good governance.

Description of the regulatory framework evaluation methodology

To evaluate the regulatory framework for governing public administration services in Latvia, it is essential to apply a systematic approach that ensures consistency and comparability across different principles of good governance. The evaluation process requires clear criteria and measurable indicators to guide the assessment. The authors have established a specific assessment scale to ensure a systematic and objective evaluation of the regulatory framework according to each good governance principle (Table 1).

Table 1

Rating scale for assessing compliance with the principles of good governance in the regulatory framework for public administration services

Rating	Criteria for assigning the rating	Points
Fully compliant	The legal act contains clear, unambiguous and practically applicable provisions that fully ensure the observance of the respective principle. No obvious contradictions, gaps or exceptions have been identified that could significantly restrict the application of the principle in practice.	2
Partially compliant	The principle is declared or included in the legal act; however, its implementation in practice is limited: the provisions are incomplete, overly general, or contain exceptions that may significantly undermine the principle's effectiveness (for example, designating the digital channel as the priority channel).	1
Non-compliant	The legal act lacks provisions to ensure adherence to the respective principle, or the existing regulation contradicts the principle of good governance (for instance, a service is available exclusively electronically without providing alternatives for vulnerable groups, or unjustified exceptions to rights-protection mechanisms are established).	0
Not applicable	By its nature, the respective principle does not apply to the regulation contained in the given legal act. This rating is not interpreted as non-compliance but as a case of the principle's objective inapplicability.	No points awarded

Source: authors' construction.

To ensure an objective and well-founded assessment of the regulatory framework, the authors' assessment scale is applied in accordance with the following methodological principles:

1) the evaluation of each principle begins with an analysis of the text of the legal act, looking for direct and indirect references to the respective principle;
2) a numerical score (0, 1 or 2) is assigned only after the identification of all related provisions;
3) if, concerning a single principle, the legal act contains both progressive provisions and significant shortcomings or contradictions, priority is given to the lower score (1 – partially compliant) – this is done to highlight the risks within the legal act that may hinder the full implementation of good governance;
4) if a principle is mentioned (for example, in the objectives section) but no mechanisms for its practical implementation are provided, the score cannot be higher than 1;
5) if a principle is assessed as 'Not applicable', it is excluded from the total points calculation for the respective legal act so as not to artificially lower the compliance indicator;
6) the compliance indicator (%) is calculated based on the theoretically possible maximum score;
7) interpretation of results (according to the compliance indicator):
   a) high compliance (≥ 75% of the maximum possible score) – indicates that the legal act largely complies with good governance standards (any shortcomings identified, if present, are mainly of a technical nature and do not affect the overall quality of the legal act);
   b) medium compliance (50–74% of the maximum possible score) – indicates a fragmented regulatory approach reflected in the assessed legal act, whereby certain principles of good governance are ensured, while deficiencies remain in terms of practical implementation or the clarity of specific provisions (in such cases, targeted improvements are required both in the substance of the legal act and in the associated implementation mechanisms);
   c) low compliance (< 50% of the maximum possible score) – indicates a significant or even critical non-compliance with good governance principles, which may create legal certainty risks, foster unequal treatment and weaken public trust in public administration (in such cases, an in-depth review of the legal act and substantial improvements are recommended).

Results and Discussion

The regulatory framework for governing public administration services in Latvia consists of five legal acts, which are directly applicable to the governance of public administration services. The State Administration Structure Law (2002) seeks to ensure that state administration operates in a democratic, lawful, efficient, transparent and publicly accessible manner. Under this Law, state administration is required to adhere to the principles of good governance, necessitating a continuous evaluation and enhancement of service quality. Furthermore, it mandates the simplification of administrative procedures to better serve the interests of citizens. According to the State Administration Structure Law, several Cabinet regulations have been issued:

1) Cabinet Regulation No 399 'Procedures for Accounting, Quality Control and Provision of State Administration Services' (2017);

2) Cabinet Regulation No 400 'Regulations of the State Administration Service Portal' (2017);
3) Cabinet Regulation No 401 'Regulations regarding the Types of the Unified Customer Service Centres of the State Administration, the Scope of Services Provided and the Procedures for the Provision of Services' (2017);
4) Cabinet Regulation No 402 'Regulations Regarding the Public Administration E-services' (2017).

Furthermore, the Public Service Environment Improvement Plan 2024–2027, together with its two annexes, constitutes a significant element of Latvia's regulatory framework for governing public administration services, even though it is a strategic planning and development policy document rather than a legal act.

The principles of good governance

An analysis of existing relevant studies and reports indicates that a universally recognised set of good governance principles for the public sector has yet to be established. Rather, different organisations and authors emphasise partly overlapping dimensions of good governance, reflecting their institutional mandates and the specific governance challenges they address. The International Framework: Good Governance in the Public Sector (2014) conceptualises good governance primarily through the lens of public value creation and stewardship of public resources. It highlights integrity, ethics and the rule of law; openness and stakeholder engagement; sustainable economic, social and environmental outcomes; the selection of effective interventions; organisational capacity and leadership capability; risk management, internal control and public financial management; transparency and accountability. This framework underlines that good governance is not limited to formal legality but also requires ethical standards, a long-term orientation and sound financial and risk management.

Herasymiuk et al. (2020) offer a distinct perspective on good governance within public administration by prioritizing its relational and structural dimensions. They argue that the concept rests on the principles of subsidiarity, participation and trust, which together imply the delegation of functions to the most appropriate level, the preservation of the independence of the actors involved and mutual responsibility, control and transparency in the pursuit of common goals. This perspective particularly stresses shared responsibility and partnership between the state, private sector and civil society.

The Good Governance Standard for Public Services (2004) of the UK further refines the discussion by formulating six principles tailored to organisations that deliver public services. Good governance is characterised by a primary focus on organisational goals and delivering tangible results for the service users. It requires institutions to operate efficiently within established roles while upholding core values through ethical conduct. Furthermore, it involves evidence-based and transparent decision-making, robust risk management, and continuous development of organisational leadership. Finally, meaningful stakeholder engagement and genuine accountability are essential components of this framework. Compared with the International Framework: Good Governance in the Public Sector (2014), the Good Governance Standard for Public Services (2004) places stronger emphasis on governance structures and the behaviour of governors in their relationships with users, staff and other stakeholders.

Other authors and institutions propose more concise formulations that nonetheless point to similar core elements. Anđelković (2023) argues that good governance presupposes the rule of law, the protection of human rights, a fair and efficient system of government as well as accountability, transparency, predictability and openness. Likewise, the European Commission's White Paper on European Governance (2001) identifies five principles at the heart of good governance: openness, participation, responsibility, efficiency and coherence, applicable to every tier of governance, from global to local. These approaches underline in particular the importance of legality, openness, participation, responsibility and effectiveness of public institutions. The Council of Europe (2026) offers perhaps the broadest and most operationalised list, having adopted 12 principles of good democratic governance at the local level: democratic participation; human rights; rule of law; ethical conduct; accountability; openness and transparency; efficiency and effectiveness; sound financial management; leadership and capacity; responsiveness; sustainability and long-term orientation; openness to change and innovation. This confirms the multidimensional nature of good governance: it simultaneously concerns legal guarantees (human rights, rule of law), ethical standards (ethical conduct, accountability, transparency), performance (efficiency, effectiveness, sound financial management), organisational capacity (leadership, responsiveness) and adaptability (sustainability, innovation).

Taken together, these frameworks and studies demonstrate a high degree of conceptual convergence around several recurring themes: human rights and rule of law; openness, transparency and participation; accountability; efficiency and effectiveness in the use of public resources; ethical conduct and integrity; institutional capacity and leadership; and responsiveness to citizens' needs. At the same time, none of the analysed sources offers a set of principles specifically designed to assess the regulatory framework governing public administration services. Based on this comparative analysis, the authors formulated 10 principles of good governance to evaluate Latvia's regulatory framework:

1) rule of law – the legal act is based on a clear and statutory delegation, complying with the Constitution and fundamental rights, avoiding any discrimination;
2) openness and transparency – the legal act prescribes an obligation for the institution to provide accessible,

timely and easily understandable information regarding service procedures, citizens rights and the decision-making process;
3) accountability – the legal act clearly identifies the competent institutions and officials as well as their responsibilities and powers;
4) fair procedures – the legal act provides that legal relations between public administration and individuals are fair, impartial and predictable; decisions are based on objective facts and guarantee the person's right to be heard;
5) efficiency and effectiveness – the legal act ensures that public assets are used judiciously to achieve objectives with minimal possible administrative burden for both the institution and the individual, avoiding unnecessary or duplicative procedures;
6) service accessibility – the legal act supports the accessibility of public services for all groups of society; the priority of digital channels does not exclude the use of alternative channels (face-to-face, by post or by telephone), in particular to protect the right of vulnerable groups and persons with special needs to access the public services;
7) user-centricity – the legal act supports that the public administration service delivery process is primarily designed around the user's needs and life situation, prioritising simple procedures, easily understandable forms and necessary support;
8) public participation – the legal act provides meaningful involvement of the public and target groups in the design, testing and improvement of public services as well as promotes the establishment and use of feedback mechanisms (for example, surveys and recommendation channels);
9) services monitoring and improvement – the legal act provides that regular monitoring of service quality and accessibility be established, assessing not only quantitative indicators but also user satisfaction to ensure continuous improvement of public services;
10) data protection – the legal act provides that the processing of personal data has a clearly defined legal basis and purpose, ensuring data security and the right of individuals to control their personal information.
These principles synthesise the core elements identified in international frameworks into concrete criteria tailored for evaluating Latvia's regulatory framework for governing public services.

Results of the evaluation

The assessment results of Latvia's regulatory framework for governing public administration services are presented in Table 2.

Table 2

Assessment results of Latvia's regulatory framework for governing public administration services

No.	Principle	State Administration Structure Law	Cabinet Regulation No 399	Cabinet Regulation No 400	Cabinet Regulation No 401	Cabinet Regulation No 402	Service Governance Policy
1.	Rule of law	2	2	2	2	2	N/A
2.	Openness and transparency	1	1	1	1	1	1
3.	Accountability	1	2	2	2	2	1
4.	Fair procedures	N/A	2	N/A	1	N/A	N/A
5.	Efficiency and effectiveness	1	2	2	1	2	2
6.	Service accessibility	2	2	1	2	1	2
7.	User-centricity	1	2	1	2	2	2
8.	Public participation	2	1	2	2	2	2
9.	Service monitoring and improvement	1	2	2	2	2	2
10.	Data protection	2	0	2	2	0	2
	Total scores	**13**	**16**	**15**	**17**	**14**	**14**
	Compliance indicator	**72%**	**80%**	**83%**	**85%**	**78%**	**88%**

Source: authors' construction.

The principle of fair procedures does not apply to the State Administration Structure Law (2002), as the Law does not regulate specific procedures. The Law is fully compliant with the following good governance principles: rule of law, service accessibility, public participation and data protection, by promoting a democratic and transparent public administration. It requires institutions to act within their legal competence and in the public interest, ensures convenient service delivery through the once-only principle and digitalisation (without excluding other service delivery channels) and limits personal data processing to what is strictly necessary. Partial compliance is identified regarding principles – openness and transparency, accountability, efficiency and effectiveness, user-centricity and services monitoring and improvement. The Law establishes a centralised e-services portal, requires proactive

information to individuals whose rights may be affected and promotes maximum efficiency through single customer service centres. While the State Administration Structure Law authorises the Cabinet to define detailed procedures and monitor mechanisms, the Law itself focuses on the general obligation to simplify procedures and continuously improve the quality of public services.

The Cabinet Regulation No 399 of the Republic of Latvia 'Procedures for Accounting, Quality Control and Provision of State Administration Services' (2017) is non-compliant with the principle of data protection, as it does not contain specific provisions on data protection in the governance of public administration services. However, this Regulation does comply fully with the principles: rule of law, accountability, fair procedures, efficiency and effectiveness, service accessibility, user-centricity, services monitoring and improvement. This Regulation requires equal treatment, objective decision-making and clearly defined responsibilities for owners and providers of public services. The Ministry of Smart Administration and Regional Development of the Republic of Latvia is responsible for providing methodological support for governing public administration services. This Regulation promotes efficiency by enabling delegated service provision and unified customer service centres. Furthermore, it mandates that delivery channels be selected based on accessibility, client convenience, cost-effectiveness and reduction of administrative burdens. Descriptions of public services shall include clear application information, including online forms. Continuous quality improvement is ensured through performance monitoring, including client satisfaction indicators. This Regulation demonstrates partial compliance with the principles of good administration of openness and transparency and public participation. The Cabinet Regulation No. 399 requires up-to-date descriptions of the public services (application procedures, applicable fees and appeal mechanisms). Although this promotes transparency, access to the information is largely confined to internet users and e-service recipients. Furthermore, although institutions are required to establish internal procedures to inform clients of their right to lodge complaints, the regulation does not specify broader feedback mechanisms or formal platforms for public participation in public services development.

The Cabinet Regulation No 400 'Regulations of the State Administration Service Portal' (2017) does not apply the principle of fair procedures as this Regulation does not specify the implementation of specific procedures. However, the following principles are fully complied – rule of law, accountability, efficiency and effectiveness, public participation, services monitoring and improvement, data protection. This Regulation establishes the Public Administration Services Portal as a centralised electronic hub for public services, information and communication. By integrating online payments, machine translation and automated service descriptions through the system 'VIRSIS' (State Information Resources, Systems and Interoperability Information System), it enhances efficiency. This Regulation requires quarterly publication of performance indicators, annual user satisfaction surveys, user reporting options and strict limits on personal data processing. The Cabinet Regulation No 400 partially complies with the principles of good governance, namely openness and transparency, service accessibility and user-centricity. This Regulation ensures advance notice of planned e-service interruptions and unplanned outages. Furthermore, this Regulation defines end-user rights, including the ability to access all available e-services. While the Public Administration Services Portal (www.latvija.gov.lv) provides unified access to e-services and the official electronic address – ensuring mobile functionality and integrated user support – it remains accessible only to those with the requisite digital skills and technical means. Furthermore, a user-oriented approach is reinforced through the inclusion of 'life-event' descriptions.

The Cabinet Regulation No 401 'Regulations regarding the Types of the Unified Customer Service Centres of the State Administration, the Scope of Services Provided and the Procedures for the Provision of Services' (2017) fully complies with the following principles of good governance: rule of law, accountability, service accessibility, user-centricity, public participation, services monitoring and improvement, data protection. Adopted under the State Administration Structure Law, it establishes a governance framework for unified customer service centres, defining their types, responsibilities and service procedures. Centres ensure accessibility by providing public-access computers, free internet, staff assistance and the possibility to apply for e-services through an employee for individuals without digital skills or identification tools. Information regarding the centres is publicly available, and regular customer satisfaction surveys facilitate the continuous improvement of public services. Centre staff may process only the personal data essential for the delivery of e-services. The Cabinet Regulation no 401 partially complies with the principles of good governance: openness and transparency, fair procedures and efficiency and effectiveness. This Regulation requires owners of public services to publish e-service information through the Public Administration Services Portal, institutional websites and mass media and to notify users of both planned and unplanned service interruptions. To maintain high standards in the delivery of public services, institutions are required to provide annual training and up-to-date methodological materials for staff at unified customer service centres. By enabling institutions to use unified centres instead of separate local facilities, the system ensures a more efficient use of public resources. However, as communication is mainly digital, it primarily reaches

those with the internet access and adequate digital skills.

The Cabinet Regulation No 402 'Regulations Regarding the Public Administration E-services' (2017) does not apply the principle of fair procedures, since it lacks specific procedural guidelines, indicating that this area remains outside the current Regulations' scope. This Regulation is also not compliant with the principle of data protection due to the absence of related provisions. This Regulation is fully compliant with the following principles of good governance: the rule of law, accountability, efficiency and effectiveness, user-centricity, public participation, service monitoring and improvement. It defines clear responsibilities for owners, providers and recipients of public services, ensuring all e-services to meet technical and security standards. According to the Cabinet Regulation No 402, digitalisation should be cost-effective and impact-based, applying the 'once-only' principle and user-centred approach. This Regulation promotes proactive service delivery, user involvement in e-service development and continuous improvement through mandatory feedback mechanisms and performance indicators such as adoption rates and user satisfaction. This Regulation partially complies with the good governance principles of openness and transparency and service accessibility. Although comprehensive e-service information and outage notifications should be published, this Regulation focuses exclusively on digital delivery of public services, providing no structured alternatives beyond in-person support for accessing e-services.

The Public Service Environment Improvement Plan 2024–2027 and its Annex No 1 'Service Governance Policy' (2024) do not apply either the principle of the rule of law as they serve as a policy framework and a strategic planning instrument and the principle of fair procedures, as they do not establish specific procedures. The Service Governance Policy fully complies with the following principles of good governance: efficiency and effectiveness, service accessibility, user-centricity, public participation, service monitoring and improvement, data protection. It promotes automation, digitalisation and multi-channel, inclusive and cross-border access. Service development, delivery and improvement shall be needs-based and guided by the 'once-only' principle for convenience. The Service Governance Policy requires the user involvement, measurable services with key performance indicators, oversight at all governance levels. Finally, the Service Governance Policy ensures confidentiality and the protection of personal data. The Service Governance Policy partially complies with the good governance principles of openness and transparency and accountability. Although the Service Governance Policy promotes information-sharing and defines responsibilities across governance levels, these principles are formulated broadly and do not create direct legal obligations or specify detailed transparency requirements.

Overall, according to the established methodology for assessing regulation, the regulatory framework for governing public administration services in Latvia can be considered compliant with the principles of good governance. The framework fosters user-oriented and high-quality service development, including digital services as well as the optimised utilisation of public assets. The assessment shows that, among the six analysed documents regulating the governance of public administration services in Latvia, the highest level of compliance with good governance principles is observed in the Service Governance Policy (88%), which constitutes Annex No 1 of the Public Service Environment Improvement Plan 2024–2027. Since the Plan's approval in 2024, this document has been regarded as the primary instrument for implementing a unified approach to governance of public administration services.

Slightly lower, yet still high, levels of compliance are achieved by the Cabinet Regulation No 401 (85%), the Cabinet Regulation No 400 (83%) and the Cabinet Regulation No 399 (80%), which together provide detailed regulations for specific aspects of public service governance. The Cabinet Regulation No 402 (78%) demonstrates relatively lower compliance, for example, due to the absence of provisions on data protection, which are currently highly relevant. Nevertheless, this score is still considered positive overall. The lowest level of compliance is observed in the State Administration Structure Law (72%), which should not be interpreted as a poor result. Rather, it reflects the nature of the Law, which establishes only general guidelines and principles concerning the governance of public administration services, rather than detailed procedures for service provision. The Law confers authority upon the Cabinet to establish specific norms for governing public services. The higher compliance scores of the analysed regulations support this observation.

Conclusions

1. The compliance of public administration services with established regulations should be assessed not only through formal legal assessments but also by incorporating citizen perceptions, trust and the quality of repeated interactions with public institutions.
2. Digitalisation offers significant potential to reduce costs, improve accessibility of public services and enhance the user experience. However, it may also exacerbate inequality, as some individuals face difficulties in accessing and using digital services. Identifying groups at particular risk of digital marginalisation is thus essential to designing more inclusive digital public services.
3. Based on the assessment of Latvia's regulatory framework for governing public administration services, all analysed legal acts and policy documents demonstrate relatively high compliance with fundamental principles of good governance such as rule of law, accountability, public participation, service

monitoring and improvement. Lower compliance in specific cases is associated with insufficient specification of the principles of fair procedures and data protection in certain Cabinet regulations.

4. Overall, Latvia has established a comparatively strong normative foundation for governing public administration services. Future improvements should focus on the consistent and detailed integration of the principles – fair procedures and data protection across all legal acts related to governance of public administration services.

5. Future research could aim to reduce the subjectivity in the assessment of legal acts and policy documents by involving a broader range of experts in the evaluation process. This would allow for a more objective appraisal of the compliance of legal acts and policy documents with the principles of good governance and enable the calculation of statistically significant differences between expert assessments.

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SUSTAINABLE WORKFORCE DEVELOPMENT IN EUROPE: HR STRATEGIES FOR SUPPORTING GENERATION Z IN RURAL AND REGIONAL LABOUR MARKETS

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Abstract
Generation Z is entering the European labour market at a time when rural and regional areas face acute demographic decline, skills shortages and intensified competition for talent. As digital natives with strong preferences for flexibility, meaningful work and inclusive cultures, Gen Z employees represent both a critical opportunity and a challenge for organisations seeking long-term regional sustainability. This study looks at whether Organisation Human Resource (HR) practices align with Gen Z expectations and how this fit affects engagement and retention in the European context, especially for keeping for sustaining rural and regional workforce capacity. Utilizing a mixed-methods approach based on a survey of 100 Gen Z employees and their qualitative insights from semi-structured interviews, the research evaluates perceived HR awareness, satisfaction with key HR practices and priority improvement areas. The findings highlight a significant awareness gap with 48% of respondents rating HR as not aware of their needs, versus only 16% considering them as fully aware. Satisfaction scores were lowest for flexibility, communication and career development, and qualitative responses underscored the need for personalised onboarding, mentoring and mental-health support. The study argues that closing the HR awareness gap is not merely an internal organisational issue but a strategic requirement for sustaining regional labour markets. By putting things like active listening programs, open communication, hybrid work options and clear development pathways, organisations can reduce talent drain, this also strengthens Gen Z engagement and support to the socio-economic resilience of rural and regional areas in Europe.
Keywords: generation Z, HR awareness, employee engagement, retention, Europe.

Introduction

Generation Z those born broadly between 1997 and 2012 is entering the European workforce market in growing numbers. They arrive with workplace expectations that diverge considerably from preceding cohorts: a strong preference for flexible arrangements, visible career development, and employment that aligns with personal values (Seemiller & Grace, 2018; Chillakuri, 2020). For HR practitioners, this generational transition creates a practical challenge. Many organisations continue to operate with HR practices developed for Millennial and Generation X employees, and the resulting mismatch shows up in engagement data, in turnover intentions, and as this study presents in how Gen Z employees describe their own working lives when asked directly.

The territorial dimension of this challenge is important and often overlooked. This study defines Europe as the 27 EU member states a frame that encompasses highly diverse labour market conditions. Urban centres, where most HR research has been conducted, differ fundamentally from rural and peripheral regions, which face demographic ageing, persistent youth outmigration and structural workforce shortages (European Commission, 2021). In those settings, HR quality is not simply an operational concern. When rural organisations cannot offer the work experience that Gen Z expects, and when young people leave for cities as a result, the communities they leave behind become harder to sustain. HR practice, in that context, is a territorial issue.

The literature on Gen Z workplace expectations has grown substantially, but it tends to focus on urban organisational contexts and rarely examines the rural dimension (Knapp, 2017; Pandita, 2021). Equally, research on rural workforce sustainability tends not to engage seriously with HR practice. This paper focus at the intersection of these two bodies of work. The study examines how HR departments are currently perceived by Gen Z employees, the specific improvements they prioritise, and the implications for organizations in rural and regional settings.

The study draws on survey data from 100 Gen Z respondents across EU member states, combining quantitative ratings with qualitative open-ended responses. The aim is not to produce a comprehensive generational theory but to provide empirical evidence on a practical management problem, and to situate that evidence within the rural sustainability context where it carries greatest weight.

Literature Review

Defining Generation Z and the European Labour Market Context

Generation Z individuals born between 1997 and 2012 are the first cohort to have been raised entirely within a digitally networked world (Seemiller & Grace, 2018). This matters for HR practice because the formative environment shapes workplace expectations in quite specific ways. Gen Z employees tend to place considerable weight on purpose and values alignment, often more so than on salary stability. They expect digital-first communication as a default rather than an option. And, as Chillakuri (2020) and Pichler et al. (2021) both documents, they are more willing than preceding generations to exit employment that does not reflect their values often early in their tenure. Against this backdrop, the European labour market is also dealing with widening skill shortages, demographic ageing and a growing geographic divide between urban and peripheral regions (European Commission, 2021).

That rural–urban divide deserves particular attention

here. Rural and regional areas in the EU face a specific kind of disadvantage: it is not simply that there are fewer workers, but that the employment available often does not match what Gen Z is looking for. Limited flexibility, unclear career paths and organisational cultures that have not kept pace with urban counterparts create a structural weakness that salary adjustments alone cannot resolve. Rural employers are in effect, competing against metropolitan organisations that offer better-developed HR environments, broader professional networks and higher pay. The result skilled young workers moving to cities is well-documented (European Commission, 2021) and accelerates the demographic decline that rural regions are already struggling to reverse.

HR Practices and Generation Z Engagement

Three HR domains consistently emerge from the literature as shaping Gen Z engagement and retention. The first is flexibility. Hybrid, remote and flexible-hours arrangements have moved beyond being attractive features of a job offer; for Gen Z they function as prerequisites. Wadhwa (2022) documents that Gen Z employees denied flexible working report substantially elevated turnover intentions, and this holds even after controlling for salary levels. For rural employers specifically, there is an underappreciated opportunity here: geographic distance from city centres matters considerably less when daily commuting is not required. The organisations that have not yet formalised flexible policies are, in practice, forfeiting one of the few structural advantages they have.

Career development is the second domain. The Gen Z orientation towards continuous learning and upward mobility is well-established in the literature (Jayathilake et al., 2021), and the practical implications for HR are fairly direct: clear promotion criteria, accessible mentorship and personalised development plans are associated with meaningfully higher engagement among early-career employees. What Pandita (2021) adds to this picture is a useful distinction: it is the outright absence of development support, not merely its inadequacy, that most strongly predicts voluntary early-career departure. An organisation with an imperfect mentorship scheme is in a better position than one with none at all.

Communication is the third domain, and it may be the most overlooked. Gen Z employees are sensitive to gaps between what organisations claim to stand for and how they actually operate what (Fernandez, 2021) call values-practice misalignment. Transparent, timely communication about role expectations, career prospects and organisational direction improves engagement and, in rural contexts contributes to employer reputation in ways that are difficult to recover once lost. Small communities are not forgiving of inconsistent communication word travels quickly, and employer credibility, once damaged, is hard to rebuild.

Sustainability, Rural Regions and Workforce Policy

The European Commission's Long-Term Vision for Rural Areas (2021) is explicit about the workforce dimension of rural sustainability: demographic decline in peripheral regions is self-reinforcing. Young people leave; services contract; economic opportunities narrow; the remaining population ages. Reversing this requires more than broadband investment and infrastructure grants. It requires the quality of employment itself to improve—and HR practice is a significant part of that. The Commission acknowledges this but does not specify how. That gap is part of what this paper attempts to address.

Materials and Methods

This study used a descriptive mixed-methods design, combining a structured survey with open-ended response questions. The quantitative component was intended to provide breadth to identify patterns in HR awareness and satisfaction across a reasonably sized sample. The qualitative component served a different purpose: it gave respondents the opportunity to describe their actual experiences in their own words, adding texture that rating scales cannot capture. Both elements were necessary; neither would have been sufficient on its own.

Data were gathered from 100 Generation Z employees (aged 18–27) drawn from across EU member states. Participants were taken through purposive sampling via LinkedIn and social media platforms, targeting individuals who were employed, or actively seeking employment, within the EU. The survey was administered through Google Forms. As part of the instrument, respondents were asked to classify the location of their primary workplace as an urban centre, a regional city or a rural/peripheral area. This item was included deliberately to allow territorial comparisons—a dimension absent from most comparable studies.

The survey measured three constructs. Perceived HR awareness was rated on a five-point scale running from 'not aware at all' to 'fully aware'. Satisfaction was assessed across five HR practice areas: recruitment and onboarding, training and development, performance feedback, employee engagement initiatives, and work flexibility options, each rated on the same five-point scale. Goal alignment, the degree of fit between personal career objectives and organisational direction, was rated identically. Open-ended questions asked what HR improvements respondents most wanted and what would make their current or prospective employer more attractive. Descriptive statistics were calculated for closed-ended items; open-ended responses were coded thematically. Participation was voluntary throughout, and all data were anonymised in accordance with GDPR.

Results and Discussion

Results are presented across four sub-sections: (i) respondent profile; (ii) HR awareness levels; (iii) satisfaction with HR practices; and (iv) qualitative improvement themes and rural/regional dimensions.

Respondent profile

The sample of 100 respondents ranged in age from 18 to 27, with 22-year-olds most represented (23%), followed by those aged 23 and 25 (15% each). The majority were currently employed (81%), though 19% were between roles - a detail worth noting given the retention focus of the study. Employment types were predominantly entry-level: internships and part-time work each accounted for 37%, with full-time employment at 16%. Half of respondents worked in private for-profit organisations, 15% in non-profit entities and 5% in the public sector. The territorial breakdown showed 31% based in urban centres, 42% in regional cities and 27% in rural or peripheral areas. That last figure - more than a quarter of the sample - provides a meaningful basis for urban-rural comparison, which is a central concern of this paper.

HR awareness levels

Figure 1 presents the distribution of HR awareness ratings. Almost half of respondents (48%) rated HR awareness as low (levels 1–2), indicating that HR departments are broadly perceived as unaware of Gen Z needs. Only 16% rated HR as fully aware (level 5), while 28% gave moderate-to-high ratings. This pronounced awareness gap is consistent with evidence that misalignment between HR practices and employee expectations directly reduces engagement and intention to stay (Jayathilake et al., 2021).

Figure 2 shows the average satisfaction scores for the five HR practice areas. The scores were consistently low, ranging from 2.1 to 2.4 on a five-point scale. Work flexibility options received the lowest score (2.1), with 39% of respondents indicating they were 'very dissatisfied' a sign of significant dissatisfaction with the limited hybrid and remote work options. Employee engagement initiatives scored 2.2, and performance feedback scored 2.3.

Figure 1

Distribution of HR awareness ratings among Gen Z employees (n = 100)

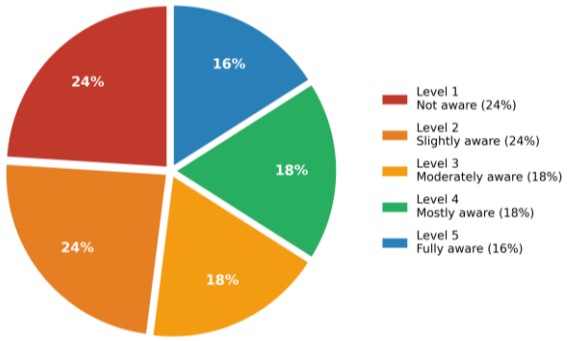


Figure 2

Average satisfaction ratings for key HR practices (n = 100)

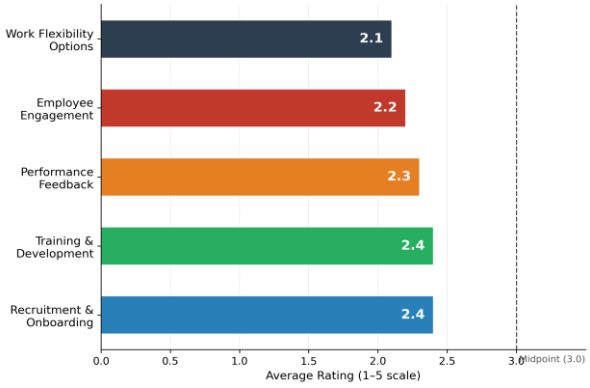


Table 1

Satisfaction ratings for HR practices (scale 1–5)

HR Practice	Avg.	Rating 1	Rating 2	Rating 3	Rating 4	Rating 5
Recruitment & Onboarding	2.4	36	15	19	22	8
Training & Development	2.4	22	32	23	18	5
Performance Feedback	2.3	33	19	26	16	6
Employee Engagement	2.2	32	31	12	20	5
Work Flexibility Options	2.1	39	15	18	22	6

Note: Avg = mean score (1–5 scale); Low = % selecting 1–2; Mod. = % selecting 3; High = % selecting 4–5. Source: Author's own research (2025).

Satisfaction with HR practices

Recruitment and onboarding, as well as training and development, both had a score of 2.4, suggesting slightly better HR performance in initial engagement activities, even though these scores were still below an acceptable level. These findings confirm that flexibility and career development are now basic expectations for Gen Z, rather than optional benefits, not discretionary benefits (Wadhwa, 2022).

Preferred HR initiatives

When asked which HR initiatives would most effectively attract and retain Gen Z employees, flexible work arrangements were the clear desire (65%), followed jointly by competitive compensation and career development opportunities (59% each). Employee well-being and clear communication were each cited by 45% of respondents. Figure 3 and Table 2 summarise all preferences ranked by frequency.

Figure 3
Preferred HR initiatives for attracting and retaining Gen Z employees (n = 100)

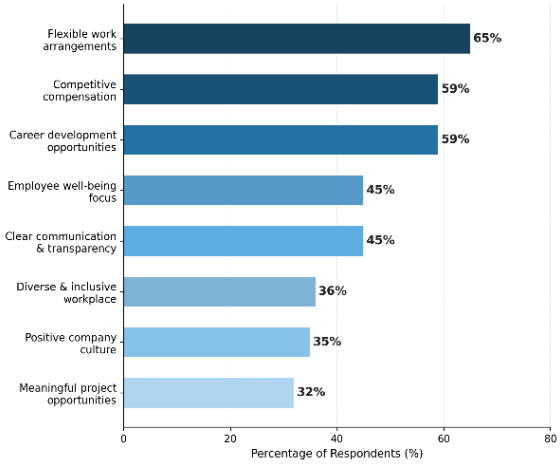


Table 2
Preferred HR initiatives for Gen Z attraction and retention

HR Initiative	n (%)
Flexible work arrangements	65 (65%)
Competitive compensation & benefits	59 (59%)
Career development opportunities	59 (59%)
Employee well-being focus	45 (45%)
Clear communication & transparency	45 (45%)
Diverse & inclusive workplace	36 (36%)
Positive & supportive culture	35 (35%)
Meaningful project opportunities	32 (32%)

Source: author's own research (2025).

Qualitative improvement themes

Thematic coding of open-ended responses (n = 42 substantive responses) identified six improvement categories. Better communication was the most frequently cited theme (26%), with respondents requesting clearer role expectations, transparent leave policies and better-defined responsibilities. Career development followed at 21%, with calls for visible promotion pathways and mentorship programmes. Better training accounted for 19%, with respondents criticising outdated programmes that did not reflect current technological demands. Improved onboarding was cited by 14%, mentorship programmes by 10%, and support for international staff by 5%. Figure 4 illustrates the distribution of themes, while Table 3 provides supporting response examples.

Work preferences and sustainability orientation

The survey also examined Generation Z's work preferences and their views on sustainability. Regarding preferred working hours, 40% of those surveyed preferred a 30-hour workweek, 32% preferred the standard 40-hour week, and 19% preferred a 20-hour part-time schedule. Only 4% of respondents were willing to work 50 or more hours each week. These preferences suggest that flexible scheduling is an important tool for keeping employees, especially for rural employers who may not be able to offer high salaries but can attract talent by providing a good work-life balance.

Figure 4
Qualitative improvement themes from open-ended responses (n = 42)

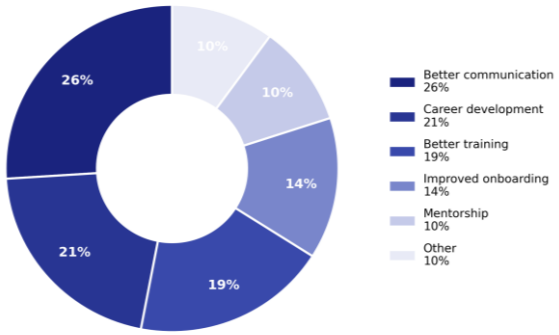


Table 3
Improvement themes with example responses

Theme	%	Example Responses
Better communication	26%	Clearer role expectations; transparent policies
Career development	21%	Promotion plans; career advancement support
Better training	19%	Personalised, up-to-date training programmes
Improved onboarding	14%	People-centred orientation; cultural integration
Mentorship programmes	10%	Structured mentoring from senior professionals
International staff support	5%	Visa support; relocation assistance

Source: author's own research (2025); n = 42 substantive responses.

Regarding preferred work style, 40% of respondents favoured a mix of independent and collaborative work, 26% preferred primarily collaborative environments, and only 8% preferred working primarily independently. This strong collaborative orientation has practical implications for HR design: rural organisations that can foster team cohesion, shared purpose and
collegial culture which are often natural advantages of smaller organisations may be well-positioned to meet Gen Z preferences if they communicate these attributes effectively in recruitment.

Sustainability orientation data revealed that 72% of respondents rated working for an organisation that prioritises sustainability and social responsibility as important or very important (ratings 4–5), with 47% selecting the highest importance rating. Only 8% rated

sustainability as unimportant. This finding is directly relevant to rural HR strategy: organisations located in rural areas can legitimately frame their work as contributing to local community sustainability, environmental stewardship and regional food systems narratives that resonate strongly with Gen Z's values-driven orientation and which urban employers cannot authentically replicate.

Collaboration and teamwork preferences

When asked to identify factors contributing to effective collaboration, respondents most frequently selected defined roles and responsibilities (55%), followed by access to collaborative tools and technologies (50%), mutual respect and trust (49%), open and inclusive discussions (43%), clear communication channels (41%), shared goals and objectives (45%), and opportunities for social interaction (34%). These findings highlight that Gen Z's collaborative effectiveness is not purely technological – interpersonal dynamics, role clarity and psychological safety are equally important. For HR practitioners, this reinforces the need for structured onboarding programmes that clarify roles, team-building initiatives that build trust, and communication frameworks that support open dialogue.

Organisational goal alignment

Beyond HR awareness and satisfaction, the study examined whether Gen Z respondents felt their personal career goals aligned with those of their employing organisations. Results were concerning: 49% rated alignment as low (ratings 1–2), with 19% selecting 'not aligned at all', and only 32% reporting high alignment. Similarly, 38% rated their understanding of their organisation's mission as low, while 38% rated it as high. These findings reveal a dual communication failure: HR is not only poorly aligned with what Gen Z employees want, but is also failing to communicate organisational purpose and direction. This disconnect is a significant driver of early-career disengagement and turnover (Pandita, 2021).

Table 4

Alignment with organisational goals and mission understanding (n = 100)

Category	Low (1-2)	Mid (3)	High (4-5)
Alignment with Org. Goals	49%	4%	32%
Understanding of Org. Mission	38%	4%	38%

Note: Percentages do not sum to 100% due to non-response (15–20%). Source: Author's own research (2025).

Rural, regional and sustainability dimensions

A cross-territorial analysis of survey responses revealed that respondents employed in rural and peripheral EU regions consistently reported lower satisfaction with HR flexibility provisions (average 1.8 vs 2.4 for urban respondents) and career development opportunities (average 1.9 vs 2.6) than their urban counterparts. This disparity reflects the structural constraints under which rural and regional employers operate: smaller HR teams, constrained budgets, weaker digital infrastructure and limited access to specialised talent pipelines. The consequence is a self-reinforcing cycle – inadequate HR practices accelerate talent outmigration, which further depletes the human capital needed to sustain local economies and public services (European Commission, 2021).

This finding carries direct implications for the sustainability dimensions of this conference. In the EU context, the rural–urban divide in HR quality is not merely a management issue but a territorial sustainability challenge. If rural and regional organisations cannot close the HR awareness gap, they risk losing their most mobile and entrepreneurially-minded young workers to metropolitan centres – exacerbating existing demographic imbalances and undermining the viability of place-based development strategies. HR investment in rural and regional contexts should therefore be recognised as a contribution to regional sustainability, not merely as an organisational cost.

The results present a coherent and somewhat uncomfortable picture. HR departments across the EU are not meeting Gen Z expectations not on awareness, not on flexibility, not on development, and not on communication. The 48% low-awareness rating is not an outlier result; it aligns with a growing body of research suggesting that traditional HR frameworks, built around earlier generational cohorts, are a poor fit for how Gen Z experiences work (Chillakuri, 2020; Wadhwa, 2022).

What makes the qualitative findings valuable is the specificity. Respondents were not just dissatisfied in a vague sense – they pointed to concrete gaps. The most commonly mentioned was communication (26%), but it was not about volume; it was about clarity and honesty. People wanted to know what was expected of them, what policies actually were, and whether their managers would be straight with them. Career development (21%) and training (19%) followed, reflecting a generation that entered the workforce during a period of significant economic uncertainty and wants visible reasons to stay. The mentorship finding (10%) reinforces this: relational guidance from more experienced colleagues is valued precisely, because it makes an uncertain career path feel more navigable (Jayathilake et al., 2021).

In the context of rural sustainability, these findings take on added weight. Rural organisations that do not address the HR awareness gap are not simply losing individual employees; they are accelerating the outmigration that hollows out rural communities. But the data also point towards a practical argument for optimism. Rural workplaces, at their best, can offer exactly what Gen Z values: genuine purpose, community connection, environmental significance, and the kind of trust-based team culture that is harder to sustain in large urban organisations. The problem is that most rural HR strategies are not making this

case (Fernandez, 2021). The sustainability orientation data – with 72% of respondents rating it as important - suggests that if rural employers told this story better, some proportion of Gen Z would listen.

The collaboration data add another dimension. Gen Z does not just want flexibility and development, they want to work well with other people. They care about roles being clear, communication being open, and trust being genuine. These are not expensive things to provide. They are principally about leadership, culture and HR practice. Smaller rural organisations, which often have the advantage of closer working relationships and flatter hierarchies, are in principle well-placed here. Whether they capitalise on it depends on whether they see HR as a strategic function rather than an administrative one.

The goal alignment finding deserves a final word. When 49% of respondents report low alignment between what they want from their careers and what their organisation is doing, and 38% do not understand their organisation's mission, the most direct fix is not to recruit different people. It is to communicate better. Regular conversations about career direction, clear frameworks for progression, and onboarding that genuinely situates a new employee within the organisation's purpose - these are not complex interventions. They are, however, ones that require HR to take an active rather than reactive role.

This study has several limitations worth acknowledging. Purposive sampling means the findings cannot be straightforwardly generalised beyond the studied group. Self-reported data carry the usual risks of perception and social desirability bias. The cross-sectional design means that we cannot make causal claims. And with a sample of 100 across multiple EU countries, sector- or country-specific conclusions are not supported. Future work should pursue longitudinal designs, larger and more stratified samples, and experimental or quasi-experimental approaches to test whether specific HR interventions actually shift retention outcomes in rural and regional contexts.

Practical implications for HR in rural and regional contexts

Based on the findings, five targeted recommendations are proposed for HR practitioners, particularly those operating in rural and regional EU contexts:

1. *Implement continuous listening mechanisms:* quarterly pulse surveys, open-door HR channels and regular listening sessions to capture Gen Z expectations and respond in real time.
2. *Enhance communication transparency:* role expectations, promotion criteria, leave policies and organisational mission should be communicated clearly via digital-first channels aligned with Gen Z communication preferences.
3. *Design visible career pathways:* structured mentorship programmes, merit-based advancement criteria and targeted skill-building workshops signal long-term organisational investment and reduce early-career disengagement.
4. *Normalise flexible and hybrid work:* formalised hybrid policies and outcome-based flexibility are baseline retention requirements for Gen Z, not supplementary perquisites.
5. *Anchor HR strategy in regional sustainability:* rural and regional organisations should explicitly frame their employment proposition around quality of life, community contribution and place-based purpose — attributes that strongly resonate with Gen Z's values-driven orientation.

Figure 5

Conceptual framework: HR awareness gap and rural sustainability outcomes



Conclusions

1. This study confirms a significant HR awareness gap across EU member states: 48% of Gen Z respondents rated HR as unaware of their needs, and satisfaction scores across all five measured HR practice areas were uniformly low (2.1–2.4 on a five-point scale). Closing this gap is a strategic priority for organisations seeking to attract and retain young talent in the EU.
2. Flexibility, communication and career development are the most critical HR improvement areas. Persistently low satisfaction in these domains reflects a systemic misalignment between current HR practice and the baseline expectations of Generation Z employees entering the European labour market.
3. Rural and regional organisations within the EU face compounded challenges: structural constraints on HR capacity, combined with talent competition from urban centres, create a self-reinforcing talent drain that threatens the demographic and economic sustainability of peripheral EU territories.
4. HR practices that embed active listening, transparent communication, hybrid work provisions, structured mentorship and visible career pathways can reduce talent outmigration from rural areas and contribute directly to their long-term socio-economic resilience – supporting broader EU rural sustainability objectives.
5. Future research should pursue longitudinal and cross-regional designs to track changes in HR awareness over time, and experimental studies to evaluate the impact of specific HR interventions on Gen Z retention and rural sustainability outcomes across EU member states.

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RURAL IDYLL AND RURAL PENALTY: THE PERSPECTIVE OF FAMILIES WITH CHILDREN

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Abstract
Rural life is often idealized, emphasizing the advantages of the rural environment, such as tranquillity, natural beauty, unlimited private space and the opportunity to enjoy home-grown products. However, the available literature suggests that rural life is not only associated with the advantages provided by the rural environment, especially if it is necessary to raise minor children in the countryside. The disadvantages of the rural environment are associated with limited access to necessary services, limited employment and leisure opportunities, as well as the lack of educational and self-realization opportunities for children. Therefore, the analysis is grounded in the quality of life concept, with an emphasis on the subjective well-being, to find out how families themselves evaluate their living in rural area. Thus, the aim of the article is to explore the advantages and disadvantages of rural life from the perspective of families with children, based on the quality of life approach. The study is based on a qualitative research design using semi-structured interviews with families with children residing in rural homesteads of the Zemgale region. The answers to the research questions allow us to conclude that the rural environment can be both an idyll for families with children, providing ideal conditions for meeting the family's needs, and a burden, where parents only think about how to get away from the countryside, because their opportunities to meet the family's needs are very limited.
Keywords: rural idyll, rural penalty, quality of life.

Introduction

Rural areas have long been described in social science research as a contradictory and multi-layered environment, where both idealized notions of rural life and critical attention to structural inequalities coexist. This contradiction is often conceptualized using the concepts of rural idyll and rural penalty (Cloke, 2006; Halfacree, 2006). The rural idyll refers to a normative and often romanticized view of the countryside - a safe, nature-enclosed and socially cohesive place to live. The rural penalty perspective highlights systemic challenges such as inadequate and limited access to services, few employment opportunities, and strong dependence on private transport (OECD, 2024; Shucksmith, 2018). Contemporary research increasingly emphasizes that these two aspects frequently coexist in the everyday lives of the population. In this respect, families with children are of interest to researchers as a particularly sensitive group in whose experience this dual nature is clearly manifested.

The choice of place of residence for families is closely linked to the well-being of children, their needs, and the organization of daily life. Rural environments are often perceived as beneficial for children's physical and emotional development, emphasizing freedom, contact with nature, and closer social relationships (Gross-Manos & Shimoni, 2020). At the same time, families with children, especially mothers, often experience the effects of the rural penalty particularly strongly, as care responsibilities increase the burden caused by the inaccessibility of services, mobility restrictions, etc. (OECD, 2020a; Shucksmith, 2018).

The quality of life approach is particularly suitable for studying this contradictory experience, as it allows the integration of the concepts of rural idyll and rural penalty into a single analytical framework, avoiding the one-sided romanization or problematization of rural life. Quality of life is viewed as a multidimensional and contextually conditioned phenomenon, shaped by interaction between objective living conditions and subjective interpretations of experience (Knies & Hopkins, 2025; OECD, 2020b).

The relevance is increased by the fact that the subjective experience of families in rural areas has been studied comparatively little in Latvia. The aim of the article is to explore the advantages and disadvantages of rural life from the perspective of families with children, based on the quality of life approach.

The article seeks answers to the following research questions: 1) What aspects of quality of life in families' narratives correspond to the rural idyll and rural penalty? 2) How do these aspects coexist in the everyday life of families with children?

The study is based on a qualitative research design, as the data collection method, semi-structured interviews with families with children residing in rural homesteads of the Zemgale planning region, were used.

Materials and Methods

To achieve the set aim and answer the research questions, a qualitative research design was chosen, which allows for a better understanding of subjective experiences. The study used semi-structured interviews as a method for obtaining empirical data. The purposive sampling was applied (n=5). Respondents were recruited through the researchers' professional networks to find information-rich cases that meet the study criteria - a family with at least one child and living on a rural homestead in the Zemgale planning region. To ensure geographical diversity, one family from each of the region's municipalities - Jelgava, Bauska, Dobele, Aizkraukle, and Jekabpils - was selected. The interviews were conducted in January and February 2026.

The interview guidelines were organized around the following topics: the context of life in rural areas,

perceived advantages and disadvantages, and aspects related to the experience of rural idyll and rural penalty, as well as the impact of life in rural areas on children's well-being and future prospects.

The basic principles of research ethics were followed in the collection and analysis of empirical data. Participation in the study was voluntary, and informed consent was obtained from each respondent; also, personal data protection and confidentiality were ensured. Interviews were audio-recorded, and interview transcripts were created using the TurboScribe tool. The transcripts were then manually checked and edited to ensure their complete accuracy, and a thematic analysis of the interviews was conducted. The article was translated using Google Translate, and the Grammarly tool was used to improve spelling and grammar.

Results and Discussion

Concepts of rural idyll and rural penalty

Rural idyll is not a 'natural' or unchanging phenomenon or an objectively descriptive category. Instead, it is a culturally formed, historically changing, and socially determined construct (Wilson et al., 2025). This concept views the countryside as a contrast to urban space, incorporating into the concept everything that a city dweller lacks and could dream of - peace, naturalness, security, close social relations, and community. Wilson et al. (2025), based on research conducted by authorities in the field, have summarized the characteristics of the rural idyll as a normative nostalgic ideal, which they have grouped into two dimensions. The physical dimension is mainly associated with nature – 'pre-industrial landscapes, untouched by signs of manufacturing; open, green spaces and rich nature; aesthetically pleasing, quiet, and clean'. The rural environment is perceived here as ideal, contrasting everything that is seen as undesirable in the urban environment. The social dimension is characterized by human relationships and a slower pace of life, protected from upheavals and rapid changes. 'Sense of community, close ties and neighbourliness; traditional practices, associated with pre-modern times; static, even backward; security; authentic: a more genuine way of life, in touch with heritage and customs; simple living, closer to the land and nature' (Wilson et al., 2025).

Slower pace of life, predictability, stability, which sometimes can border on backwardness, genuine human relationships, and connection with the land allow people to take a breath and release from the stress caused by the city. The countryside is associated with good, peace, and security. Children in the countryside also have greater freedom; they can play outdoors unaccompanied, and they feel much freer than in the city. Such an environment is considered ideal for raising children.

Previous research also suggests that the rural idyll often acts as a symbolic resource that influences individuals' and families' choices of where to live, as well as reinforcing the perception of the countryside as a place of a high quality of life (Bell, 2006). It cannot be denied that such a perception of the countryside is often idealized.

However, real life often threatens this idyll not only by changing the landscape, which is an integral part of the idea of an 'ideal' living space (Klepers & Druva-Druvaskalne, 2020), but also by many other aspects affecting the quality of life. As Wilson et al. (2025), citing Shucksmith and Gorman-Murray, point out, 'rural society is traditional and backward, literally left behind by processes of modernisation ... also by social progression'.

The discourse of the rural idyll, which focuses mainly on the good, can mask inequality, deprivation, and daily challenges faced by rural residents. In this context, the concept of rural penalty is applied, which emphasizes the socio-economic and institutional constraints characteristic of rural areas - limited access to services such as healthcare, education, and public transport, as well as a lack of employment opportunities and higher dependence on individual mobility.

It should be noted that the rural penalty does not refer to individual choices or lifestyle, but to the limitations imposed by the rural environment on the availability of services, opportunities, and resources, which significantly affect the quality of life (Shucksmith, 2018). In the rural context, this penalty manifests itself in multidimensional, mutually reinforcing forms of deprivation, which place rural residents in an unequal situation compared to urban residents, and this also applies to rural Latvia.

A significant dimension of the rural penalty is the limited availability of various services, which is a direct consequence of the closure of schools, family doctor practices, post offices, bank branches, and shops, encouraged by austerity policies. The situation is further worsened by the reduction in the provision of public transport. Such decisions, although often based on an objective assessment of the situation and the depopulation of rural areas, increase the dependence of rural residents on private transport (Camarero & Oliva, 2019), thereby increasing their daily costs. The limited availability of public transport (Ministry of Transport, 2024) has an impact on labour mobility, thus reinforcing employment deprivation. A pronounced manifestation of the rural penalty is income deprivation or pay penalty (Culliney, 2014). There is a high concentration of low-income and poor households in rural areas (CSB, MIV010). Researchers point to educational deprivation manifested as unequal access to educational opportunities (CSB, IZG070), lower performance, higher drop-out and grade repetition rates, which are characteristic of rural schools (OECD, 2019). Finally, housing and living environment deprivation should be mentioned, which is characterised by a lack of affordable housing, poor quality of housing amenities, and poor energy efficiency of the housing stock. The limited housing

supply makes it difficult to attract labour in the education, health, and social care sectors, thus further strengthening spatial inequality. These processes are also well recognized in the Latvian rural context (Dobelniece & Millere, 2025).

Rural penalty challenges have a significant impact on the decisions of families with children about where to live, and especially on their quality of life and well-being. A vicious circle is forming: the population is decreasing due to various socio-demographic processes, which result in closed schools, a reduced offer of services, creating an unattractive living space, especially for families with children, which in turn leads to an unwillingness to stay in the countryside, causing an outflow to areas with a higher degree of urbanization and, as a result, a decrease in the population in rural areas.

Subjective dimension of quality of rural life

According to Diener and Oishi, subjective well-being is very democratic because it allows people to judge their own lives, rather than relying on 'expert' judgments (Phillips, 2006).

Building on this idea, the subjective well-being approach defines quality of life as an individual's understanding of their position in society in relation to their culture and value system, as well as their own goals, desires, values, and problems - including physical health, psychological state, and level of independence, social relationships, personal beliefs, and their connection with the environment (Phillips, 2006). The term 'quality of life' therefore helps distinguish between different concepts describing a 'good life'. Quality of life is evidenced by the interaction between life opportunities and life outcomes, which reflect both external and internal qualities (Veenhoven, 2007). The combination of these dichotomies creates a four-part matrix.

Typically, quality of life encompasses aspects of life that can be characterized based on two distinctions. The first is between life opportunities and life outcomes. The second is between external and internal qualities.

Table 1

Rural Quality of Life Matrix

	External qualities	Internal qualities
Life opportunities	**Surrounding conditions or environmental suitability**: Ecologically clean environment, spacious living space, housing that meets needs, garden and attractive environment, job opportunities, transport accessibility, health, education and other services, social contacts according to needs, leisure opportunities.	**Individual's life skills or individual's life-ability:** ability to adapt to the living environment in the countryside, health status, appropriate education.
Life outcomes	**Life usefulness or being valuable to the world**: I have to live here because my ancestors lived here; belonging to the place of residence - this is my place, my home; this place has great value, and it is not just a place to live, it is a place to which I belong!	**Individual's life skills or individual's life-ability:** ability to adapt to the living environment in the countryside, health status, appropriate education.

Source: Authors created based on Veenhoven, 2007.

The quality of life in rural areas is specific to the rural environment. The proposed model reveals the existing tension between rural idyll and rural penalty. Rural environments can provide several positive aspects of the surrounding environment, belonging, meaning of life, and a positive understanding of the good life (idyll), but limited availability of services and deprivation of opportunities can reduce the suitability of the environment and the individual's life skills (penalty). Therefore, it can be said that rural areas are a specific living environment that has a significant impact on the subjective well-being of individuals and families, as well as the socialization and future opportunities of children.

Family characteristics

In 2022, a family of six - a wife, a husband, three adult children and a 9-year-old daughter from the Dobele municipality – purchased a homestead. Drawn by desire for freedom, space, and a rural environment, they transitioned to countryside after previously residing in an apartment.

A family from Jekabpils municipality – three people – a mother and two children (one adult, the other - 16 years old) have lived in the homestead since 2017. Motive for moving to the countryside – they wanted a farm in the countryside, their own farm, to grow and sell flowers.

A family from Aizkraukle municipality – four people – a mother, a father and two children – 17 and 14 years old, who have lived in the homestead for five years. Before that, they rented a flat. Motive for moving to the countryside – they wanted to stay in Skriveri municipality.

A family from Jelgava municipality – three people – a mother, a father and a 6-year-old child. They have been living in a farmhouse for ten years. Before that, they lived in a flat in the same area. Motive for moving to the countryside – that was their goal to live in a house.

A family from Bauska municipality – a father, a mother and one child, 6 years old. They bought a property near Iecava in 2018. Before that they lived in a flat. Motive for moving to the countryside – it was their dream, because a mother has been a horsewoman for 35 years, and she had a dream to breed her own horses…'

Aspects of quality of life in families' narratives that correspond to the rural idyll and a rural penalty

As the theoretical insights reflect, the rural environment is often described as an idyll – healthy, quiet, clean and peaceful. Also, researchers Watkins & Jacoby (2007), found out that villagers associated village life with improved physical and emotional well-being, reflecting historical notions of a healthy rural lifestyle. They attributed these improvements to living in a healthier, cleaner environment, surrounded by open countryside and away from urban problems such as noise, pollution and excessive water pollution. As the interviewed families attest, it is the fresh rural air, the spacious living space, and the freedom that are the main advantages of the rural environment. For example, the family from Jelgava municipality appreciates the spaciousness of the living space: *'I like the fact that you have your own space in the countryside, that you can feel and act freely, and you are not dependent on anyone and have a lot of freedom'*. Also, families emphasize that instilling a genuine love of work in children is one of the greatest advantages of rural life: *'Our young people work in the garden, chop wood. We give them a piece of work to do and say, you have to do it. They can organize their own time and figure out how to do it. We also teach how to connect theory with practice. For example, if a water pipe is frozen, you need to understand what to do to solve it. Do young people living in the city have the opportunity to acquire such skills? No. That is why I like living in the countryside and raising children right here. We have the feeling that they are growing up different, more mature, and more responsible'* (Family, Aizkraukle municipality). The rural lifestyle helps children learn responsibility and a good work ethic from an early age: *'our daughter's task is to pick apples or collect pine cones or help her parents, seeing that we work and take care of the house. She grows up with that and learns both work and responsibility'* (Family, Jelgava municipality).

The interview data align with previous research emphasizing closer social ties and a slower pace of life in rural areas (Wilson et al., 2025). As an advantage of living in the countryside, families also mention the opportunity to improve their living environment, because in the countryside, interaction between community members is closer. These closer relationships also facilitate collective action, which families identify as an important advantage of rural living. *'Now we are more advocating for the common good, such as improving life. For example, we don't have extracurricular activities at school here, so we wrote an initiative to create and offer them, because now all extracurricular activities take place in Jelgava'* (Family, Jelgava municipality). The family from Jekabpils municipality also sees this advantage: *'We created our own Atasiene community WhatsApp group. Now we quickly receive information about everything as well as we can also ask for help if we need it and find someone who can help in a flash'*. When living in the countryside, the support of neighbours is important. Even if the relationship is not close, neighbours are the ones who help in difficult times: *'One advantage is that this one neighbour is local and knows everyone, and when we started living there, he told us where to call to get what we need'* (Family, Jelgava municipality). However, this neighbourly relationship is not valued unambiguously, there are families who consider being neighbours to be an aspect that interferes with life: *'The closest neighbours? A kilometre or so. Well, we have one neighbour here, but yes, she also watches us and peeks at what we do all the time. That is also a very annoying factor in reality. We don't want neighbours closer, because, you see, in the countryside, having a neighbour is conditional, because in the countryside you have land, you carry out economic activities. The neighbour is jealous'* (Family, Bauska municipality).

As the information obtained in the interviews shows, safety in the countryside is relative. There are families who really feel safe, but there are also families who do not feel safe, like the family from Bauska municipality: *'Here in the countryside, anyone can drive into your homestead, hit you on the head and everything else....'* The family in Jekabpils municipality also does not feel safe in their place of residence: *'Well, it is not safe, alcoholics are banging on the door, and you never know when someone will show up. We lock the door'*. On the other hand, the family living in Jelgava municipality feels very safe in their place of residence: *'Well, I think we feel safer in the countryside now. For example, I do not lock the car in the homestead. The area is safe'*. There is also no consensus among families in the area of employment – there are families who have found their own occupation while living in the countryside and are satisfied with this opportunity, for example, the family from Jelgava municipality believes that if a person wants to work, they can find work in the countryside: *'Most people here work either in institutions that are on site, say, a school, someone in a shop, someone at a gas station, or on their own farms. And then there are the big farmers, people who work for them, but a very large number travel to Olaine, Jelgava or Riga. My husband is an entrepreneur. He already employs 12–13 people'*. The interviews also expressed opinions about the difficulties of developing one's own business in rural areas. The family from Jekabpils municipality believes that living in rural areas should have their own vision of employment: *'When I came to the countryside, I knew that I would be engaged in flower growing, so I needed land. I have my own farm. I grow daffodils, dahlias, gladioli. I have 1ha of land. I grow*

100,000 daffodil bulbs for sale. The area is too big for me alone. I don't hire workers. I struggle alone, and my children help'. Also it is difficult for people with higher education to find employment in the countryside that corresponds to their qualifications: *'Well, I would like to work, for example, in Iecava nearby, because I have a bachelor's degree, a master's degree, I have a bunch of other educations. What,'ll I go work at Astartes Nafta, Cheeseburger or as a saleswoman*?*'* (Family, Bauska municipality). The family from Dobele municipality also agrees that employment opportunities in the countryside are limited.

The study shows that the quality of life in rural areas is significantly affected by health: *'I had a stroke 2.5 years ago. Now I can barely walk and I have a disability. That's why we don't have a garden. I'm alone at home all day; only a friend comes to help. It is very difficult for me'* (Family, Dobele municipality). Therefore, it can be concluded that for people with health problems, the idyll of rural life seems to 'disappear' under the heavy burden of everyday life, and rural life turns into a 'penalty'. This reflects the concept of rural penalty, which emphasizes not individual choices or lifestyles, but structural constraints (Shucksmith, 2018) related to the availability of services, opportunities, and resources that shape the quality of life in rural areas. As a very important factor that families mention, is public transport. Having reliable transit heavily impacts their ability to get around when needed, especially when it comes to reaching healthcare and other essential services. The limited access to public transport also cuts off employment opportunities, making it harder for families to meet their basic needs (Culliney, 2014) and ultimately contributing to the higher concentration of lower-income households in rural areas (CSB, MIV010). For example, the family from Bauska municipality believes that the lack of public transport affects their quality of life the most: *'For my life to be better, I miss public transport. And I would gladly take public transport if it only ran more often. But it runs so rarely and at such inconvenient times. If I go to the city to see a doctor, I have to sit for two or three hours and wait for the bus home'*. The family from Jelgava municipality also shares similar thoughts: *'Well, the options are so limited, and if you don't have your own transport, then, in principle, stay where you are'*. The family from Jelgava municipality emphasises the proximity of the city as an advantage of living in the countryside: *'The advantage is that the place of residence is quite close to Jelgava'*. As the information obtained in the interviews reflects, the availability of services is not unambiguously assessed, it largely depends on the specific place of residence and the availability of services there. For example, the family living in Bauska municipality believes that the services available in their place of residence are unsatisfactory: *'All services are at a very poor level...'* As well as the family from Dobele municipality does not even have a shop in their place of residence: *'The nearest grocery store is in Auce, 15 km away, and the doctor is right there. I can't get anywhere myself, I ask relatives and friends for help, I give money to take me. There is only one bus in the morning at 6.15 and the same one comes back in the evening a little before 6.00. If the car breaks down, we can't get anywhere*!*'* On the other hand, the family from Jelgava municipality receives all services in Jelgava and considers this to be a shortcoming: *'All services are in Jelgava, both my husband and I have a family doctor, and the child has a pediatrician, everything is in Jelgava, because the family doctor who is on our side has very bad reviews. There is also no pharmacy any more. The fact that all major services are in Jelgava, including the post office, ATM, health care services, is also a problem'*. As it is mentioned by James et al. (2022), there is a lack of quality healthcare services in rural areas, the authors justify this by stating that the relationship between rural areas and high mortality rates is statistically significant.

For families raising minor children, the issue of access to education is important, which greatly affects the quality of life of these families, because access to education is not limited to basic education, it also includes extracurricular activities and leisure opportunities. For example, the family living in Bauska municipality believes that their place of residence does not provide sufficient opportunities for children's social interaction and education: *'The level of educational services both at school and in kindergarten is very low. That is why we take our child to kindergarten in Jelgava and drive 100km every day. Speaking of education, children, for example, from large families... have terrible vocabulary and terrible behaviour. They have lice and dirt. We did not want our child to see that. They have already been taught to lie and behave in a way that does not comply with the generally accepted norms in the society. They are degraded'*. The family from Dobele municipality also shares similar thoughts: *'My daughter studies at Auce secondary school. The attitude of the teachers is terrible. Many children come from large families – the contingent is terrible. The craziest thing is that there is no school to change to'*. Leisure opportunities are also lacking in the countryside: *'…the limitations in the countryside are definitely that there are not many leisure opportunities for children, except outdoor playgrounds. We don't have physical activities, sports, or a swimming pool, then you have to go to the city, which we do'* (Family, Jelgava municipality). In general, the family from Jelgava municipality is satisfied with the quality of preschool education offered in their place of residence. From the information obtained in the interviews, it can be concluded that nowadays children already have other demands for leisure opportunities which the current rural environment cannot provide.

The specifics of the rural environment reflect the interaction of the rural idyll with the challenges of rural

life (Cloke, 2006; Halfacree, 2006). This is also confirmed by the families: *'Currently, home heating is the biggest problem. You have to heat the house three times a day, you have to get briquettes. It's not like you can go to the seaside for three days and not think about anything. A house requires work, but it also gives such great satisfaction'* (Family, Jelgava municipality). We can conclude that, on the one hand, the rural environment is associated with difficulties that must be overcome, but on the other hand, it provides great joy and satisfaction. As it is mentioned by the family from Jelgava municipality: *'Well, you have to clear the snow, you have to pay the tractor driver, but, well, in general, I don't know, the feeling of living in your own house is much better than some work that you do and invest there'*. The family from Aizkraukle municipality believes that it used to be difficult to live in the countryside, but now that technology is available that significantly simplifies everyday life and the life in countryside turn to be more and more enjoyable.

Aspects that coexist in the everyday life of families with children in rural area

The information obtained in the interviews shows that families, when choosing rural life, understand its advantages and disadvantages: *'We will definitely stay in the countryside. When we were still living in a city apartment with my future husband during our studies, it was very difficult, because we were both from the countryside. Okey, I spend the time driving, about 20 minutes each way, and also financially, sometimes it is difficult. But would I live somewhere in Jelgava for that? Probably not. Well, I just put up with it'* (Family, Jelgava municipality). On the other hand, the family living in Dobele municipality sees more disadvantages than advantages in their everyday life, but they are not ready to give it up either, which shows that the daily advantages and disadvantages of rural life cannot be assessed unambiguously: *'I don't have an idyll here, it's hard for me, I'd like to live in an apartment. I don't see a future for my children here, in the countryside either. My eldest daughter is studying to be a cook in Dobele and is staying there. My youngest daughter is not a farm girl either. We don't plan to leave. I'll stay as long as I can'*. Among the interviewed families, there are also those whose expectations for rural life have not been fulfilled and life in the countryside brings neither satisfaction nor joy: *'We don't like the countryside, there's nothing to like here. I would like to live in the city, definitely in the city. No, I don't see myself in the countryside at all. In the city, yes'* (Family, Bauska municipality).

Interviews highlighted the link between a good life and belonging to one's place of residence: *'This is my place, I am happy, and I wish to get old here, in my own home'* (Family, Aizkraukle municipality). The Swedish researcher also emphasises family life in the countryside that a sense of place refers to the unique character and identity of a particular location, shaped by the cultural, physical, social and emotional experiences of those who encounter it. It is for this reason that people living in the countryside feel a strong connection to their place of residence (Syrjäpalo, 2025). The interviewed families confirm the fact that the advantages provided by the countryside, such as freedom, independence and fresh air, coexist with the disadvantages of the rural environment, such as limited access to services. Ultimately, the most important factor is what rural families with children value most in their day-to-day lives. Their personal priorities and view of a 'good life' are what truly determine how they assess their own well-being.

Conclusions

1. Rural idyll and rural penalty are not mutually exclusive; they can coexist, while ensuring high subjective well-being in certain areas of life, such as the quality of the living environment or social relations, and at the same time creating significant restrictions in other areas, such as the availability of services.
2. The understanding of a good life in the countryside is influenced by both the values of families with children and the opportunities to satisfy their needs.
3. The conducted research reflects the view that families with children often associate the rural environment with symbolic elements of the 'good life' like freedom, peace and the opportunity to create their own living space. These aspects form the perception of the rural environment as an ideal living place, which corresponds to the interpretation of the rural idyll.
4. The information obtained in the interviews indicates that the quality of life of families with children in the countryside is significantly influenced by external living conditions – employment opportunities, mobility and availability of services. Limited access to transport, healthcare, education and leisure activities, in turn, can create practical obstacles in everyday life and create experiences that correspond to the Rural Penalty dimension.
5. The subjective quality of life of families in rural areas is related to the ability of these families to adapt to specific living conditions, organise their daily lives and find individual solutions in difficult situations.

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BROADER ECONOMIC IMPACTS EVIDENCE OF GENOMICS IN BEEF CATTLE PRODUCTION SYSTEMS

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Abstract
This review examines the broader economic impacts of genomic technologies in beef cattle production systems, addressing the problem of uncertain value realisation across complex and fragmented supply chains. The research aim is to synthesise current evidence on how genomics influences productivity, profitability, risk, and sustainability outcomes in beef systems. A narrative review methodology was employed to integrate interdisciplinary evidence from quantitative genetics, production economics, supply-chain analysis, and sustainability policy literature. The findings indicate that genomic technologies enhance selection accuracy and reduce generation intervals, thereby accelerating genetic gain and improving performance in economically important traits such as feed efficiency, fertility, survival, and carcass quality. Economic modelling and empirical studies demonstrate that genomics can generate substantial value per genotyped animal, particularly in seedstock and vertically integrated systems. However, the distribution of benefits is uneven, and the realisation of economic gains depends on the effective transmission of value along the supply chain, as well as cost structures related to genotyping and phenotyping. Key constraints include limited phenotypic data, multi-breed population structures, and misaligned incentives among industry stakeholders. The review concludes that genomics represents a transformative but conditional economic innovation in beef production. Its full potential is realised when supported by coordinated investment in data infrastructure, incentive alignment, and governance frameworks. Additionally, genomics contributes to sustainability objectives by improving efficiency and reducing emissions intensity, reinforcing its role in future competitive and low-carbon livestock systems.
Keywords: beef cattle, genomics, economic impact, genomic selection, sustainability.

Introduction

Beef production systems operate under a chronic 'tightrope' of biological variability, market volatility, and increasing sustainability and welfare expectations. According to Berry et al. (2016), in many regions, production is extensive and heterogeneous, with diverse breeds and crossbreeding systems, variable forage resources, and wide variation in performance recording intensity. These characteristics affect both the feasibility and the economic returns of breeding and innovation strategies (Berry et al., 2016). Genomic technologies have shifted from specialised applications (e.g., parentage verification, defect testing) to routine components of genetic evaluation in some beef populations, particularly where breed associations have invested in genotyped reference populations and evaluation infrastructure following Moser et al. (2019). The central premise is that genome-wide markers can be used to predict breeding values more accurately and earlier than pedigree-based methods alone, thereby, when embedded in an appropriate breeding programme, increasing the rate of genetic gain and improving economic performance (Meuwissen et al., 2001).

Van Eenennaam & Drake (2012) assume that from an economic standpoint, genomics in beef has 'broader impacts' because it affects multiple decision layers. First, it alters breeding decisions (which animals become parents), thereby changing the long-run distribution of performance in traits that drive cost and revenue. Second, it alters risk by reducing uncertainty in evaluating animals with late-expressed or difficult-to-measure traits (e.g., carcass traits, intake). Third, it affects the transmission of value along the beef supply chain. If downstream sectors (feedlots, processors) realise value from improved genetics, economic mechanisms are required to transmit that value upstream to the sector paying for genotyping and recording (Van Eenennaam & Drake, 2012).

Sustainability increases the economic salience of genomic improvement. International assessments emphasise that livestock contributes materially to global greenhouse-gas emissions and that cattle supply chains account for a major share of livestock-sector emissions, making efficiency gains economically relevant in the context of regulation, market access, and reputational risk (Food and Agriculture Organisation of the United Nations (FAO), 2013; Intergovernmental Panel on Climate Change (IPCC), 2019). National low-emissions strategies for beef production explicitly frame productivity and genetic improvement as levers to reduce emissions intensity while supporting livelihoods, reinforcing that 'economic impact' increasingly includes sustainability-linked premiums, compliance costs, and investment incentives (FAO & New Zealand Agricultural Greenhouse Gas Research Centre, 2017).

This review aims to synthesise evidence on the broader economic impacts of cattle genomics in beef production systems. To achieve the aim, two tasks are set: 1) to summarise genomic technologies relevant to beef breeding and the principal pathways through which they generate economic value; and 2) to evaluate evidence on their economic impacts, including effects on productivity, efficiency and value-chain performance, as well as cost–benefit considerations, adoption barriers, and the roles of sustainability, policy, and social acceptance.

Materials and Methods

This study used a narrative review design to integrate heterogeneous evidence spanning quantitative genetic

evaluation, production economics, supply-chain organisation, and sustainability policy. A narrative review was selected because the topic spans multiple disciplines and includes a mix of modelling studies, field-based economic evaluations, sector reports, and governance/ethics literature that is not readily synthesised within a single effect-size framework.

Search strategy

Targeted searches were undertaken using combinations of terms such as 'beef cattle genomic selection economics', 'DNA test value supply chain', 'genomic enhanced breeding value cost', '25K SNP economic return beef', 'residual feed intake genomic selection profit', and 'genotyping cost evaluation'. The search prioritised peer-reviewed journal articles, reputable institutional reports, and openly accessible conference proceedings central to beef genomic economics (e.g., Journal of Animal Science, Animal Production Science, Animal Frontiers; FAO and IPCC reports).

Inclusion criteria

Sources were included as 'core beef economic genomics' if they (i) addressed beef cattle systems directly (or maternal beef breeding programmes), and (ii) reported explicit economic metrics or investment implications (e.g., value per DNA test, discounted returns/net present value, break-even time, genotyping cost trajectories, sectoral value distribution). Sources were included as 'supporting' if they supplied evidence on enabling conditions (e.g., identification/traceability regulations), innovation constraints (e.g., regulatory hurdles), or ethical/social licence issues relevant to economic adoption.

Exclusion criteria. Studies were excluded from economic synthesis if they focused on genomics without economic implications (e.g., GWAS without decision relevance) or had a livestock species focus without direct transferability to beef economic mechanisms (e.g., sheep studies not linked to comparable investment or adoption structures). Such studies could still be referenced sparingly for methodological illustration, where they clarified general genomic concepts.

Manuscript editing

A large language model, ChatGPT (OpenAI, 2026), was used to assist with editing the manuscript for the English language and grammar; the entire content was critically reviewed and validated by the authors to ensure accuracy, originality, and compliance with academic standards.

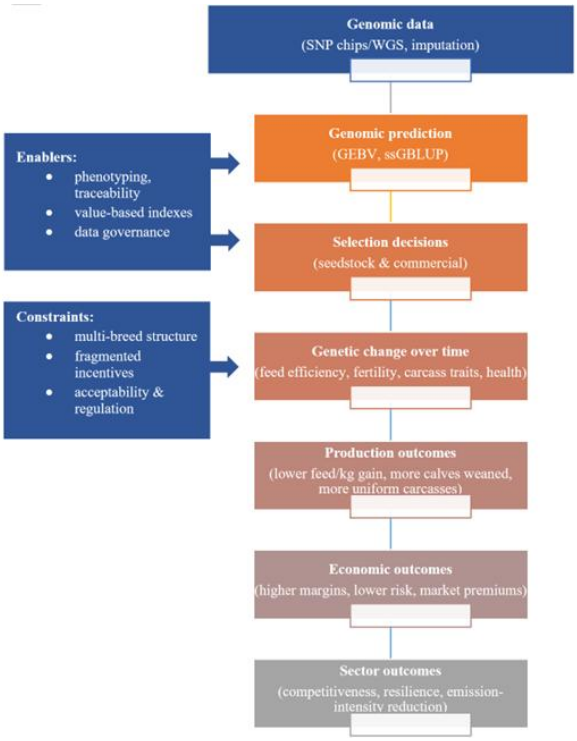
Results and Discussion

Genomics influences beef-system economics through a chain of causation: genomic data support improved prediction of genetic merit; improved predictions change selection and mating decisions; genetic change accumulates across generations; and cumulative genetic change alters biological performance and the cost/revenue structure of beef production. This is the foundational rationale of genomic selection and underpins the economic analyses reviewed here (Meuwissen et al., 2001).

The conceptual relationships among genotype information, breeding decisions, supply-chain value creation, and sustainability-linked economics are summarised in Figure 1 (Berry et al., 2016; Van Eenennaam & Drake, 2021).

Figure 1

Conceptual relationships linking genomic information, breeding decisions and economic outcomes in beef production systems



Comparative evidence base

Table 1 summarises key studies emphasising economic metrics and decision relevance. It includes core beef economic evaluations and modelling, as well as selected supporting sources that inform adoption barriers, governance, and the sustainability/economic context.

Table 1 summarises selected studies examining the economic implications of genomic technologies in beef cattle production systems. The literature highlights potential gains in selection accuracy, productivity, and value-chain performance, while also emphasising the importance of cost structures, data infrastructure, and incentive alignment for successful adoption.

Genomic technologies as economic infrastructure

The economic 'technology stack' in beef genomics can be characterised as: (i) genotyping (high-density or low-density with imputation), (ii) reference populations combining genotypes with phenotypes, and (iii) evaluation systems that integrate pedigree, genotype and performance data, often via single-step

frameworks. These components are complementary: genotypes without phenotypes do not generate accurate prediction equations, and predictions without industry deployment mechanisms (recording, dissemination, incentives) deliver limited economic value (Berry et al., 2016; Meuwissen et al., 2001).

Table 1

Key studies comparing genomic methods and economic findings

Study	Species	Genomic method	Economic metric	Main finding
Van Eenennaam et al., 2011	Beef cattle	Hypothetical DNA tests integrated in the selection index; discounted gene flow modelling	Discounted return per DNA test; value per bull; % increase in selection response	DNA information increased selection response (reported range 29-158%) and generated substantial discounted value, with larger gains in stud sires than commercial sires.
Van Eenennaam & Drake, 2012	Beef cattle	Supply-chain analysis of DNA testing/value pathways	Sectoral value distribution; incentive alignment	Value can arise in breeding, cow–calf, feedlot, and processing; widespread adoption likely requires mechanisms to share downstream value with upstream sectors paying costs.
Buchanan et al., 2018	Beef cattle (Charolais-sired system)	25K SNP genotypes; scenarios with/without commercial phenotypes	Annual economic genetic gain (ΔG); 30-year CNPV per calf; break-even time	Adding genotypes and commercial phenotypes improved accuracy and ΔG, but delayed break-even due to data costs; nucleus genotyping without full commercial phenotyping produced the highest 30-year CNPV in the reported scenario.
Navajas et al., 2010	Beef cattle (UK maternal programmes)	Genomic selection scenarios for residual feed intake and survival	Cumulative marginal net discounted return; GHG mitigation indicators	Genomic strategies modelled as cost-effective; reduced genotyping costs materially improved net returns, with co-benefits for emissions intensity under model assumptions.
Berry et al., 2016	Beef cattle (global/Irish context)	Review of genomic prediction implementation: multi-breed and infrastructure issues	Implementation constraints with economic implications	Beef adoption is slower than dairy due to multi-breed structure, limited AI and phenotyping, weaker connectedness, and a lower-margin business model; infrastructure and incentives are central.
Moser et al., 2019	Beef cattle (Angus case)	Genomic testing integrated into routine evaluations	Genotyping cost trend; scale of adoption	Large-scale adoption coincided with marked cost declines and an increase in the number of genotyped animals; the primary benefit was higher prediction accuracy for young animals.
Helmute & Mazure, 2025	Beef cattle	Literature review of genomic selection economics	Synthesis of economic impacts and barriers	Emphasises profitability pathways (feed efficiency, carcass value, disease resistance) and the need for policy/ industry collaboration to overcome adoption costs.
Mohammaddiyeh et al., 2023	Beef cattle (simulation)	Selective genotyping strategies in multi-breed evaluation	Comparative prediction accuracy under budget constraints	Selective genotyping design affects accuracy; strategic genotyping of subsets (e.g., ancestors vs candidates; male vs female pathways) can improve cost-effectiveness in constrained systems.
Ahmed et al., 2023	Dairy - beef interface	Beef-on-dairy breeding strategy review (supporting)	Production and risk trade-offs affecting profitability	Beef-on-dairy can improve calf value and growth traits but may increase gestation length and dystocia/stillbirth risks—economic outcomes depend on balancing these trade-offs.
Ammendrup & Füssel, 2001	Cattle (EU farm animals)	Identification/traceability systems (supporting infrastructure)	Compliance requirements shaping information systems	EU identification and traceability requirements (e.g., passports, ear tags) provide infrastructure for information flow; relevant for recording, assurance and supply-chain governance.

Beef populations create particular technical-economic challenges relative to dairy. Beef production typically uses multiple breeds and crossbreds, lower artificial insemination intensity, and more extensive cow-calf systems with less systematic phenotyping and weaker pedigree recording. These factors reduce genetic connectedness and require larger, more diverse reference populations to achieve stable prediction accuracy across breeds and environments (Berry et al., 2016). The mentioned structural features directly translate into higher fixed costs for building reference populations and greater uncertainty over returns - key economic barriers to adoption.

Nevertheless, evidence from breed-association genomic evaluation scaling illustrates that once infrastructure is in place, costs per genotype can decline sharply and benefits become more accessible. In the Angus case described by Moser et al. (2019), routine genomic testing scaled rapidly, with reported genotyping costs decreasing from ca. USD 139 per animal (2011) to ca. USD 37 (2017) and hundreds of thousands of genotypes integrated into joint evaluations (Moser et al., 2019). Economically, such cost declines can shift the feasible adoption boundary from 'elite seedstock only' toward broader commercial use, provided that prediction accuracy and value capture mechanisms are also in place.

Economic benefits across the beef supply chain

A central insight from supply-chain economics is that the value of genetic improvement is not captured equally by all actors. Van Eenennaam & Drake (2012) consider that DNA information can generate value across sectors, but who pays and who benefits are often misaligned; the economic viability of widespread DNA testing depends on how effectively downstream value is transmitted upstream. In practical terms, genetic improvement expressed over many descendants is far more valuable than the same improvement expressed over a few. This explains why economic returns to increasing selection accuracy are typically highest in the breeding sector, especially for elite stud sires and replacement seedstock animals whose genetics diffuse widely (Van Eenennaam & Drake, 2012). In contrast, genotyping a single commercial bull with limited descendants may generate smaller private returns unless the bull is used extensively or unless the buyer receives robust price signals for genomic merit.

The seedstock-focused economic modelling by Van Eenennaam et al. (2011) provides a clear quantitative illustration. Under their selection-index and discounted-gene-flow framework, hypothetical DNA tests increasing selection accuracy were modelled to increase selection response by ca. 29-158%. The net value of improvement above traditional recording was estimated at USD 89-565 per commercial bull and USD 5,332-27,910 per stud bull; assuming the entire bull calf crop was tested, the implied value of genetic gain derived from DNA testing was USD 204-1,119 per test, contingent on benefits being efficiently transferred along the chain to the seedstock party paying for genotyping (Van Eenennaam et al., 2011). These results are economically instructive because they show both the magnitude of potential value and the dependence of realised value on market structure and price transmission.

Field-based evidence from a vertically integrated system shows that economic outcomes depend on data costs and planning horizons. Buchanan et al. (2018) compared four evaluation scenarios combining phenotypes, pedigree, and 25K SNP genotypes across a two-tier (purebred nucleus and commercial) Charolais-sired system producing terminal sires for 10,000 commercial cows. They reported that adding genotypes and commercial phenotypes increased selection accuracy and economic genetic gain; the highest annual ΔG in the purebred herd occurred in the scenario with both purebred and commercial data and genotypes (PBCM_H) at USD 11.91 per head. However, including commercial phenotypes and parentage information increased break-even time (e.g., from 12 years in PB_A to 19 years in PBCM_A; and from 12 years in PB_H to 18 years in PBCM_H), reflecting substantial information costs. Importantly, the highest 30-year cumulative net present value per slaughtered commercial calf was observed for the purebred genotyping scenario (PB_H) at USD 371.16, despite lower annual ΔG than the most data-intensive scenario (Buchanan et al., 2018).

Economically, these results highlight three broader points applicable to beef systems. First, genomic information can increase returns, but the marginal return to additional phenotyping may diminish when costs rise faster than predictive value. Second, vertically integrated operations that retain ownership through finishing and can measure carcass and intake traits are better positioned to monetise genomic improvement, because the breeding objective aligns with realised returns. Third, time horizons matter: data-heavy strategies may yield higher long-run value but require patience or financing mechanisms, which are often constraints for commercial enterprises (Buchanan et al., 2018; Van Eenennaam & Drake, 2012).

Productivity, efficiency and risk: the economically dominant trait pathways

The economic impact of genomics depends on which traits receive improved selection response. Beef systems are typically dominated by (i) reproduction (calving rate, survival, days-to-calving), because each additional live calf weaned spreads fixed cow costs; (ii) feed efficiency, because feed is a major variable cost; (iii) health and robustness, because morbidity and mortality directly reduce saleable output and increase treatment costs; and (iv) carcass traits, because price grids at the processor level determine revenue. The reviewed beef-focused sources explicitly emphasise these trait categories as the highest-value pathways for genomic information, particularly where phenotypes are costly or unavailable without genomics (Berry et

al., 2016; Van Eenennaam & Drake, 2012).

However, beef faces a practical bottleneck: the most economically important traits are often expensive or difficult to measure on selection candidates (e.g., individual intake, methane-related proxies, detailed carcass quality, disease resilience). Genomics offers leverage by enabling selection for these traits using genomic predictions derived from reference populations, effectively 'spreading' the effects of expensive phenotypes across a larger population via marker effects. However, this requires coordinated investment in phenotyping and training populations (Berry et al., 2016; Meuwissen et al., 2001).

Selective genotyping research provides an economic logic for constrained systems: if genotyping budgets are limited, strategically genotyping subsets (e.g., key ancestors or high-impact selection candidates; certain sex pathways) can improve prediction accuracy per unit cost compared with indiscriminate genotyping. In a multi-breed beef simulation study, Mohammaddiyeh et al. (2023) evaluated different genotyping strategies. They reported that prediction accuracy differed meaningfully by cohort, reinforcing that 'whom to genotype' is an economic design decision rather than a purely technical one (Mohammaddiyeh et al., 2023).

Sustainability as a component of economic impact

Sustainability increasingly shapes beef economics through regulatory risk, certification and market access, financing conditions, and consumer preferences. From a global perspective, FAO's assessment estimated livestock-sector emissions at 7.1 gigatonnes CO_2-eq annually (14.5% of human-induced emissions), with beef and cattle milk together accounting for the majority of livestock emissions shares in their framework (FAO, 2013). IPCC assessments further emphasise the significance of land-based systems and the interaction between food systems, land use, and climate mitigation, underscoring that livestock system transitions are economically and politically contested (IPCC, 2019).

At the national level, policy frameworks can explicitly treat productivity and genetic improvement as mitigation levers. In Uruguay's low-emissions development analysis, the stated objective was to identify low-cost strategies to reduce the intensity of enteric methane emissions while improving productivity and supporting livelihoods, indicating that efficiency-linked interventions can be positioned as both private-benefit and public-benefit strategies (FAO & New Zealand Agricultural Greenhouse Gas Research Centre, 2017). This matters economically because sustainability performance can affect access to high-value export markets, eligibility for support programmes, and compliance costs. In Latvia, similar principles apply, as genetic improvement and the use of genomic technologies in cattle breeding can enhance productivity, lower emissions intensity, and improve economic performance within the European Union's climate and agricultural policy frameworks.

Beef-focused genomic economic modelling can explicitly incorporate sustainability. Navajas et al. (2010) modelled genomic selection strategies that incorporated residual feed intake (RFI) and survival in the UK maternal breeding programmes and assessed outcomes in terms of both discounted economic returns and greenhouse-gas mitigation. They reported baseline values for the current breeding programme of GBP 62.6 million cumulative discounted income and 1.5 million tonnes CO_2-eq mitigation. They indicated that genomic strategies could improve both economic outcomes and (modestly) emissions mitigation under most scenarios. They also modelled genotyping costs (e.g., GBP 200 or GBP 100 per sample) and the cost of training-population RFI measurement (reported at GBP 1,700 per animal), finding that lower genotyping costs materially increased net returns (average increase of ~42% when the cost was reduced from GBP 200 to GBP 100) (Navajas et al., 2010).

These findings support a broader economic interpretation: genomics can be part of an 'efficiency portfolio' that reduces emissions intensity by reducing feed use per kg output or increasing output per breeding cow, but financial viability depends on cost structures and policy/market incentives. They also highlight the value of integrating sustainability metrics into breeding objectives when externalities are priced or when market access depends on carbon credentials (FAO & New Zealand Agricultural Greenhouse Gas Research Centre, 2017; Navajas et al., 2010).

Finally, sustainability in the bovine sector is not limited to emissions. Circular economy and waste valorisation narratives connect to economic competitiveness through input utilisation and by-product value creation. A recent bovine-sector sustainability review argues that policy frameworks (e.g., EU Green Deal / Circular Economy Action Plan) and advanced technologies (AI, precision farming, real-time analytics) can support resource efficiency and waste-to-value pathways across the bovine supply chain. While not genomics-specific, this reinforces that genomic information is economically most valuable when embedded in broader data-centric production systems (Terpou et al., 2025).

Adoption barriers and 'who decides': economics of governance, regulation, and social licence

Adoption barriers in beef genomics are not adequately explained by genotyping price alone. The beef sector's multi-breed structure, limited AI and phenotypic recording, weaker genetic connectedness, and lower average margins all reduce the private expected return to genotyping, particularly for commercial cow–calf producers, while increasing the collective-action problem of building large reference populations (Berry et al., 2016).

Supply-chain incentive alignment is a recurring barrier. Van Eenennaam & Drake (2012) explicitly state that DNA information can generate value across the breeding, commercial, feedlot, and processing

sectors. However, the distribution of value depends on marketing, and widespread adoption likely requires mechanisms to share downstream value with upstream sectors that incur DNA collection and testing expenses (Van Eenennaam & Drake, 2012). The economic implication is that contracts, premiums, or cooperative arrangements may be required for the cow–calf sector to invest in genomic improvement that benefits downstream sectors (e.g., feedlot efficiency, carcass value).

The governance and 'decision ecology' of breeding objectives also matter. A review on selection decisions emphasises that breeding programmes rely on indices aggregating economically important traits, and that new technologies (including sensor-based phenotypes) create both opportunities and challenges for what traits are measured and prioritised. While written in a dairy context, the principle applies: the economic impact of genomics depends on what is measured, who funds the measurement, and who has the legitimacy to decide trait emphasis (Cole et al., 2021).

Regulation can either enable or constrain innovation, affecting the realised economic value of genomic technologies. A review of red-meat safety legislation across jurisdictions argues that prescriptive, process-focused regulatory formulations may unintentionally create barriers to the implementation of innovative technologies, whereas outcome-based frameworks may better support innovation. This is relevant to genomics, where model-based, data-driven tools may require flexibility in verification, auditing, and process standards (Nagel-Alne et al., 2022).

Traceability and identification systems are complementary infrastructure for the creation of genomic value. Within the EU, identification and registration requirements for bovine animals underpin disease control, trade certification, and 'stable-to-table' traceability, supporting the credibility of information flow and (indirectly) the economics of data-driven evaluation and product assurance (Ammendrup & Füssel, 2001). Breed-assignment and breed-origin tests, while not equivalent to genomic selection, illustrate how genomic tools can reduce information asymmetry by classifying animals without pedigree data, potentially expanding the population eligible for recording and genetic improvement programmes (Hulsegge et al., 2019).

Finally, Eriksson et al. (2018) admit that social licence and ethics can shape adoption economics by influencing consumer acceptance, retailer standards, and regulatory pathways. An invited review on genetically modified and genome-edited cattle argues that while such technologies can be framed as rapid solutions, large-scale application and integration into breeding schemes face practical and ethical challenges. Even if gene editing is not the primary focus of beef genomics today, the broader lesson is economic: contested technologies can face increased regulatory costs, delayed deployment, and reputational risk, which affect expected returns (Eriksson et al., 2018).

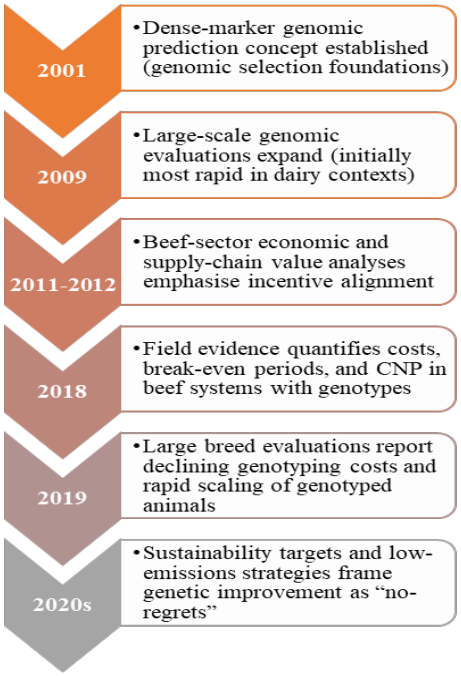
Timeline of key developments relevant to beef genomic economics

The trajectory of beef genomic economics can be read as a shift from theoretical potential to scaled industry implementation, with adoption accelerating where infrastructure and business models align (Berry et al., 2016; Meuwissen et al., 2001; Moser et al., 2019).

The timeline in Figure 2 illustrates key milestones in the development and economic integration of genomic selection in cattle breeding. It traces the progression from the establishment of dense-marker genomic prediction methods in the early 2000s to the expansion of large-scale genomic evaluations, initially driven by the dairy sector. Subsequent milestones highlight the growing focus on economic value, supply-chain incentives, and empirical evidence on costs and benefits in beef systems.

Figure 2

Key milestones in the development and economic adoption of genomic selection in cattle breeding



More recent developments reflect declining genotyping costs, the rapid scaling of genotyped animal populations, and the increasing alignment of genetic improvement with sustainability and low-emissions strategies. Together, these milestones demonstrate how genomic technologies have evolved from a methodological innovation into a central component of productivity, economic performance, and environmental policy in livestock systems.

Implications for 'broader economic impacts'

Synthesising across the evidence, the broader economic impacts of beef cattle genomics can be summarised as conditional but potentially substantial.

First, genomics increases the productivity of the reeding process: by increasing accuracy and reducing decision time, it can materially increase genetic gain

and therefore shift long-run profitability. The clearest quantified values appear in seedstock and vertically integrated systems, where returns are expressed across many descendants and where performance data exist (Buchanan et al., 2018; Van Eenennaam et al., 2011).

Second, genomics is an information technology that reduces transaction costs and information asymmetry, enabling verification and selection in traits not routinely measured. This creates potential value across the chain (including processors and consumers). However, it also creates an incentive alignment problem: benefits may not accrue to the actor paying for genotyping unless price signals or contracts transmit value (Van Eenennaam & Drake, 2012).

Third, genomics interacts with sustainability economics. Efficiency-related genetic improvement can support emission-intensity reductions and resource efficiency agendas, potentially lowering risk and improving competitiveness under policy and market pressures. Nevertheless, sustainability-linked returns depend on governance: without appropriate policy design and market frameworks, efficiency gains may not translate to desired system-level outcomes (FAO, 2013; FAO & New Zealand Agricultural Greenhouse Gas Research Centre, 2017; Navajas et al., 2010).

Fourth, adoption constraints are fundamentally economic and institutional: phenotyping scarcity, multi-breed structure, infrastructure costs, and social licence shape the profitability of adoption. The Angus case shows that scaling can dramatically reduce genotyping costs, but it requires governance capacity and producer participation (Berry et al., 2016; Moser et al., 2019).

Conclusions

1. The aim of this review was achieved: evidence indicates that cattle genomics affects beef-system economics by accelerating genetic gain, improving performance in high-value traits, and reducing information asymmetry across the supply chain.
2. Quantitative evaluations show that genomic information can generate substantial discounted economic value, particularly in seedstock and vertically integrated systems, but realised returns depend on data costs, planning horizons, and mechanisms that transmit downstream value to upstream investors.
3. The most economically important pathways for genomics in beef are improvements in fertility/survival, feed efficiency, carcass traits, and health; these benefits are greatest where phenotyping and reference populations support stable prediction accuracy.
4. Sustainability pressures increasingly shape the economic case for genomics: efficiency-oriented genomic improvement can be part of cost-effective strategies to reduce emissions intensity and enhance competitiveness, while economic outcomes depend on policy and market incentives.
5. Persistent adoption barriers in beef are institutional rather than purely technological, including multi-breed population structure, limited phenotyping, fragmented incentives, and governance and social-licence challenges related to data standards, traceability and acceptability.

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URBANIZATION AND DEMOGRAPHIC CHALLENGES OF FUNDING EDUCATIONAL INSTITUTIONS IN MUNICIPALITIES IN LATVIA

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Abstract
Urbanization is a social phenomenon accompanied by economic development. More than half of the world's population lives in cities today, and many of those who do not live in cities would choose to do so if given the opportunity. This phenomenon of urbanization has resulted in harmful effects. It changes the usual procedure and financial expenses for local governments. For municipalities in Latvia, education funding is one of the most significant public finance challenges, especially in the context of demographic changes, reorganization of school networks, and rising maintenance costs. Despite a decrease in the number of students, total expenditure on general education continues to increase, thereby raising the issue of financial sustainability and efficient use of resources. The research aims to analyse changes in municipal budget expenditure on general education in Latvia in the period from 2019 to 2024, identify the main line items of expenditure increase, and analyse territorial disparities by urbanization level. The results showed that since 2021, expenditure per student has increased by 33% during the analysis period, reaching EUR 1263, whereas the number of students has decreased by 2%. The increase in expenditure was mainly driven by remuneration and goods and services procured, while capital expenditure made short-term fluctuations. The analysis of urbanization levels revealed that in sparsely populated areas, expenditure per student was significantly higher, thereby indicating an increased financial burden for municipalities.
Keywords: urbanization, general education, municipal expenditure on education, number of students.

Introduction

Municipal expenditure on general education is one of the most significant items of public financial expenditure, which directly affects the accessibility, quality and long-term socio-economic development of education (Villela & Paredes, 2022). In municipal budgets, education expenditure accounted for a significant proportion in the Baltic States in 2021: 35.7% in Lithuania and 40% in Latvia and Estonia. Moreover, during the last years, significant changes in education expenditure in Latvia have been observed both in absolute and relative terms. The changes are associated with the growing desire of the population to live in development centers – cities –, demographic processes, as well as with the reorganization of the network of educational institutions by closing schools with an insufficient number of students or by merging several educational institutions. Teacher salaries have also increased. The growing financial burden in the education system raises the issue of the ability of local governments to maintain a financially sustainable education system in the long term.

Increasing education funding does not in itself lead to higher education quality or better learning outcomes. Not only the amount of funding but also the distribution, targeted use, and effective management at the local level are essential. The OECD points out that in education systems with similar amounts of funding, the learning outcomes achieved might differ significantly, thus indicating differences in the effectiveness of use of public resources (OECD, 2022). This underlines that the effectiveness of spending is strongly linked to the sustainability of public finances, as inefficient use of funding increases the economic burden in the long term.

The effectiveness of education spending is the ability to maximize educational performance, given the resources invested. Although public education expenditure tends to increase in many countries, including Latvia, this does not always guarantee high-quality educational services; at the same time, there is education-driven urbanization. Education plays a special role in urbanization, as it acts both as a consumer product and as an essential element of government wealth redistribution (Chen et al., 2025). Greater attention is therefore paid to resource effectiveness, which is an essential prerequisite for sustainable economic and wealth growth (Legenzova et al., 2023). Disparities in the maintenance of the education system remain between urban and rural areas, and the question of a fairer funding policy for rural schools arises (Ma, 2025; Lu, 2024).

The Latvian education system is funded both from the State budget and from local government budgets, with the State budget funding state-founded educational institutions and providing municipalities with targeted subsidies for teacher salaries, while municipalities cover all maintenance costs and other services related to the provision of education.

It is the municipalities that bear most of the burden of funding education, which makes effective budgeting and expenditure management an essential prerequisite for the sustainability of the education system. At the same time, several scientific research papers also mention financial decentralization as an element of improving the effectiveness of spending municipal funding (Bezpartochnyi & Bezpartochna, 2024; Meoded & BenDavid-Hadar, 2025) and digital modification in the education system (Grinberga-Zalite & Hernik, 2019; Wang & Cai, 2025). Research studies on the effectiveness of education spending indicate that education quality depends not only on the amount of funding but also on how effectively this funding is used. A research study by E.W. Miningou concluded that, on average, 16% of public education funding was not used effectively, and the effectiveness

of education funding varied significantly across countries, with marked inefficiency observed in lower-income countries (Miningou, 2019). M. S. Dincă (2021) analysed the effectiveness of education in European Union Member States and found that education systems with relatively less funding could achieve high-quality education if the available resources were used rationally (Dincă et al., 2021). At the same time, some research studies have highlighted that due to growing urbanisation, countries might face a greater financial burden to provide quality educational infrastructure, adequate educators and funding, with particular emphasis on rural areas (Wang & Cai, 2025), thus discussing bridging the education gap between urban and rural areas (Gao & Li, 2025).

Government spending on education refers to the financial resources that national or municipal institutions allocate to providing educational services to the public. In Latvia, the general education funding model is centrally coordinated by the state with some decentralised elements. The national grant system and municipal co-funding are combined to provide education for students in all educational institutions (pre-school, primary, and secondary).

The aim of the research is to assess changes in municipal budget expenditure on general education in Latvia in the period from 2019 to 2024 in the context of demographic change and urbanization. The research assessed the effectiveness of education expenditure not from the perspective of achievement of educational outcomes, but from the perspective of financial management, analysing the composition of expenditure, changes therein, and the municipal budget burden per student.

Materials and Methods

The research employed theoretical analysis methods and quantitative analysis methods for secondary data. A monographic and bibliographic approach has been applied for the theoretical part, reviewing the scientific literature, with sources selected from Scopus, Web of Science, and Google Scholar databases, as well as research studies and reports published by international institutions: the OECD and the European Commission. The empirical part analysed secondary statistical data on the expenditures of Latvian municipalities on general education. The research used data from the State Education Information System on maintenance expenditures on general education institutions, as well as data from the Official Statistics Portal and Eurostat.

Education expenditure changes were analysed in absolute and relative terms, with averages calculated for all absolute changes. In addition, a coefficient of variation was calculated to make it possible to identify the volatility of capital expenditure over time. Given that the interpretation of the coefficient of variation depends on the nature of the data to be analysed (Santos & Dias, 2021), municipalities were grouped by level of fluctuations in capital expenditure, thereby distinguishing low (CV<40%), medium (CV 40-80%), and high (CV>80%) fluctuations. Fluctuations in capital expenditure indicate the irregularity of investments by municipalities rather than the effectiveness of annual expenditures. A high level of volatility indicates one-off investments in infrastructure and should therefore be interpreted as an indication of the stability of budgets rather than education costs.

During the period from 2019 to 2024, there were 43 municipalities in Latvia, including 7 state city municipalities, in which the city represents a separate municipality without a rural area. The research employed comparative analysis and the grouping method to classify municipalities by level of urbanization. The classification of populated areas of Latvia developed by the Central Statistical Bureau (hereinafter the CSB) according to the Eurostat classification DEGURBA (degree of urbanisation) has been used to determine the degree of urbanisation, which, based on the share of population living in a territory and the population density, divides local administrative territories into seven groups. Given that the levels of urbanization, based on the CSB classification, are initially applicable at the level of rural territories (parishes) and State cities, yet the analysis was performed for the level of municipalities (rural municipalities and state city municipalities), the urbanization indicators were adjusted to the level of municipalities and aggregated, combining them into three groups: densely populated areas (1-2), moderately populated areas (3-4) and sparsely populated areas (5-7). The degrees of urbanisation were used as a comparative indicator to assess disparities in expenditure per student between the municipalities of Latvia.

The research had a number of limitations that affected the interpretation of the results. The analysis focused only on the expenses for the maintenance of general education institutions, which were covered from municipal budgets, excluding special education and preschool educational institutions. Besides, expenditures covered by state earmarked grants, funding from the European Union Funds, donations, or other external sources of finance were not analysed, focusing on the direct financial burden for municipalities in maintaining educational institutions.

Results and Discussion

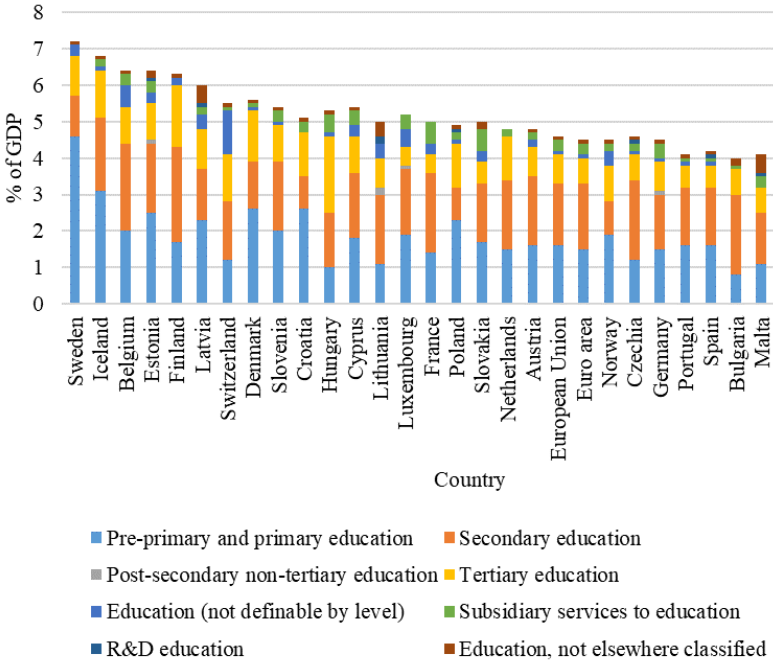
To place the Latvian case in a broader context, Figure 1 presents the latest comparable Eurostat data on total general government expenditure on education as a percentage of GDP EU Member States. Although this indicator is available for 2023 only, it is used here as a contextual benchmark that highlights Latvia's overall position in the EU before turning to the municipal level analysis for 2019- 2024.

In Latvia, total general government expenditure on education reached 6,1% of GDP in 2023, significantly exceeding EU average of 4.7% and placing Latvia among the EU Member States with the highest relative

spending on education. The breakdown of expenditure by education level shows that most of the public funding in Latvia was allocated to pre-school, primary, and secondary education, which accounted for 3.2% of GDP.

Figure 1

Total government expenditure on education in 2023, % of GDP

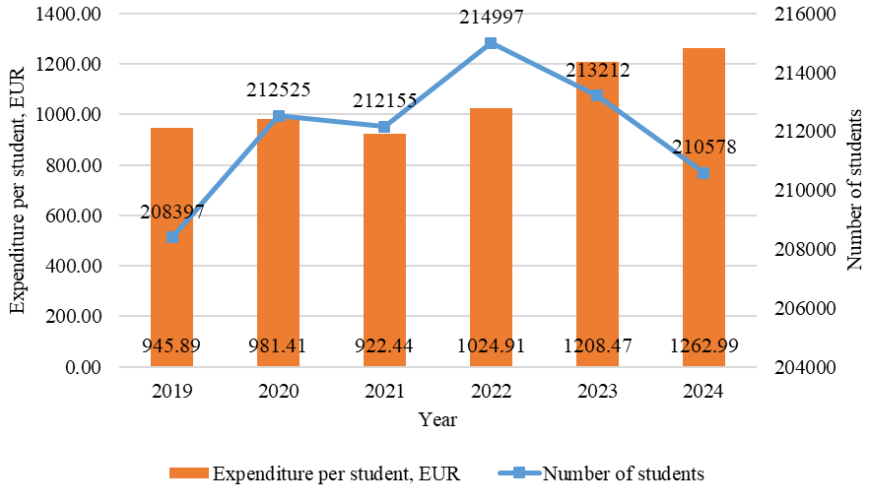


Source: authors' construction based on Eurostat, 2025.

Overall, the data confirmed that Latvia allocated significant public resources to education in the EU context; therefore, an analysis of the composition of and changes in education expenditure at the local government level becomes important to identify the effectiveness of resource use. These issues are also raised in the demographic context. The demographic changes in Latvia represent a prolonged negative natural increase in the population. The population changes because of migration are fluctuating.

Figure 2

Municipal expenditure per student and the number of students in Latvia from 2019 to 2024



Source: authors' calculations based on State Education Information System, n.d.

There is also a pronounced internal migration of population in Latvia; as a result, the areas around the capital city – Riga – have a positive balance of population, whereas in other areas, especially in the most remote areas from cities, the population is decreasing. For example, in Augsdaugava

municipality in five years (2019-2024), the population has decreased by 573, while in Daugavpils municipality by 630 (Official Statistics Portal, n.d.), and these are those located not only in the border area of Latvia but also alongside the EU's external border.

Despite the demographic challenges, access to education, especially primary education, is an important prerequisite for the viability of any area.

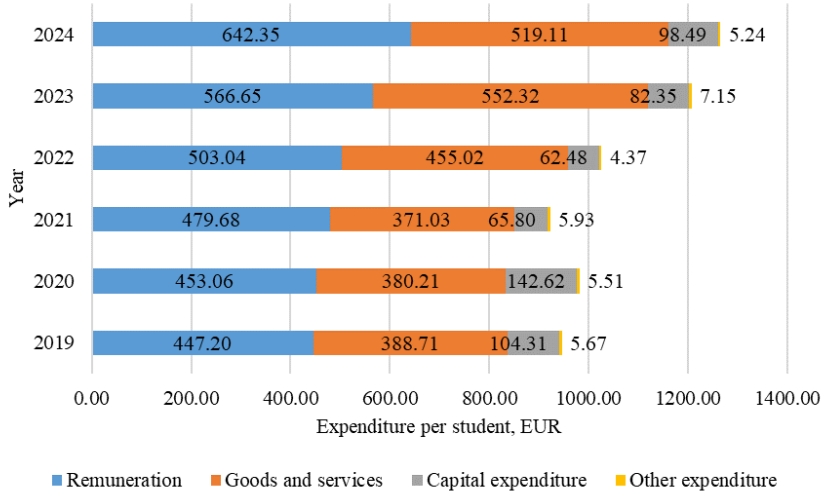
As shown in Figure 2, during the period from 2019 to 2024, the municipal expenditure per student has increased significantly from EUR 946 to EUR 1263, which is 33% or EUR 317 more. At the same time, the number of students has decreased during this period, with the most pronounced decrease being observed from 2021 to 2024 when their number decreased by 4419 or 2%. This trend is strongly related to demographic changes in Latvia, i.e., low natural growth and migration; as a result, the population decreased by more than 41 thousand or 1% in 2024 compared with 2019 (Official Statistics Portal, n.d.).

At the same time, given that not only the number of students tends to decrease in Latvia, but also the number of educational institutions decreased from 707 in 2019 to 586 in 2024 (State Education Information System, n.d), it can be concluded that the optimization of the school network has not significantly reduced the overall financial burden on the budgets of municipalities, which raises the issue of the composition of education expenditure, effectiveness of resource use and financial sustainability in the long term.

With a decrease in the number of both students and educational institutions, the provision of educational services becomes financially more expensive per student; therefore, it raises the need to assess the composition and effectiveness of education expenditure, as the financial burden for local governments increases regardless of changes in the amount of educational services.

Figure 3

Municipal expenditure on education by economic category per student in Latvia from 2019 to 2024, EUR



Source: authors' calculations based on State Education Information System, n.d.

During the period from 2019 to 2024, as shown in Figure 3, the expenditures by local governments on general education per student increased across all main economic categories; however, the amount and structure of the increase differed significantly. The largest proportion of expenditure during the entire period was made up of remuneration expenses, which increased by EUR 195 or 44%, indicating that targeted funding was allocated to increase teacher salaries.

In 2024, expenditure on goods and services rose by EUR 130 (34%) per student compared to 2019. This significantly increased the financial burden on local governments, particularly as student enrollment was simultaneously declining.

However, capital expenditure has been volatile, reflecting its one-off or short-term nature: after making capital investments, there was often a significant reduction in the costs covered from the municipal budget, which led to drastic changes in expenditure. The coefficient of variation showed that only in 8 municipalities, the fluctuations in capital expenditure were low (CV<40%), while other municipalities had medium (25 municipalities with CV 40% to 80%) or very high fluctuations (10 municipalities with CV>80%), which indicated that the expenditure on educational infrastructure was mostly carried out through periodic investments, rather than according to a continuous and even investment plan.

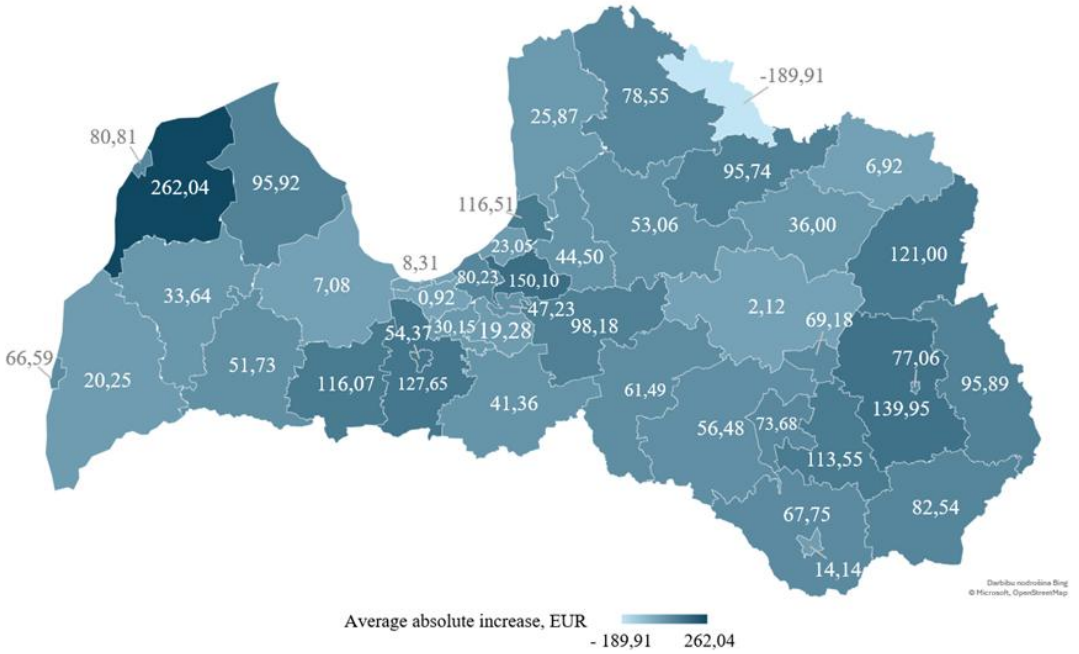
Overall, the composition of education expenditure shows a high proportion of fixed costs, as remuneration and expenditure on goods and services remained unchanged in the short term, despite changes in the number of students. Such a composition of expenditure limited the ability of municipalities to adjust expenditure flexibly in the face of demographic change and raises the need to assess the effectiveness of education expenditure in terms of these categories.

During the period from 2019 to 2024 in municipalities,

the average absolute increase in expenditure per student on remuneration, as well as goods and services, was uneven and territorially different. Almost all municipalities of Latvia (42) have experienced an increase in expenditure every year, with the most significant increase being in Ventspils, Ropazi, and Rezekne municipalities, while in only one municipality, the expenditure was decreasing, which was Valka municipality, where the average absolute decrease per student was 190 EUR or 12%.

Figure 4

Average absolute increase in expenditure on remuneration and goods and services per student from 2019 to 2024, EUR



Source: authors' calculations based on State Education Information System, n.d.

To identify disparities in education expenditure between municipalities, the research applied an urbanization level approach, which allowed the authors to analyse the composition of and changes in municipal expenditure in different population conditions, where DEG 1 to 2 denotes densely populated areas or metropolitan areas and dense cities, DEG 3 to 4 – moderately populated areas or moderately dense cities and suburbs, and DEG 5 to 7 – sparsely populated areas or villages, scattered rural areas and mostly uninhabited areas.

Table 1

Median number of students and education expenditure per student in the municipalities of Latvia by urbanisation level in 2024

Degree of urbanisation	Number of municipalities	Number of students	Total expenditure, EUR	Remuneration, EUR	Goods and services, EUR
DEG 1 to 2	7	7205	995.87	430.82	346.47
DEG 3 to 4	7	3891	1084.20	463.18	503.96
DEG 5 to 7	29	2121	1543.28	821.09	582.80

Source: authors' calculations based on State Education Information System, n.d. and RAIM, n.d.

As shown in Table 1, the median education expenditure per student in 2024 in municipalities varied significantly, depending on the degree of urbanisation. The lowest expenditure was found in densely populated areas (DEG 1-2), while the highest was in sparsely populated areas (DEG 5-7). This trend suggests a higher financial burden per student in areas with lower population density.

The analysis of the composition of expenditure revealed that a significant difference between urbanisation groups was made up of remuneration expenditure, with the difference between densely populated and sparsely populated areas being EUR 390 per student, which could probably be explained by the need to maintain small classrooms, attract teachers, and retain existing ones. A similar, albeit less pronounced, trend can also be observed in expenditure on goods and services. The disparity between densely populated areas and sparsely

populated areas was EUR 236 per student.

It should be considered that with the increase in the level of urbanization, there is a negative correlation between the number of students and the education expenditure per student: the smaller the number of students in the municipality, the higher the expenditure per student.

Overall, the data show that the degree of urbanisation is an important factor in disparity in education expenditure between municipalities: the lower the population density, the higher the expenditure per student. These results highlight the need to pay increased attention to the financial sustainability of the education system in sparsely populated areas in the context of education policy and municipal financial planning, as well as to increase the effectiveness of resource use in the long term, considering structural differences and territorial specifics. This is also indicated by some scientific research studies and their findings.

The research results showed that an increase in expenditure by local governments on general education from 2019 to 2024 was determined by structural factors, including teacher salaries, as well as an increase in expenditure on goods and services. Despite a decrease in the number of students and educational institutions, expenditure per student was increasing significantly, and this trend is territorially uneven. These results indicate that applying a uniform funding approach to the distribution of education expenditure among all municipalities might exacerbate territorial disparities and, therefore, greater emphasis should be placed on education funding policies to deal with differences in the population structure, municipal size, and concentration of students.

Conclusions

1. In 2023, Latvia allocated one of the highest proportions of public funding to education in the EU, reaching 6.1% of GDP and significantly exceeding the EU average of 4.7%. However, most of the funding was allocated to pre-school, primary, and secondary education (3.2% of GDP), with this amount of expenditure emphasizing the important role of local governments in funding general education.
2. Between 2019 and 2024 in Latvia, the expenditure per student increased by EUR 317 (33%), while the student population decreased by 4419 (2%). Despite the consolidation of the institutional network, those rising costs indicate that educational service delivery is becoming increasingly resource-intensive, challenging the fiscal sustainability of municipal budgets.
3. During the analysis period, the expenditure by municipalities per student increased across all economic categories: remuneration increased by EUR 195 (44%), and the expenditure on goods and services by EUR 130 (34%). The data reveals that rising expenditures were driven primarily by the increase in teacher salaries and the procurement of goods and services. In contrast, capital expenditure remained volatile and only influenced total spending in the short term. This highlights a high proportion of fixed operational costs, limiting the ability of municipalities to adjust spending in response to demographic shifts.
4. With a decrease in the degree of urbanisation, educational expenditure per student increased significantly from EUR 996 in densely populated areas to EUR 1543 in sparsely populated areas, which is 55% higher than in densely populated areas; the disparity in expenditure on remuneration exceeded EUR 390, while on goods and services it exceeded EUR 236. This indicated a negative correlation between the number of students and expenditure per student, thereby confirming a higher financial burden in sparsely populated municipalities. Consequently, the combination of negative demographic trends and accelerated urbanization in Latvia requires new solutions in the municipal funding system.
5. The current system of funding general education in Latvia, under the conditions of negative demographic and urbanization processes, might lead to an increase in territorial disparity. When designing an education funding policy in Latvia, more emphasis should be placed on population structure, municipal size, and student population trends; furthermore, differentiated approaches should be applied to both the provision of education and the allocation of its funding.

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THE IMPACT OF HUMAN LIFE CYCLE STAGES ON INDIVIDUALS' SUSTAINABLE CONSUMPTION CHOICES

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Abstract
This study addresses a highly relevant topic, as there is an increasing need today to design ways to steer society toward sustainable consumption, which is a cornerstone of resilient rural and regional development. The life cycle approach provides a fresh perspective by viewing consumption as a dynamic process influenced by an individual's age, social roles, and life experiences. This study aims to assess how human life cycle stages influence sustainable consumption and to identify the primary socio-demographic drivers of individual behavior throughout different stages. The empirical study is based on a quantitative research method - a population survey. The main contribution of the study is the application of the life cycle approach to the analysis of sustainable consumption in the Latvian context, both in cities and rural areas. The study reveals that more sustainable choices are most commonly observed among individuals aged 30 to 64. Young people tend to choose second-hand goods and engage in waste sorting partially, but pay less attention to product sustainability. Seniors demonstrate consistent behavior; however, their level of awareness about sustainability issues is lower. Factor analysis identified four main directions of sustainable behavior, and research results confirm the significant role of education in making sustainable decisions. The results lead to a compelling conclusion: the transition through various life stages acts as a significant determinant, exerting a transformative influence on both the practical habits and the underlying values of sustainable consumption.
Keywords: sustainable consumption, human life cycle approach, consumer behavior, sustainability.

Introduction

Nowadays sustainable development is one of the most significant global goals, as formally established in the United Nations Sustainable Development Goals within the 2030 Agenda, with a particular emphasis on Goal 12: 'Ensure sustainable consumption and production patterns'. Its achievement can be driven not only by global initiatives but also by the everyday consumption choices of every citizen, which play a crucial role in the socio-economic resilience of rural territories. Consumer choices significantly determine the aggregate environmental footprint and resource utilization of society (Flint Ashery, 2022; Shahmohammadi et al., 2019; Sala & Castellani, 2019); however, these choices cannot be fully comprehended without a rigorous analysis of how individual life cycle stages influence consumption patterns. In the context of rural development, understanding these patterns is essential, as the demographic structure and the transitions between life stages directly affect the demand for local ecosystem services, the viability of short food supply chains, and the overall transition towards a circular bioeconomy. Initiatives aimed at promoting sustainable consumption are frequently implemented without a comprehensive understanding of how individual values, priorities, and behaviors evolve across different life cycle stages. This oversight may diminish policy effectiveness, as the decision-making process fails to account for the life cycle as a dynamic trajectory, which subsequently shapes an individual's sustainable consumption choices and their impact on the sustainable development of the surrounding rural environment.

The concept of 'sustainable consumption' was defined at the Oslo Symposium in 1994 as 'the use of services and related products, which respond to basic needs and bring a better quality of life while minimizing the use of natural resources and toxic materials as well as the emissions of waste and pollutants over the life cycle of the service or product so as not to jeopardize the needs of future generations' (United Nations, 1994). This definition has remained unchanged over the years and continues to be highly relevant.

To achieve sustainable consumption, several principles are observed within society. Among the primary fundamental principles are the more efficient use of raw materials, energy, and water, as well as the extension of product life cycles. These principles can be implemented by adhering to the 3R (Reduce, Reuse, Recycle) strategy, which minimizes waste volumes in both production and consumption (Glavič, 2021). Over time, this framework has evolved into 9R and 10R strategies (Khaw-ngern et al., 2021), with current discourse expanding toward a 12R strategy (Modak, 2021). Other research indicates that the adaptability of product design and the availability of repair or service options are crucial for promoting sustainable consumption (da Silva et al., 2024).

This study addresses a highly relevant topic, as there is a growing need today to plan ways to steer society toward sustainable consumption; however, these actions must be deliberate and evidence-based. Social and economic factors play a decisive role in promoting sustainable consumption, as they influence not only individual habits but also the broader societal structure and market development (Fischer et al., 2021). Within urban contexts, sustainable choices are largely facilitated by a broad range of eco-friendly services and market options; in contrast, rural sustainability relies heavily on community-driven cooperation and resource independence, though these efforts are frequently shaped by specific regional income levels and transport challenges. Research regarding the disparities between urban and rural consumer habits yields ambiguous results. For instance, research from

Egypt (Marzouk, 2019) indicate comparable levels of sustainable consumption and motivation in both environments; conversely, evidence from Pakistan (Rasheed et al., 2025) suggests that socioeconomic factors exert a significantly more potent influence on the behaviour of urban residents than on those in rural areas. In Poland (Utzig, 2017), urban and rural households both shift towards less sustainable consumption patterns, and in some areas urban households are less sustainable than rural ones. At the European scale, a carbon-footprint study found that footprints are on average 7% lower in cities than in rural areas after controlling for income and household characteristics, but the pattern is not uniform across countries (Ottelin et al., 2017).

The life-cycle approach provides a fresh perspective by viewing consumption as a dynamic process influenced by an individual's age, social roles, and life experiences. Huinink & Hollstein (2021) argue that life cycle research demonstrates how personal choices at various life cycle stages shape life trajectories, which subsequently continue to influence society as a whole. An individual's understanding of life's value and its significance changes depending on age, health, and economic conditions. A study analyzing the desire to extend life based on resources, health, and quality of life concludes that as age increases, the willingness to pay for life extension decreases, while interest in quality of life and comfort grows (St-Amour, 2024). Such a shift in attitude influences not only personal decisions but also societal pressure on health, welfare, and consumption policies throughout various life cycle stages.

The novelty of this research lies in the application of life-cycle theory to the analysis of sustainable consumption choices, which, until now, has received relatively little research attention in Latvia.

Research on youth engagement in the implementation of sustainable consumption reveals that higher levels of involvement foster environmentally friendly and socially responsible behavior, generating positive transformations within broader society (Kadic-Maglajlic et al., 2019).

The aim of the study is to evaluate the impact of the human life cycle on sustainable consumption choices in Latvia and to identify the most significant factors influencing individual behavior at different stages of the life cycle. The following hypothesis was formulated within the scope of the study: the stage of the human life cycle influences attitudes toward sustainable consumption, as value systems, living conditions, and the significance of sustainable choices vary across different age groups.

Materials and Methods

To achieve the research aim, a quantitative research method – a population survey – was selected. Data collection was conducted from February to March 2025 via an online survey instrument, which assessed individual consumption habits, attitudes toward sustainability, and related behaviors. The questionnaire comprised sections on respondents' demographic and socioeconomic characteristics (age, education, employment status, and number of children in the household), as well as questions regarding consumer behavior and attitudes. The analysis will cover respondents' answers regarding their shopping habits, waste sorting practices, levels of awareness, attitudes toward various types of packaging, and their willingness to pay for environmentally friendly products. Additionally, the survey included open-ended questions, allowing participants to provide qualitative insights and express their perspectives on the specific issues addressed. A total of 205 valid responses were obtained through the survey. The collected data were processed using *IBM SPSS Statistics* software, employing various statistical analysis techniques appropriate for the data types, including the Kruskal–Wallis H test, Principal Component Analysis (PCA) with Varimax rotation, and linear regression analysis. The open-ended questions were analyzed using qualitative content analysis, where responses were grouped by thematic relevance and coded into distinct categories based on content similarity.

Participants were informed about the aim of the research and provided their informed consent before participating. To ensure confidentiality, all data were collected anonymously, and no personally identifiable information was recorded.

The survey process successfully reached all age groups included in the study, facilitating the generation of objective data across all age categories. The majority of respondents fell within the 30–44 age group (33.2%, n=68), followed by the 45–64 age group (25.4%, n=52). Younger age groups were less represented in the study, with 17.6% (n=36) in the 16–23 range and 16.6% (n=34) in the 24–29 range. The smallest proportion of respondents belonged to the 65 and older age group (7.3%, n=15). Regarding the respondent profile, 76% were female and 24% were male. The most represented group in the survey consisted of individuals with higher education (65%), followed by those with secondary education (27%) and primary education (7%). In terms of employment, the majority of respondents were employed full-time (57%), while 19% were students and 7% worked part-time. The remaining participants were retirees, individuals on parental leave, or those who preferred not to disclose their employment status.

The study is subject to several limitations. Primarily, the relatively small sample size of respondents may not be fully representative of the entire Latvian population, thereby limiting the generalizability of the findings. Furthermore, the results may be affected by inherent biases, such as social desirability bias, where participants might overreport sustainable behaviors to align with societal expectations. Thirdly, the study faces certain methodological constraints; as a quantitative survey, it prioritizes broad trends over the

nuanced, in-depth contextual understanding that qualitative methods might provide regarding individual motivations. Additionally, the current survey did not account for the respondents' specific place of residence, which precludes a comparative analysis of sustainable consumption patterns between urban and rural populations. However, the authors posit that exploring the geographical nuances of these behaviors represents a critical direction for future research, particularly to assess how regional infrastructure and community settings further moderate life cycle-driven choices.

The linguistic processing and stylistic refinement of this article were conducted using the artificial intelligence tool *Gemini*.

Results and Discussion

Within the framework of the research, the initial analysis focused on the respondents' purchasing patterns.

One of the survey questions aimed to determine whether and under what circumstances individuals would be willing to pay a higher price for a product. Respondents could indicate their preference by choosing between options such as sustainable production, high quality and durability, a combination of both factors, or a lack of willingness to pay any price premium. The results reveal distinct differences between the age groups. The most frequently selected option across all groups was 'In both cases'; this choice was particularly dominant in the 30–44 and 45–64 age groups. This trend can be attributed to the development of long-term thinking and the financial stability characteristic of these demographics. The prevalence of this response indicates that sustainability and quality are perceived as complementary values, for which consumers believe it is worth paying a premium. A significant proportion of support for choices involving sustainability or quality aspects is also observed in the 24–29 and 65+ age groups. Conversely, respondents in the youngest age group (16–23) appear to be the most critical of higher prices, most frequently indicating a lack of willingness to pay more. This choice may be explained by limited financial resources or a yet-to-be-developed long-term perspective on consumption. Similar caution is evident in a segment of the 65+ group, which could be attributed to fixed incomes or other priorities characteristic of that particular life stage.

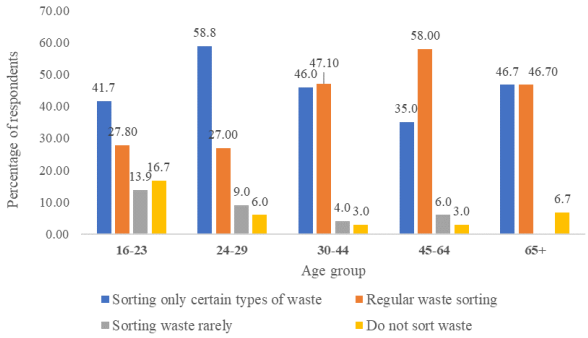
The analysis suggests that age is a significant factor influencing how individuals value long-term benefits and their readiness to pay for them. Life experience, income stability, and the evolution of a long-term outlook appear to be the key aspects driving these differences between age groups.

The survey also examined the significance of product quality as a factor in purchasing decisions, and whether variations in this regard are observable across different age groups. The results indicate that the average importance of product quality is rated highly across all groups, though certain differences exist. The highest average quality rating was observed in the 45–64 age group (9.36 points out of 10), followed by the 30–44 age group (9.04 points out of 10). Respondents aged 16–23 rated quality at an average of 8.74 points, while the 24–29 group gave it a rating of 8.64. In contrast, the lowest rating was recorded in the 65+ age group, with an average value of only 8.47 points out of 10. The results of the Kruskal–Wallis test further confirm statistically significant differences in product selection based on quality between the groups ($H = 11.264$; $p = 0.024$), indicating that age significantly influences how individuals perceive product quality. These data suggest that product quality is most highly valued by individuals of working age, particularly the 45–64 age group, whereas younger respondents and seniors may be more guided by other criteria, such as price, brand, or habit.

Sustainable everyday choices can be made not only in relation to shopping but also across various other daily habits. One of these choices involves waste sorting. To determine whether differences in waste sorting habits exist across different age groups, a Pearson's chi-square test (χ^2) was conducted. The results reveal a statistically significant difference between age group and waste sorting habits ($\chi^2(12) = 23.927$; $p = 0.021$), and this implies that the intensity of waste sorting varies significantly across different age groups.

Figure 1

Waste sorting habits across different age groups



More than half (57.7%) of respondents (Figure 1) aged 45 to 64 sort their waste regularly, as do 47.1% of those in the 30–44 age group. Similarly, just under half, or 46.7%, of respondents aged 65+ also sort waste regularly. These data indicate that regular waste sorting is most prevalent among individuals starting from approximately 30 years of age. In contrast, younger people tend to engage in more selective practices; while they do participate in waste sorting, they often focus only on certain waste types. For example, 58.8% of those aged 24–29 and 41.7% of those aged 18–23 reported sorting only specific categories of waste.

The results of the analysis lead to the conclusion that residents aged 30–44 and 45–64 are the most active participants in waste sorting, with more than half of them doing so regularly. Conversely, engagement is

lowest among individuals aged 16–23 and 24–29, who mostly sort only specific types of waste or do so inconsistently. This may be related to different life priorities at this stage of the life cycle, as well as lifestyle factors such as living in rented apartments or a more transient daily routine.

A lower intensity of waste sorting is also observed in the 65+ age group. Potential reasons for this could include various barriers to sorting (e.g., containers located far from home, physical difficulties), as well as a possible lack of information and a reluctance to use new systems, such as deposit return technologies.

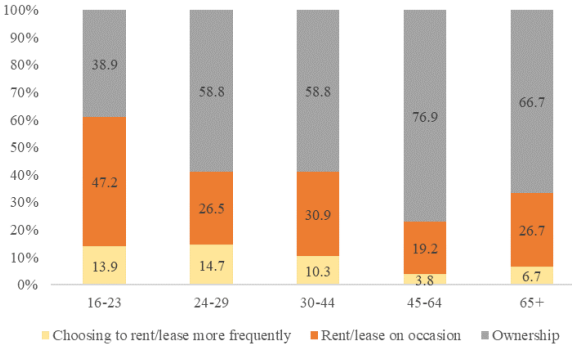
The overall trend indicates that age influences sorting habits and their regularity. The highest level of engagement in this practice is found among the working-age population.

A key trend in the field of sustainability is the flourishing of sharing and leasing/rental models, which has seen significant growth recently (Silva et al., 2024). The survey participants were requested to evaluate their preference for ownership versus rental models. To determine whether a significant difference in opinions exists between age groups on this matter, the Kruskal–Wallis test was applied. The study results revealed no statistically significant differences across various age groups ($H = 3.530$; $p = 0.473$); however, certain trends are apparent when examining the data descriptively. The results show (Figure 2) that respondents in the older age categories are much more likely to prefer owning products over renting them. Specifically, 76.9% of respondents in the 45–64 age group and 66.7% in the 65+ group indicated that they always prefer to own their products. In contrast, this figure is considerably lower among the younger age groups—38.9% for those aged 16–23 and 58.8% for those aged 24–29—where rental or sharing options are more frequently chosen. The 16–23 age group is particularly noteworthy, with 47.2% of respondents stating that they occasionally use sharing or rental services, and an additional 13.9% noting that they choose these options more frequently to reduce expenses. This trend is likely influenced by both financial considerations and limited opportunities for ownership among young people. The results reveal that the preference for ownership increases with age, whereas younger individuals more frequently use or consider sharing options. These data also align with other studies (Varpa et al., 2024; Dobewall et al., 2017), which argue that younger people are more likely to choose second-hand items, furniture, and interior elements, thereby extending their life cycle, at the same time as people age, their values often shift—they become more cautious, less hedonistic, and place a higher value on security and tradition. Such shifts can also influence their attitudes toward sustainable consumption, making them more responsible in their choices.

Regarding rental and sharing services, respondents had the opportunity to express their views through open-ended questions. More than half of the respondents (52%) voiced support for such solutions.

Figure 2

Ownership versus rental choices across different age groups



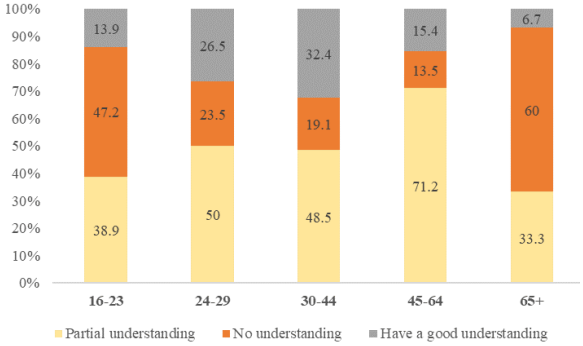
They frequently described this as a practical or acceptable choice for daily life without specifying particular reasons. Furthermore, 11% justified their positive attitude with economic considerations, stating that sharing allows for savings and the avoidance of unnecessary expenses, especially when goods or services are needed only for a short period. Notably, only 3% of respondents praised this option specifically from an environmental sustainability perspective, emphasizing that it helps reduce resource consumption and fosters a more responsible attitude toward the environment. However, 12% of respondents held a critical view toward sharing services, primarily expressing concerns regarding the quality, wear and tear, or hygiene risks of shared or rented items. These responses indicate certain prejudices, such as the perception that shared items might be 'damaged', 'worn out', or 'unreliable'.

Respondents were asked to evaluate the factors influencing shifts in their consumption habits toward more sustainable practices. Chi-square test results reveal that social pressure and rising prices have a statistically more significant impact on the younger age groups—respondents aged 16–23 and 24–29. Specifically, 33.3% of respondents in the 16–23 age bracket cited social pressure as a key factor. In contrast, this reason was not mentioned at all in the 45 – 64 age group, and only in 6.7% of cases among those aged 65+ ($\chi^2(4) = 21.380$, $p < 0.001$). Rising prices were also frequently cited as a driver for change, particularly among the youngest groups — 50% in both the 18–23 and 24–29 categories — compared to only 21.2% in the 45–64 age group ($\chi^2(4) = 13.011$, $p = 0.011$).

Sustainable practices in daily habits can be fostered by the circular economy; therefore, as part of the survey, respondents were asked to evaluate their self-perceived knowledge of the circular economy. The results, using the Kruskal–Wallis test, revealed no statistically significant differences in the perceived understanding of the circular economy across the analyzed age groups ($H = 8.540$; $p = 0.074$). The highest level of self-assessed awareness ('I understand

very well') was most frequently reported by respondents in the 30–44 (32.4%) and 24–29 (26.5%) age groups (Figure 3). Conversely, the response 'I am not familiar with this concept' was most common in the 65+ (60%) and 16–23 (47.2%) age categories. This indicates that knowledge of the circular economy is most widespread among the working-age population, while it is significantly less known among the youngest and oldest age groups. Such a trend likely suggests that the amount of information regarding the circular economy varies across age groups, or that, due to differing priorities, individuals pay varying levels of attention to such information depending on their current stage in the life cycle. Furthermore, it must be considered that since the question was based on self-assessment, subsequent analysis might require correlating these data with actual behaviors or choices.

Figure 3
Assessment of circular economy comprehension across different age groups



During the survey, respondents were asked to provide suggestions in an open-ended format on what could promote sustainable consumption. The respondents' answers were analyzed using a qualitative content analysis approach – categorized into themes and coded based on content similarity into nine distinct categories (Table 1).

Education and awareness-raising is the most frequently mentioned theme (K1). This indicates that respondents emphasized the need to enhance education on sustainable consumption and its principles, particularly highlighting the importance of early childhood education in this field. A large share of respondents stressed that the education system should focus on teaching sustainability concepts starting from kindergartens and schools. Additionally, the role of mass media was mentioned as a crucial factor in promoting public awareness of environmental issues.

Regulations and legislation were also highlighted in the respondents' opinions (K2). They asserted that there is a need to establish clear regulations at the national level to promote sustainable consumption. In their view, this would include tax policies, the enforcement of laws, and governance initiatives, thereby significantly influencing both business practices and consumer behavior.

Financial instruments (K3) - financial incentives and tax policy - were also mentioned as ways to promote sustainable consumption. The respondents' views led to the conclusion that people believe state support, tax relief, and subsidies for environmentally friendly products would help motivate consumers to make more sustainable consumption choices.

Waste sorting and recycling (K4) were highlighted as practical and necessary actions. Respondents emphasized both the lack of infrastructure and the need for clear labeling and convenient options for returning reusable materials.

In the respondents' views, the necessity to change societal habits and behavioral patterns (K5) was frequently mentioned. In their responses, participants stated several times that the adoption of sustainable consumption is closely linked to behavioral change, a process that requires both patience and time.

In their responses, respondents repeatedly stated that corporate responsibility (K6) is critically important for promoting sustainability. It was mentioned that manufacturers must be compelled to consider packaging types, product quality, and their responsibility for sustainability throughout the entire product life cycle.

Furthermore, according to the respondents, societal behavior is significantly influenced by social norms, the environment (K7), and the style of communication. Social networks, mass media, information campaigns, and public role models were mentioned as effective communication channels for sustainability.

Many respondents emphasized in their answers that sustainable consumption choices often depend on their accessibility (K8). The need to develop better infrastructure was pointed out, particularly outside of cities and urban centers, as well as in major cities. Providing easier access to alternative goods and services was highlighted as essential.

Table 1
Thematic categories of recommendations for sustainable consumption

Category	Frequency of mentions
K1- Education & Awareness	51
K2 - Regulations & Policy	14
K3 - Financial Instruments	7
K4 - Waste Sorting & Management	18
K5 - Habit Change & Behavioral Shifts	7
K6 - Corporate & Market Influence	18
K7 - Social Environment & Norms	28
K8 - Accessibility & Infrastructure	14
K9 - Personal Responsibility	10

A small proportion of respondents emphasized the importance of personal action in fostering sustainable consumption (K9). The responses indicated that individuals must take responsibility for their own habits and that, by acting sustainably, they can serve as

a positive example to others.

Overall, the analysis shows that promoting sustainable consumption requires an interdisciplinary approach - combining education, policy instruments, business practices, and public engagement. The respondents' views and suggested solutions emphasize that the development of sustainable consumption necessitates collective action, manifesting both as systemic changes within society as a whole and as the development of personal responsibility among individuals.

Identifying Factors Influencing Sustainable Consumption

To identify the key factors characterizing consumer behavior and attitudes toward sustainable consumption, factor analysis was performed using the Principal Component Analysis (PCA) method with Varimax rotation. The factor analysis incorporated thirteen variables, encompassing dimensions such as willingness to pay a premium for sustainable products, attitudes toward product quality and design, the preference for access over ownership, awareness of the circular economy, and consumer behavior regarding item repair or disposal. The analysis revealed four factors that explain a significant share of the total data variance. The interpretation of each factor was derived from the nature of the included variables and the strength of their factor loadings.

Factor 1: Willingness to Invest in Sustainable Solutions - This factor integrated variables related to the readiness to pay a premium for sustainable, high-quality, and environmentally friendly products, as well as the preference for reduced packaging.

Factor 2: Practicality and Design - This component included aspects concerning the significance of packaging design and functionality, as well as the overall influence of design on purchasing decisions.

Factor 3: Sustainable Behavior and Circularity

This factor encompassed attitudes toward access-based consumption (ownership vs. leasing), repair habits, and literacy regarding the circular economy.

Factor 4: Transformation of Consumption Habits

This factor grouped variables assessing whether consumption patterns have shifted over the past five years and identifying the primary drivers behind these changes.

According to the regression analysis, the respondent's current life cycle stage or age significantly influences only Factor 2: 'Practicality and Design' ($p = 0.003$). This indicates that these aspects are more highly valued by older respondents.

In alignment with the findings of previous studies (e.g. Fischer et al., 2021), the results of this research confirm that an individual's specific life cycle stage significantly shapes their daily choices and attitudes, including those related to sustainable consumption. These findings suggest that transitions between life stages—marked by changes in household responsibilities, financial stability, and time availability—act as pivotal moments that redefine consumer behavior. By acknowledging that consumption drivers differ across the life cycle, local authorities and businesses can move away from 'one-size-fits-all' approaches and instead develop age-specific communication strategies and community-based programs. Such tailored initiatives are essential for fostering long-term behavioral shifts that support the sustainable development and socio-economic resilience of both urban and rural territories.

The study's results offer empirical validation for the hypothesis that an individual's life cycle stage shapes their approach to sustainable consumption, because moving between life stages alters both personal value systems and daily habits. The data reveals that shifts in social roles and financial stability directly drive changes in consumption priorities. Driven by resource limitations and a fast-paced lifestyle, youth place a premium on price and design. At the same time, the working-age demographic (aged 30–64) exhibits a stronger long-term perspective, highly valuing product quality, durability, and sustainability. This shift in values is reinforced by distinct living circumstances, highlighted by statistically significant variations in waste sorting habits and views on ownership; younger groups show greater openness to collaborative sharing models, while older generations prioritize security and tradition.

Conclusions

1. Consumer behavior and its alignment with sustainability principles are closely linked to an individual's specific life cycle stage. At different ages, needs, priorities, and attitudes toward both current life and the future undergo shifts. These distinct values are reflected in both immediate actions and long-term thinking.
2. The empirical evidence suggests that the primary practitioners of sustainable consumption are individuals within the 30–44 and 45–64 age cohorts. These demographic segments demonstrate a more profound integration of sustainability into their retail choices and daily routine practices, such as systematic waste sorting.
3. Younger respondents (aged 16–29) prioritize price and design in their purchasing decisions, whereas adults in the 30–44 and 45–64 age cohorts place a higher value on quality, functionality, durability, recyclability, and overall sustainability.
4. While the level of awareness regarding sustainable consumption is similar across all age groups, distinct differences are observed in actual behavioral patterns. Sustainability principles are most frequently practiced by individuals in the 30–44 and 45–64 age cohorts, and relatively less often by youth aged 16–23. However, younger respondents exhibit a more positive attitude toward sharing and leasing models, indicating an openness to specific circular economy principles.
5. Sustainable consumption behavior is shaped by the interaction of various factors. The most significant among these are the willingness to invest in sustainable

solutions, the importance of practicality and design, sustainable actions, and the transformation of consumption habits.

6. The research hypothesis is confirmed: life cycle stages dictate attitudes toward sustainable consumption, as moving from one stage to the next alters both personal values and practical habits.

7. Regarding data reliability and generalizability, the internal consistency of the survey instrument was validated, ensuring that the findings accurately reflect the attitudes of the sampled group. However, the generalizability of these results to the entire Latvian population is limited by the sample's demographic composition, particularly the overrepresentation of female respondents and individuals with higher education. Consequently, while the trends provide significant insights into life-cycle-based consumption patterns, they should be interpreted as indicative rather than strictly representative of the broader population.

8. To further refine the understanding of sustainable consumption, subsequent empirical research is necessary to determine whether significant differences in daily consumption patterns exist between urban and rural populations. Such comparative analysis would provide a more granular perspective on how geographical factors and infrastructure availability influence the practical application of sustainability principles across various life-cycle stages.

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REGIONAL DIFFERENCES IN FACTORS AFFECTING THE EMPLOYMENT OF THE SILVER GENERATION IN LATVIA

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Abstract
The objective of this publication is to analyse differences in factors affecting the employment of the silver generation, i.e., the over-working-age population, across regions of Latvia. The hypothesis of the research is that there are no statistically significant differences in the views of individuals over working age regarding their decisions to work or not work. The study uses data from a survey conducted by the authors in collaboration with the Market and Public Opinion Research Centre SKDS in 2025. A total of 733 residents over the age of 65 participated in the survey. The survey covered all statistical regions in Latvia and the Pieriga region. The survey data were analysed using the following methods: scientific publication analysis, statistical analysis and databases of the Official Statistics portal (OSP) with data from the EU-SILC survey of Latvia's population. Although data from the Central Statistical Bureau for 2026 show that the highest share of people at risk of poverty was in the Latgale region (35.8%) but the lowest one was in the Riga region (15.6%), the survey results did not show any differences in the responses of silver generation respondents in these regions regarding the fact that the most important reason for continuing employment is material considerations: this was indicated by 69% of respondents in Latgale and 68% in Pieriga. However, regional differences are detected in other factors influencing seniors' employment choices, such as social interaction and self-empowerment with no statistically significant evaluations for 'interesting, pleasant work' by respondents in all statistical regions.
Keywords: silver generation, employment, affecting factors, silver economy, regional differences.

Introduction

Population ageing is a global demographic challenge with significant impacts on national economies, healthcare, social policy, and consumer markets. Consequently, both within the European Union (EU) and in developed countries outside it, solutions are being sought to make the most of the potential of the silver generation's workforce. At the beginning of 2025, the number of people aged 65 and over was 406.8 thousand (22%), almost one-fourth of the Republic of Latvia's population (OSP, 2025b). The shares of the working-age population (15–64 years old) in regions and state cities do not differ significantly, but the proportions of the population before the working age (0–14 years old) and over the working age (aged 65 and over) differ. At the beginning of 2025, almost a quarter or 24.4% of the total population of the region above the working age lived in Latgale, the least, 20.8% in Riga (CSB, 2025). The different regional numbers and age structure of the population affect the GDP per capita across statistical regions. The highest GDP per capita in 2023 was shown in the Riga region (30.4 thousand euros), but the lowest was in the Latgale region (11.5 thousand euros). Thus, the productivity in the Riga region is 2.6 times higher than in the Latgale region. In Kurzeme, GDP per capita is 14.5 thousand euros, in Vidzeme – 12.8 thousand euros, and in Zemgale – 13.6 thousand euros (OSP, 2025a). According to the state social insurance data, at the end of 2024, almost 70 thousand or 16% of the population over the working age were employed. Compared to the proportion of employed seniors in other EU Member States, this indicator is one of the highest in the EU (the average figure was 6.8%). In the Baltic States, the higher share of employed old-age pensioners was only in Lithuania – 18%, while in Estonia it was lower – 13% (Ministry of Welfare, 2025). Several factors affect the choice of people over the working age who decide to continue participating in economic activities. One of the factors is 'material considerations', which employed pensioners identified as the most important in a survey conducted by the authors in 2025 (Seimuskane & Sloka, 2025). Data on the share of people at risk of poverty or social exclusion in 2024 also indicate this as a significant socio-economic problem. Latvia, with the indicator of 24.7%, exceeds the EU average indicator (21%) and ranks among the ten EU countries with the highest risk of poverty or social exclusion. The situation is further exacerbated by regional inequalities. In 2024, 22.0 % of the population in Latvia was at risk of poverty; however, in Latgale, this indicator reached 35.8 %, while in the Riga region, it reached 15.6 % (CSB, 2026). In addition, almost half (45%) of the households in the Latgale region had pensions and various benefits as the main sources of living, whereas in Riga, only 28 per cent of the households were dependent on support of the state and local government in 2024 (OSP, 2024). Academic researchers have indicated several factors on the employment of the silver generation (individuals aged 50 and above) as it is affected by several factors spanning demographic, psychological, social, economic, and policy-related dimensions with special attention to health aspects (Malik et al., 2022; Roszko-Wójtowicz et al., 2024) as older adults face physical and functional health risks, which can limit their employability and multimorbidity and disability are significant contributors to work stress and reduced participation in the labour market. Researchers have indicated factors related to employment of the aged population related to ICT applications (Butt & Draheim, 2021; Moretti, et al., 2026; Yang & Ye, 2025) and structural challenges for inclusive

development (Manzano, 2025). Researchers have underlined the importance of lifelong education (Tao & Ren, 2025), influencing employability for the older population. Several countries have different experiences and attention to population in the silver economy (Enste et al., 2008), with indications of employment opportunities and challenges for the silver generation varying significantly across regions due to differences in living standards, education, and social support systems, with suggestions to tailor, region-specific strategies necessary to address these disparities. The objective of the publication is to assess the factors underlying the employment choices of the pension-age seniors by statistical region, using both the authors' surveys and secondary statistical data from the EU survey 'EU Statistics on Income and Living Conditions' (EU-SILC) (OSP, 2026). Microdata from the EU-SILC are available for in-depth research in the Republic of Latvia.

Materials and Methods

The study utilized a computer-assisted web interview (CAWI) survey conducted throughout Latvia, creating a representative quota sample from various target groups within the silver generation. In total, 1292 respondents participated in the survey during the period from 10 April to 6 May 2025. The specific publication uses research data obtained from 733 people over working age, i.e., aged 65 and above, from all statistical regions of the Republic of Latvia, by territories (urban and rural), by both genders, proportional to all those categories. In this paper, regional differences are analysed using the chi-square test to answer the research question 'Do the views of individuals over retirement age differ significantly across statistical regions?' The survey was confidential. All data was used only in an aggregated form. The data were weighted by the following characteristics: gender, age, and region (based on data from the Office of Citizenship and Migration Affairs of the Ministry of the Interior of the Republic of Latvia as of January 27, 2025).

Results and Discussion

According to the data of the survey conducted by the authors in 2025, 31% of 733 respondents over the working age (65 years and older) were employed, divided in: 18% doing a full-time job and 13% doing a part-time job. Another 4% of respondents indicated that they worked occasionally, while 66% of respondents were no longer working (Table 1). When assessing the data in the regional breakdown, which is included in Table 1. Data indicate that the largest share of full-time employees was seniors in Riga (21%) and Zemgale (21%), but the least in Vidzeme (12%) and Latgale (15%). The number of part-time employees in Latgale is almost half that of other regions of Latvia, but in comparison with Riga, it is even three times smaller (Table 1).

Table 1

Breakdown of respondents over the working age by employment types and non-employment (%)

Statistical region	Full-time job	Part-time job	Occasional job	Did not work
Riga	21.10	17.30	3.90	57.60
Pieriga	15.60	12.40	5.80	66.20
Vidzeme	11.80	12.40	1.90	73.90
Kurzeme	17.50	11.20	5.40	67.50
Zemgale	20.50	14.30	4.50	60.70
Latgale	14.80	6.10	2.50	77.40
Total	17.60	13.20	3.90	65.60

Source: Author's construction based on Seimuskane et al., 2025 survey, n=733.

Three main groups of factors explaining why seniors continue to work beyond retirement age were highlighted in the survey (Table 2).

These are 1) 'material considerations' (64%), 2) 'interesting, pleasant work' (48%), and 3) social interaction expressed in the answers, such as 'to be with people' (35%) and 'not working is boring' (34%). The working environment and opportunities for self-empowerment, although mentioned less often, are also important factors in seniors' decisions to continue working.

The breakdown of respondents' answers in the regional perspective shows that 'material considerations' are the most important for employed seniors in Latgale (69%), Pieriga (68%), and Riga (66%).

Analysis of responses by regions indicated that there are no statistically significant differences in evaluations by regions, only for the statement 'interesting, pleasant work' (chi-square significance level 0,001) and there are statistically significant differences for all other analysed statements.

When assessing the breakdown of specific answers regarding the sufficiency of income (pensions and other income) to cover all necessary expenses, the regional context of socio-economic differences and/or inequalities is clearly evident. If, on average, 70% of

respondents in all regions and Riga and even more respondents in Pieriga, admit that their income is sufficient and rather sufficient to cover the necessary expenses, then in Latgale, the number of such respondents does not reach even half (49%) (Seimuskane et al., 2025). This only confirms that for seniors living in Latgale, 'material considerations' for the continuation of employment have a completely different weight compared to seniors in other regions of Latvia and 'interesting, pleasant work' is twice as less attractive (29%) compared to 61% of seniors working in Riga. The survey data also reveal that the number of early retirees in Latgale is almost three times higher (28%) than in Riga and Kurzeme (9%). Socialisation aspects such as 'to be with people' and 'not working is boring' are most rarely mentioned as employment-motivating reasons by seniors in Kurzeme (28% and 21%, respectively) and most often by seniors in Riga (39% and 41%). The highest share of responses 'not working is boring' was reported by seniors in both Latgale (42%) and Riga (41%) (Table 2).

Table 2
Breakdown of key factors for the continuation of employment for the population over working age (%)

Statistical region	'Material considerations'	'Interesting, pleasant work'	'To be with people'	'Not working is boring'
Riga	66.40	60.50	38.90	41.10
Pieriga	68.40	45.00	39.60	34.60
Vidzeme	51.30	45.00	34.00	24.50
Kurzeme	64.30	41.20	28.00	20.90
Zemgale	58.60	44.80	30.70	31.80
Latgale	69.10	28.80	33.20	41.50
Total	63.50	47.80	34.90	34.00

Source: Author's construction based on Seimuskane et al., 2025 survey, n=733.

The three main reasons why respondents over working age no longer work are listed in Table 3. These are: 1) 'health considerations, inability to withstand workload' (49%); 2) 'desire to focus on work at home, in the garden' (23%); 3) 'there is no suitable work in the area for a person of my age' (18%), and 'there are few jobs in the area at all' (12%). Health considerations are cited by seniors across all regions of Latvia as the main reason for leaving work. At the same time, survey data show distinct regional differences in other factors affecting their decision to terminate work. A wish to focus on work at home or gardening is mentioned more often in regions with a higher share of rural territory, such as Zemgale (37%), Pieriga, and Kurzeme (30%).

Table 3
Breakdown of the key factors influencing the decision of the population over the working age not to work anymore (%)

Statistical region	'Health considerations, inability to withstand the workload'	'The desire to focus on work at home, in the garden'	'There is no suitable work in the area for a person of my age'	'There are few jobs in the area at all'
Riga	50.70	14.60	9.60	1.50
Pieriga	59.30	29.80	17.70	4.50
Vidzeme	46.90	22.60	18.50	14.40
Kurzeme	47.90	29.70	10.00	12.10
Zemgale	47.60	36.60	38.10	27.80
Latgale	46.30	21.50	30.80	23.60
Total	49.30	22.80	18.10	12.00

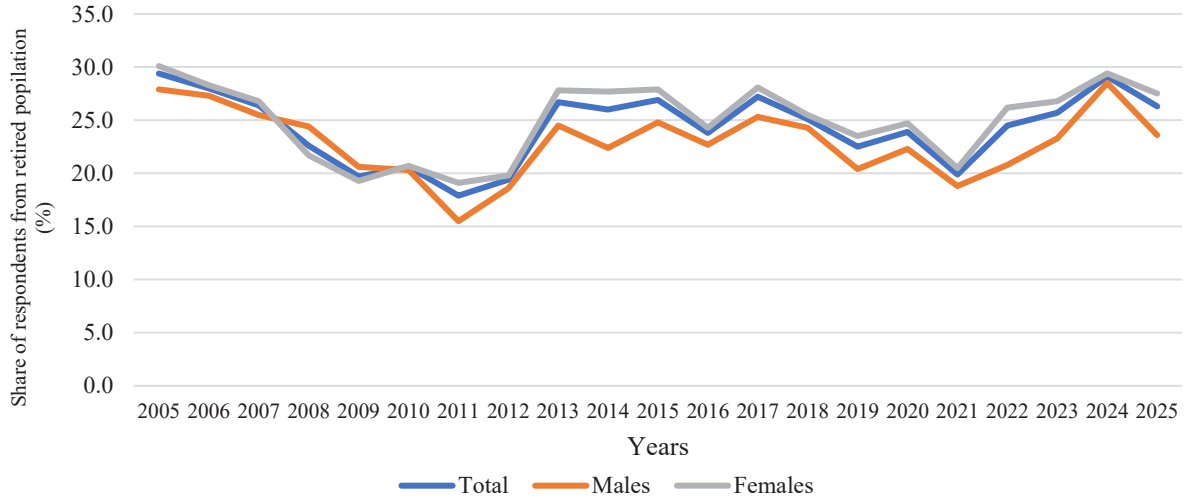
Source: Author's construction based on Seimuskane et al., 2025 survey, n=733.

Regional differences in labour market availability are particularly significant. Results show that the lack of suitable workplaces for the specific age group and the total shortage of workplaces are more evident in Zemgale and Latgale regions. In Zemgale, 38% of respondents indicate that there is no available reasonable and acceptable work for persons in the respective age group, while 28% emphasize that there are few jobs in the area at all. A similar situation is also observed in Latgale, where the respective indicators are 31% and 24%. This, in turn, proves structural inequalities of regional development and employment opportunities. It is the opposite in Riga, with these factors being significantly less marked (10% and 2% respectively), which confirms broader employment opportunities and availability.

Health problems often impose severe restrictions on activities for retired persons in Latvia. Analysis of survey data indicated that there are statistically significant differences in evaluations of those analysed aspects by all statistical regions. Data on limitations with severe restrictions of activities due to health problems for retired persons by gender in Latvia from 2005 to 2025, based on EU-SILC survey data (survey data are collected in representative surveys in all EU and EU candidate countries and data could be compared and used in analysis), are included in Figure 1.

Figure 1

Health problems that have severe restrictions for limited home, work and leisure activities for at least 6 months for retired persons by sex in 2005–2025 in Latvia



Source: Author's construction based on OSP database IVP031 data.

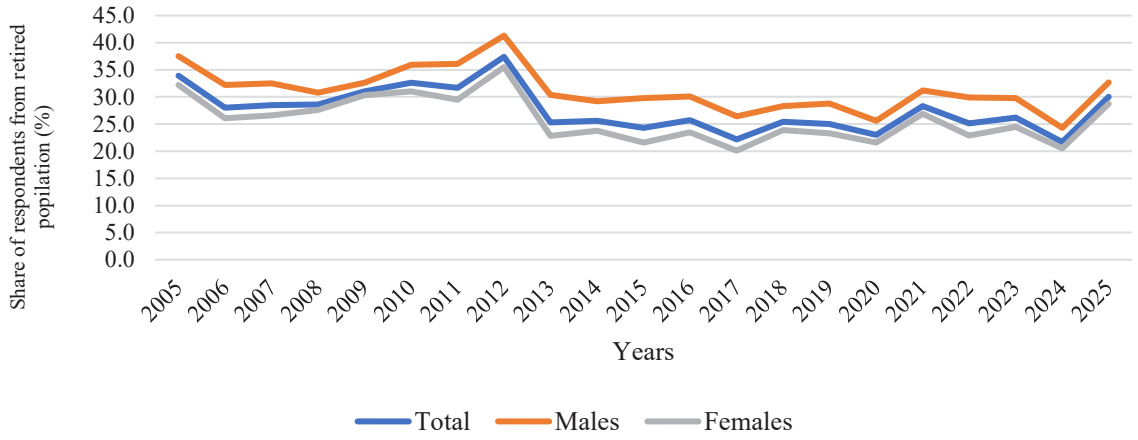
Data indicate that the severe restrictions due to the health problems that have limited home, work and leisure activities for at least 6 months for retired persons by sex in 2005–2025 in Latvia tend to increase during the last several years, with a bigger share for retired female persons in Latvia. Retired male persons since 2010 have shown fewer problems with severe restrictions due to the health problems that have limited home, work and leisure activities for at least 6 months. Trends of male and female respondents do not show statistically significant changes during the analysed period. Another question is on self-evaluations that do not have any restrictions due to health problems. Tendencies of self-evaluations by retired persons on no restrictions due to the health problems that have limited home, work and leisure activities for at least 6 months for retired persons by sex in 2005 – 2025 in Latvia are included in Figure 2.
Data indicate that male retired persons in Latvia are more optimistic about no limitations due to the health problems that have limited home, work and leisure activities for at least 6 months in 2005-2025, although it is decreasing during the analysed period.

Conclusions

1. Demographic ageing in Latvia is a structural and long-term phenomenon that is significantly altering the age structure of the population and placing a growing demographic burden on the working-age population. In regions with a higher proportion of older people (particularly in Latgale), lower GDP per capita, a higher risk of poverty, and greater dependence on social transfers are simultaneously observed. This points to structural disparities in regional development that cannot be explained solely by demographics, but also by a combination of socioeconomic factors.
2. Choice of pension-age seniors to continue work is mainly determined by material considerations; however, non-material factors, social interaction and self-empowerment opportunities, are also important. Thus, the employment of seniors is reasoned by financial, social, and emotional factors.
3. Research results confirm that nearly two-thirds of the pension-age seniors continue working mainly due to material considerations. Furthermore, these considerations are mentioned as the most significant by employed seniors in different regions of Latvia, regardless of significant demographic and socio-economic differences. However, each senior has their own motivation behind material considerations. One group of seniors, who are in a more favourable financial situation, work to achieve life satisfaction, supplement their income, and maintain social relationships. For the other group of seniors, financial considerations are driven by the necessity to work to avoid the risk of poverty.
4. Social interaction plays a crucial role in the employment of pension-age seniors, both at an individual level and within society. A working environment provides an opportunity to maintain social contacts and improve emotional well-being.

Figure 2

Health problems that have no restrictions for limited home, work and leisure activities for at least 6 months for retired persons by sex in 2005 – 2025 in Latvia



Source: Author's construction based on OSP database IVP031 data.

5. Participation of pension-age seniors in the labour market is not only affected by individual factors, such as health conditions or other choices for the termination of labour relations (a wish to focus on work at home or in the garden), but also by structural challenges of the Latvian labour market and regional differences. In economically better-developed centres, seniors have greater opportunities to keep their employment, while labour market limitations and a lack of workplaces suitable for their age in remote regions facilitate early termination of labour activities.

6. Limitations for the employment of retired persons due to health problems during the last decades are similar to better self-evaluations for male persons in Latvia.

7. Projected demographic trends point to the urgent need for the state to develop specific policies, including in the area of the silver economy, which integrates both national and region-specific approaches, taking into account that the views of people are different by statistical regions of Latvia.

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THE ROLE OF SOCIAL ENTERPRISES IN BUILDING SOCIAL CAPITAL IN THE EDUCATION SECTOR IN ZEMGALE

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Abstract
Social enterprises are important drivers of social capital. They develop initiatives that create employment, address community problems, and restore peace and socio-economic development. The research aims to examine the role of social enterprises in building social capital in the Zemgale region. Therefore, the research analyses social enterprises in the education sector in the Zemgale region and stakeholders involved in operating them. The research developed a conceptual model based on social capital theory and explains the role of social enterprises in building social capital. This theoretical model was tested in practice through a case study of social enterprises in the education sector. As part of the case study, a focus group discussion was conducted. The authors' conceptual model includes the structural, cognitive, and relational dimensions of social capital in the context of social enterprise. The research found that schools, NGOs, specialists, local governments, and entrepreneurs are in a single ecosystem. Families, educators, and volunteers are also important resources; as a result, new cooperation opportunities and forms are created: joint projects, events, training, etc. As a result, the cognitive dimension is strengthened, thus shaping a common understanding of inclusive education, its implementation, and importance. However, the relational dimension is manifested in the cohesion of the Zemgale region community. Social integration improves by promoting cooperation and mutual trust with various stakeholders. At the regional and national levels, however, a change in mentality is promoted, and children with learning difficulties are full members of society, yet they need an appropriate learning environment and approach.
Keywords: social enterprises, social capital, inclusive education, social entrepreneurship.

Introduction

The number of research studies on social enterprises (Aliaga-Isla & Huybrechts, 2018) and social capital (OECD, 2001; Gayen et al., 2019; Hidalgo et al., 2021; Loukopoulos et al., 2024) has grown substantially over the last few decades. In recent years, social capital has gained significant prominence in global discourse surrounding local development, social exclusion and social economy. Defined by the European Union (European Commission, 2005) as the structural elements – such as networks, norms and trust – that enable mutually beneficial cooperation, social capital is increasingly viewed as a vital tool for restoring social cohesion. This is particularly evident in its capacity to strengthen local networks and bolster social enterprises dedicated to integrating marginalized individuals into the labor market. Furthermore, scholars maintain that social economy entities, particularly social enterprises, serve as primary catalysts for social capital formation. This is achieved through their development of strategic initiatives aimed at fostering employment and bolstering social solidarity (Madhooshi & Samimi, 2015). Some research studies have found a correlation between social capital and community outcomes, including the reduction of systemic problems and the facilitation of both social harmony and economic progress (Krishna et al., 1997), enhancement of production, innovation (Fletcher et al., 2026), and entrepreneurial characteristics (Damirchi et al., 2011; Doh & Zolnik, 2011). It is empirically proved that integrating social capital into entrepreneurial activities enhances social intelligence and expands the range of viable livelihood strategies, thereby improving overall community well-being (Osei & Zhuang, 2020). Scientific literature affirms that extensive evidence underscores the pivotal role of social capital in driving socioeconomic progress and enhancing livelihood development (Müller, 2007; Mahato & Kumar, 2023). Besides, social capital is widely recognized as a collective resource that fosters connectivity among citizens, thereby empowering them to achieve shared objectives with greater efficiency.

Although there are many research studies on social capital and social enterprises, their mutual relationship has been little researched, especially in the Latvian context. In Latvia, Bela & Mieriņa (2022) have conducted research about social capital as a key concept to explain how personal networks, trust, and reputational ties between diaspora members and Latvian institutions support economic and social development, including in the education and research sectors. Furthermore, Latvian sociologists (e.g., Šķilteris, Vasiļjeva, and others) have analyzed social capital characteristics in Latvian society, distinguishing between bonding, bridging, and linking forms, and using survey data to map trust, civic participation, and network structures (Sechi et al., 2022, 2023). Several studies on social entrepreneurship (Licite-Kurbe & Groma, 2021; Gintere & Licite-Kurbe, 2022) in Latvia have been conducted; however, no research has linked social capital to social entrepreneurship. Therefore, the research aims to examine the role of social enterprises in building social capital in the Zemgale region. Given the fact that the majority of social enterprises in Latvia operate in the education sector (23%) (Ministry of Welfare, 31/01/2026), the research analyses social enterprises operating in this field. In addition, the activities of social enterprises in the education sector closely relate to several Sustainable Development Goals, as the enterprises simultaneously create social impact, promote inclusion, and strengthen social capital, which is one of the prerequisites for a sustainable society.

Materials and Methods

The research developed a conceptual model based on social capital theory and explains the role of social enterprises in building social capital. The theoretical model has been tested in practice by performing a case study analysis of two social enterprises that operate in the education sector in the Zemgale region: 'Sajūtu māja' Ltd, which has established a private school 'PATS' (provides inclusive education for years 1-6 and meaningful time spent after school and during breaks), and 'Barboleta' Ltd, which has created an innovative method that creates a movement-based learning environment. The choice of a case study was made based on several criteria: the organization should operate in the education sector in the Zemgale region, must contain an innovation element in solving a problem, work with different target groups, and provide inclusive education. As part of the case study, the company operations were examined, as well as semi-structured interviews with company representatives ('Barboleta' – 'Ex1', 'PATS' – 'Ex2') were conducted to identify how the company operations contribute to the formation of social capital. In addition, a focus group discussion was conducted, in which various stakeholders participated: a social entrepreneur ('Ex1'), a teacher ('Ex3') who works in a social enterprise with children with learning difficulties, two parents ('Ex4' and 'Ex5') whose children attended an alternative educational institution (social enterprise), as well as a social entrepreneurship ambassador in the Zemgale region ('Ex6'). The purpose of the focus group was to gain an in-depth understanding of the importance of social entrepreneurship in the formation of social capital and its social impact in the region. The interviews were conducted in January and February 2026, while the focus group was organized on 10 February 2026 (lasted for 1 hour and 53 minutes). The qualitative data from the interviews and focus group were analyzed using thematic analysis to identify how these enterprises contribute to social capital.

Results and Discussion

Social enterprises in the education sector in Latvia

In Latvia, almost a quarter of social enterprises operate in the education sector, including 19 private educational institutions – schools that implement an important social mission and provide significant intangible benefits. They are often founded by parents or professionals in the field who have not been able to receive what they need from the current education system. Such schools are a refuge, a safe learning environment, and an opportunity to receive education for children with special needs, learning disabilities, as well as children who have encountered bullying in traditional schools or have not been able to fit in for some other reason. Often, they are children with physical or intellectual disabilities, children with individual needs, and children who have left general education schools because the infrastructure there was not adapted to their needs, or they have suffered violence, and the classes were too large for teachers to be able to pay enough attention to them. These are also children with learning difficulties, autism, behavioural disorders, social risks, or other special needs. Social enterprises in the field of education are an important state partner in ensuring inclusive education, providing support to those children and families whose needs the traditional education system cannot meet.

In practice, it can be found that traditional schools often struggle to create an equitable and participatory environment (Cerna et al., 2021) for different reasons. However, the recognition and valuation of every learner is fundamental (Ainscow, 2020). This commitment is anchored in the Sustainable Development Goals, which advocate for inclusive and equitable quality education as a global priority. Research by Giorgi et al. (2026) suggests that such inclusivity transcends support for students with additional needs, yielding enhanced learning outcomes for the entire school community. Inclusive practice is predicated on embracing student individuality, necessitating a pedagogical shift toward personalized learning and the strategic development of individual education programmes tailored to specific student requirements (Lopatynska et al., 2023). Social enterprises are very often born out of a need to address educational disparities and to foster inclusive learning environments. Moreover, social enterprises possess significant transformative potential for the educational sector, offering innovative pathways to engage both educators and students. By fostering social capital among learners from diverse backgrounds and age groups, these entities bridge the gap between academic and entrepreneurial spheres, enabling a shared discourse between teachers and practitioners. The role of social enterprises within school systems remain a notably under-researched phenomenon in current literature.

Theoretical aspects of social capital

Social capital emerged as a sociological framework to describe the utilization of interpersonal relationships. By leveraging ties within communities, friendships, and professional or family circles, individuals are able to cultivate both social resources and economic value (Burt, 1997). Arranz et al. (2022) describes social capital as the collective resources derived from a network of social relationships. This framework extends beyond the availability of social assets to include their instrumental role in shaping human capital, optimizing corporate outcome (Arranz et al., 2020), and fostering the socio-economic advancement of entire regions and nations (Müller, 2007; Iyer et al., 2005), among others. It can be concluded that social capital is derived from the founder's personal and professional network (Bornstein, 2004). As Bornstein (2004) emphasizes, these networks are foundational to the social entrepreneurship process, underscoring the intrinsic value of social connectivity. Much like physical capital or human capital enhances efficiency,

social contacts significantly augment the productivity of both individuals and collectives. The research integrates findings from the works by Bourdieu (1986), Coleman (1990), and Putnam (2000) to create a conceptual model that explains how social enterprises can create social capital and social value in education.

The researches show that social capital can be created at the level of the individual, organization, network, community, or society. The present research study focuses on the social capital of social entrepreneurs at the individual level. Lin (2001) divides social assets into two categories: personal and social resources. According to his perspective, social resources are inherently embedded within an individual's interpersonal network and are activated solely through social interaction. Based on this, Lin's social capital theory defines social capital as resources residing within social networks that possess the potential to generate tangible returns.

Generally, researchers categorize individual social capital into three dimensions: structural, relational, and cognitive (Paunescu & Badea, 2014). This research's conceptual model contributes to the creation of social value in education.

Structural social capital refers to the formal and informal patterns of connectivity within a system. This dimension evaluates the strength of ties and the ability of social entrepreneurs to navigate interconnections with various actors (local government, NGOs, community, etc.). These relational configurations vary significantly based on their network topology, including the distinction between bonding and bridging social capital. The main structural determinants include network size, density, and the presence of structural hole, alongside the nature of the ties (strong or weak). Besides, the positioning of an actors within the network, their geographical dispersion, and their propensity for civic engagement fundamentally shape the network's overall efficacy.

The cognitive dimension encompasses resources that facilitate shared representations, interpretations, and systems of meaning, attitudes, beliefs, norms, and values among actors. Based on this conceptualization, cognitive capital can be operationalized through key indicators: the commitment to collaborate in new projects, free exchange and diffusion of knowledge, prompt entrepreneurial culture among one's social network. Thus, the cognitive dimension directly contributes to the foundational knowledge base required for future entrepreneurial ventures. It can be said that cognitive capital creates a common language (mission, vision), an understanding of why they cooperate with each other and what they want to achieve, and a coherence of culture and goals. The participants perceive the world in a similar way, share similar values, or believe in similar goals.

The relational dimension of social capital emphasizes the dyadic level, which is considered to be the personal relationships that social entrepreneurs have developed with others (Arranz et al., 2020). It refers to the characteristics and qualities of personal relationships formed over time, focusing on behavioural connections among individuals rather than just structure (Letnar & Sirok, 2025). Consequently, the relational dimension emphasizes the qualitative nature of social ties, characterized by interpersonal trust, shared identities, and a sense of solidarity that facilitates resource acquisition. It can be concluded that trust constitutes the most critical element of this dimension for long-term organizational viability. It yields positive externalities for all stakeholders, including local government, community, employees, families, etc. (Paunescu & Badea, 2014). Relational capital creates long-lasting, trusting relationships, a willingness to help others, even when there is no direct benefit, community cohesion, and emotional security.

The generation of social capital and social benefits is the core mission of social enterprises. By intersecting entrepreneurial principles with social change and innovation, these entities empower communities to build social capital, thus enhancing their capacity for socio-economic self-sufficiency and resilience. As a result, there is created social value in education – social, economic, and environmental – well-being, reflecting the full range of benefits generated by effective education and skills provision (Education and Training Foundation, 2024). Social value in education may be seen at the individual, community, and wider society levels. The conceptual model for the creation of social capital created by social enterprises is presented in Figure 1.

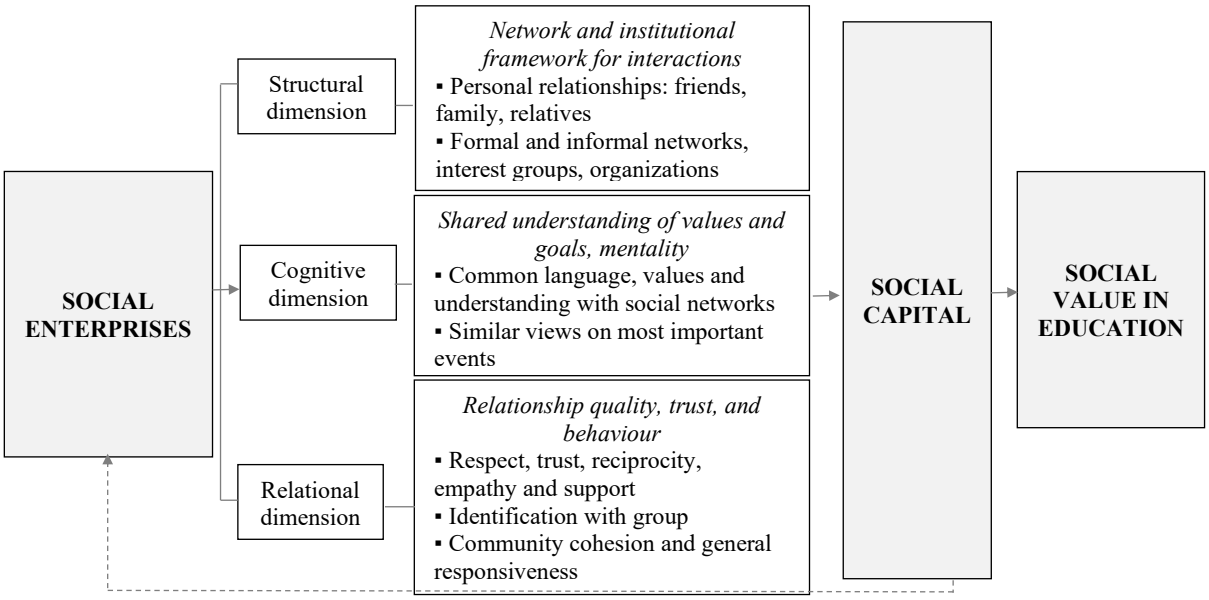
Characteristics of social capital created by social enterprises in the education sector in Zemgale

Inclusive education in Latvia is a challenge that becomes a reason for the establishment of alternative schools. In the Zemgale region, the implementation of inclusive education in practice (at traditional educational institutions) is most often limited by factors such as the availability of specialists with a low workload (speech therapists, special educators, psychologists) and large classes. The need for much greater individual support is evidenced by the fact that the number of children receiving education according to specialized curricula tends to increase every year. According to data from the State Education Information System as of 1 September 2025, 12994 students received education in special education programmes, which was 4% more compared with the previous school year. A gap increases between the needs and system capacity, which also creates a ground for the establishment of social enterprises in education (including alternative schools and learning support initiatives), as they can organize support more flexibly, integrate several approaches simultaneously, and mobilize local resources.

In practice, social enterprises create both services and social capital, which is important because inclusive education is both a set of applied educational methods and a system of relationships, norms, and cooperation.

The following study (case study and focus group discussion) reveals how social enterprises in Zemgale practically create social capital.

Figure 1
Conceptual model of social capital creation by social enterprises in education



Source: made by authors.

Structural dimension

The case study found that social enterprises in the Zemgale region actively cooperated with various stakeholders: non-governmental organizations, medical institutions (medical practices, hospitals), various specialists (speech therapists, educational development specialists, special and social pedagogues, psychologists, etc.), local governments, companies, business incubators, and educational institutions. The social enterprise 'Barboleta' connects schools, families, NGOs, specialists, medical workers, local government, and entrepreneurs in one ecosystem. The primary school 'PATS' also follows a similar operating principle, thereby forming an active community in which families, volunteers, local government, and other stakeholders work together. As the social entrepreneur ('Ex1') pointed out in the interview, cooperation was mainly established 'by word of mouth'. It could be said that new cooperation arises based on the results of social entrepreneurs' activities that have been tested in practice, their stories at public events, in the mass media, and in individual conversations and consultations, as a result of which new opportunities and forms of cooperation emerge. Often, people get information about the activities of a social enterprise from recommendations.

Because of cooperation, financial resources are attracted from the municipality and entrepreneurs, which promotes a higher-quality educational process not only in the social enterprise. Often, this type of support is used to introduce the teaching methodology developed by the social enterprise into traditional educational institutions. In addition, by sharing experience stories, parents see the potential in such educational institutions to educate their children who cannot be integrated into a traditional educational institution.

In recent years, social entrepreneurs have taken the initiative to involve entrepreneurs in discussions about the quality of education and educational needs, as their companies are the future workplaces of students. Such a pattern – creating a dialogue between the school that creates the content, the parents, and the company – generates high value added for adapting education to real needs.

The social enterprise 'PATS' also cooperates with a business incubator and the municipality. For example, in cooperation with the municipality, it has obtained premises for free use, which is allowed by the exemptions for social enterprises specified in the Social Enterprise Law.

Overall, social entrepreneurs indicate that cooperation with various institutions and organizations provides both practical support and access to a wider environment, and promotes 'systemic power'. Because of interaction, knowledge and experience sharing occur, which contributes to the company (products, services) and improves the social impact measurement system.

It could be concluded that because of cooperation, ties between different stakeholders are strengthened in both material and non-material forms. In addition, inclusive education is promoted not only within the social enterprise itself, but the sustainability of the education system is strengthened, and inclusive education projects are implemented outside it as well.

As indicated by a social entrepreneur ('Ex2'), cooperation takes place not only with external stakeholders but also with internal ones: parents, friends, and relatives of children, thus promoting community development.

However, a challenge to cooperation is often limited resources, as social enterprises in Latvia are small, and one person performs several functions at the same time, which results in limited capacity and potential for increasing cooperation opportunities.

Regarding information flow, the social entrepreneurs indicated that they could communicate more rapidly, determining where to send resources, what actions to take, what support to utilize, how to coordinate actions without bureaucratic obstacles. Consequently, a social entrepreneur can more easily attract resources (funding, premises, volunteers, equipment, transport, etc.).

Cognitive dimension

This dimension is implemented in various ways, for example, by organizing training for educators on various methods suitable for children with learning difficulties. Consequently, this fosters a shared perspective on the essence of inclusive education and its practical implementation. Social enterprises also create educational videos, posts on social networks, and on the website.

Additionally, various joint events are often held with the children's parents, which promote understanding of common goals and norms of behaviour. As a parent of one child ('Ex5') noted, there were meetings, joint meetings, festive events, excursions, theatre visits, charity fairs, and other joint events that promoted mutual trust, learning of common values, and cooperation. Being aware of common goals also promotes collective action.

Social entrepreneurs actively involve volunteers, who not only help to implement the goals of the social enterprise but also learn its values. By sharing their experience, social entrepreneurs highlight the challenges of inclusive education, thus creating a more unified understanding of its necessity and forms of solution. It could be concluded that social enterprises foster a shared understanding among parents, teachers, and specialists regarding the definition, implementation, and evaluation of inclusive practices.

Relational dimension

Social enterprises play a significant role in the relational dimension, as they involve teachers, parents, specialists, and local government representatives in their activities, thus creating interaction and horizontal relationships between different community groups. As a result, emotional bonds are strengthened and stigma against children with learning difficulties is reduced, thereby creating an environment in which cooperation is an essential prerequisite. In the focus group, a teacher ('Ex3') and also a parent of a child ('Ex4') indicated that they did not perceive themselves only as service providers or recipients, but that an educational institution was like one family, where shared values and the well-being of children are important. To implement this, the educational institution listens to, accepts the parents' opinions and seeks immediate solutions to problems.

The focus group emphasized that such a pattern of cooperation also reduced isolation and shame among parents and teachers, normalized difficulties ('we are not alone'), and contributed to mutual help between parents and teachers. This increased the child's sense of belonging and emotional security, which was a prerequisite for learning progress.

Mutual trust and support are demonstrated by people's actions. For example, traditional schools and specialists often invite social entrepreneurs to repeatedly share their experience, which results in long-term relationships. Teachers who have undergone training in the social enterprise 'Barboleta' also continued to communicate, exchange ideas and materials, and supported each other.

The active involvement of parents in school improvement initiatives, such as renovations, and relocations, provides evidence of stable, lasting relationships. As the child's parent ('Ex5') pointed out in the focus group, a sense of community, security, and very good cooperation between students, families, and teachers had developed, which allowed them to feel like 'an important part of the school community'.

It could be concluded that the mission of a social enterprise is not just a company's 'slogan', but a common goal for all stakeholders, which results in emotional bonds and trust among the stakeholders, but also in stronger social cohesion and understanding in the region that inclusive education is essential on a wider scale. The social entrepreneur ('Ex1') pointed out that 'sustainable relationships' are formed from a shared meaning. We consciously create a common understanding that a child's behaviour is a matter of skills that need to be trained. And the second is regularity – the community has a 'rhythm' where people return, receive support, and are not left alone in their daily lives' (Table 1).

It could be concluded that a social enterprise creates social capital, which in turn generates social value in the region in the education sector. This was confirmed by the results of the activities of the social enterprises – by promoting cooperation and mutual trust, students' learning outcomes improved. 'Barboleta' has found that one trained specialist provided support to at least 15 children per year, which was the minimum number of beneficiaries, yet in practice, there were even more. However, children's behaviour is positively influenced by creating common values and norms. They feel accepted, discrimination decreases, and social integration improves. At the regional and national levels, it is advocated that children with learning difficulties are not lazy or disobedient; they just lack skills, which in turn could be built up. This creates significant positive changes in children's everyday lives, but in the community, people are less left alone with their difficulties and encourage each other, share solutions, and cooperate with each other.

Table 1

Comparison of the social capital dimensions in the context of social enterprises in the education sector in Zemgale

Dimension	Main elements	Manifestation in the field of education for social enterprises	Results/benefits
Structural	▪ Cooperation networks, partnerships with different stakeholders ▪ Information flow	▪ Social enterprises cooperate with schools, municipalities, NGOs, companies, and medical institutions. Parents, volunteers, and the local community of children are also an important resource. ▪ Forms of cooperation – projects, discussions (seminars), trainings, infrastructure support	▪ Larger flow of information (visibility) and the formation of new partnerships ▪ Attraction of financial resources ▪ Premises for gratuitous use ▪ Raising the issue of inclusive education in society ▪ Community connectivity ▪ Resilience of the education system
Cognitive	▪ Common values and norms ▪ Common language ▪ Unified sense of mission ▪ Building a shared vision	Social enterprises: ▪ implement training for educators, ▪ hold events for families, ▪ publish educational videos, posts on social networks, and websites	Common understanding between parents, teachers, and professionals: what inclusion means, how to implement it, and how to measure progress.
Relational	▪ Trust ▪ Reciprocity ▪ Loyalty ▪ Empathy and support	▪ After the training, the participants maintain communication, share materials, experiences and support each other ▪ Parents voluntarily engage in school improvement work ▪ Traditional schools repeatedly invite social entrepreneurs to share their experience	▪ Long-term stable relationships with various stakeholders ▪ Sense of community and unity among the parents of children, - educators ▪ Community cohesion

Source: made by authors.

Conclusions

1. The research proposes a conceptual framework that leverages social capital theory to examine the role of social enterprises in fostering social capital, specifically focusing on structural, cognitive and relational facets. The theoretical model has been tested in practice by performing a case study of two social enterprises that operated in the education sector in the Zemgale region: 'Sajūtu māja' Ltd, which had established a private primary school 'PATS', and 'Barboleta' Ltd. For an in-depth study of the situation, a focus group discussion was conducted with experts from the respective field.
2. The study indicates that two specific social enterprises in the Zemgale region have considerable potential in the education sector, as there are limited opportunities for implementing inclusive education, and the country is also experiencing a growing need for more individual support for children with learning difficulties and behavioural disorders. However, because the findings are based on only these two organizations, the results cannot be generalized to the role of social enterprises in education or social capital-building more broadly.
3. The case study found that the structural dimension was manifested as the ability of analyzed social enterprises in the Zemgale region to connect schools, NGOs, specialists, medical professionals, local governments, and entrepreneurs in one ecosystem. Families, educators, and volunteers are also important resources for implementing cooperation, which results in new opportunities and forms of cooperation: joint projects, events, training, and infrastructure development opportunities.
4. The cognitive dimension is implemented by providing training for educators, holding events for families, publishing information materials about inclusive education in the public environment. As a result, a common understanding is formed among parents, teachers, specialists, and the wider community about inclusive education and its implementation and importance.
5. The relational dimension can be found in the cohesion of the Zemgale region community, which is manifested in the voluntary involvement of parents in school events and improvement works, and in the willingness of teachers to learn repeatedly from social entrepreneurs. Overall, the research analyzed two social enterprises in the region that promoted trust and support among teachers, parents, and children, thereby fostering a more cohesive local community.
6. The research aim has been achieved. Social enterprises play a significant role in building social capital in the Zemgale region because student learning outcomes improve, and children's behaviour is positively influenced when promoting cooperation and mutual trust with various stakeholders. Discrimination decreases, and social integration improves. At the regional and national levels, it is advocated that children with learning difficulties are not lazy or disobedient; they just lack skills, which in turn could be built up in an appropriate environment and with appropriate methods. For policymakers and practitioners, this suggests that social enterprises

should be recognized and supported as strategic partners in implementing inclusive education at the regional and national levels.

7. The findings of this study are subject to certain limitations, primarily because the theoretical model was tested on a limited sample of two social enterprises within the Zemgale region. Consequently, the results may not be fully generalizable to the broader socio-economic landscape. To address these constraints, future research could test the proposed model in other regions and with mixed methods (e.g., incorporating quantitative research methods to provide statistically significant analysis of the impact and growth of social capital within the sector) to assess the scale and dynamics of social capital created by social enterprises over time.

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A SYSTEMIC MODEL OF TECHNOLOGY TRANSFER AND COMMERCIALISATION IN LATVIAN SCIENTIFIC INSTITUTIONS

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Abstract
The study addresses the fragmentation and linearity of technology transfer and innovation commercialisation processes in scientific institutions, which limit the contribution of research to regional development and competitiveness in small and medium-capacity national innovation ecosystems. The aim of the study is to refine a systemic approach to the governance and development of technology transfer and innovation commercialisation processes in Latvian scientific institutions, drawing on innovation ecosystem theory, international best practices, and an assessment of the current situation. The study conceptualizes technology transfer as a non-linear, digitally enabled, and institutionally embedded system, whose effectiveness depends on interactions among universities, industry, public authorities, and society. The empirical analysis applies qualitative institutional analysis and comparative assessment of technology transfer practices in Latvian scientific institutions. The results reveal structural challenges, including insufficient institutional capacity, fragmented policy frameworks, weak absorptive capacity in industry, and limited use of digital tools, while identifying untapped potential for strengthening knowledge commercialisation. The main outcome of the study is the refinement of a systemic approach integrating technological readiness, intellectual property management, market validation, capital mobilization, institutional culture, and digital tools within an adaptive framework. The proposed approach provides a practical instrument for scientific institutions and policymakers, supporting knowledge-based regional competitiveness, innovation-driven bioeconomy development, and societal resilience in rural and regional contexts.
Keywords: technology transfer, innovation commercialisation, regional innovation systems, university-industry collaboration.

Introduction

Technology transfer has become one of the central mechanisms through which universities and research organisations translate scientific knowledge into economic and societal value, yet its conceptualisation remains fragmented and its empirical performance varies substantially across institutional contexts (Bradley et al., 2013; Braslina et al., 2015; Siegel et al., 2003). This challenge is particularly visible in smaller and emerging innovation systems, where scientific institutions often play a dual role as both knowledge producers and regional development actors within broader territorial and rural innovation ecosystems (Braslina et al., 2021; Kebede & Mulder, 2008; McAdam et al., 2017). In such contexts, technology transfer outcomes cannot be explained solely by the internal efficiency of technology transfer offices (TTOs), because they depend equally on institutional capacity, the surrounding innovation environment, and the quality of university–industry interaction (Bejarano et al., 2023; Waroonkun & Stewart, 2008). Consequently, understanding the architecture of technology transfer processes has become a key analytical question for innovation policy, particularly in systems where universities are expected to contribute directly to regional competitiveness and socio-economic development (Markman et al., 2005; Siegel et al., 2003).

The literature on technology transfer process modelling has evolved around several dominant conceptual logics that reflect different interpretations of how knowledge moves from research to application (Hilkevics S. & Hilkevics A., 2017; Salkovska et al., 2019). The historically most influential approach is the linear stage model, which conceptualises technology transfer as a sequential chain progressing from discovery and disclosure through intellectual property protection and licensing to market implementation (Bradley et al., 2013; Harmon et al., 1997). This architecture remains institutionally attractive because it provides a simplified and easily operationalised framework that can be translated into administrative procedures and measurable indicators such as invention disclosures, patents, licences and licensing revenues (Bradley et al., 2013; Siegel et al., 2003). However, empirical studies consistently demonstrate that real-world technology transfer rarely follows such a strictly sequential trajectory, as commercialisation often emerges through informal networks, collaborative research relationships and pre-existing ties between scientists and firms rather than through formal technology search and acquisition mechanisms alone (Harmon et al., 1997; Rocha et al., 2022). As a result, the linear model tends to overemphasise the role of patents while underestimating organisational incentives, institutional culture, relational mechanisms and market timing in shaping successful innovation outcomes (Bradley et al., 2013; Markman et al., 2005).

A second major stream of research conceptualises technology transfer as an iterative and feedback-driven process rather than a one-directional sequence of stages (Bradley et al., 2013; Kruachottikul et al., 2023). Within this perspective, progress is not defined by the completion of formal procedural steps but by the gradual reduction of uncertainty through repeated validation against market signals, technological feasibility and implementation constraints (Drivas et al., 2018; Kruachottikul et al., 2023). Decision gates

therefore become central analytical nodes, determining whether a project should proceed, pivot or terminate based on emerging evidence rather than predetermined administrative milestones (Kruachottikul et al., 2023). Empirical research further shows that signals from potential users, investors or industry partners frequently appear before the formal completion of intellectual property processes and may require organisations to reconsider both technological configuration and commercialisation pathways (Bradley et al., 2013; Drivas et al., 2018). From this perspective, technology transfer can be understood as an organisational learning system in which the ability to adapt strategies and reconfigure institutional routines becomes a key determinant of performance (Choi, 2009).

A third line of scholarship frames technology transfer as an ecosystemic or networked phenomenon embedded within a broader multi-actor innovation environment involving firms, intermediaries, investors and public institutions (Bejarano et al., 2023; Schoen et al., 2014). In this view, knowledge transfer occurs through multiple parallel channels–including collaborative research projects, consulting, mobility of researchers, incubators, science parks and informal knowledge exchange – rather than exclusively through patent licensing (Harmon et al., 1997; Waroonkun & Stewart, 2008). Consequently, the performance of university technology transfer systems is shaped not only by internal administrative procedures but also by network structure, institutional context and the absorptive capacity of external partners (Bejarano et al., 2023; Kebede & Mulder, 2008). This perspective also broadens the definition of successful transfer outcomes, emphasising long-term collaboration, innovation adoption, private investment mobilisation and regional spillovers alongside traditional intellectual property indicators (Markman et al., 2005).

More recent contributions increasingly converge on hybrid models that integrate formal intellectual property management with informal relational mechanisms and co-creation dynamics (Bradley et al., 2013; Rocha et al., 2022). These models recognise that university technology transfer typically unfolds through two parallel trajectories: a formal trajectory involving disclosure, evaluation and legal protection of intellectual property, and an informal trajectory based on collaboration, tacit knowledge exchange and market interaction (Bradley et al., 2013; Drivas et al., 2018). The analytical strength of hybrid models lies in their ability to explain why transfer systems may appear institutionally well designed yet remain practically ineffective when legal structures are not complemented by organisational flexibility, relational capacity and entrepreneurial competence (Choi, 2009; Siegel et al., 2003). Hybrid approaches also capture the structural tension observed in many universities between the traditional patent – licence model and newer co-creation approaches involving industry and end-users, which often coexist and generate institutional disequilibrium rather than a linear transition from one regime to another (McAdam et al., 2017).

Taken together, the literature suggests that the primary limitation of existing technology transfer research is not the absence of conceptual models but the persistent fragmentation of these models across stages, actors, instruments and performance indicators (Bejarano et al., 2023; Bradley et al., 2013). Many studies focus on individual components of the transfer process – such as intellectual property instruments, organisational structures or collaboration mechanisms – while fewer offer an integrated analytical architecture linking institutional conditions, decision points, coordination mechanisms and performance outcomes within a single systemic framework (Markman et al., 2005; Siegel et al., 2003). This limitation is particularly relevant for smaller innovation systems, where technology transfer performance depends strongly on contextual conditions such as industry structure, investment availability and regional network maturity (Kebede & Mulder, 2008). Addressing this gap therefore requires the development of a systemic model of technology transfer capable of integrating procedural, institutional, organisational and contextual dimensions in a way that is both analytically coherent and empirically applicable to the case of Latvian scientific institutions (Bejarano et al., 2023; McAdam et al., 2017).

Despite the extensive literature on university technology transfer, existing models remain fragmented across procedural stages, institutional arrangements and collaboration mechanisms, providing limited explanatory power for how transfer systems actually generate innovation outcomes; this study addresses this gap by developing and empirically grounding a systemic model that integrates process architecture, organisational capabilities and ecosystem conditions in the context of Latvian scientific institutions (Bejarano et al., 2023; Bradley et al., 2013; Markman et al., 2005; Siegel et al., 2003).

The study therefore addresses the following research question: *how can technology transfer systems in scientific institutions be conceptualised as systemic capabilities integrating institutional, organisational and operational dimensions?* The aim of this study is twofold: (1) to conceptualise technology transfer as a systemic capability, and (2) to develop an empirically grounded model applicable to Latvian scientific institutions.

Materials and Methods

This study employs a multi-stage mixed-method research design integrating theoretical analysis, qualitative empirical investigation and conceptual modelling. The methodological approach was selected to analyse technology transfer systems not as isolated administrative procedures, but as multi-layered institutional configurations shaped by interrelated governance, organisational and market mechanisms.

The research design follows a structural analytical logic, progressing sequentially from theoretical mapping of technology transfer models to empirical identification of structural parameters and ultimately to an integrated conceptual synthesis. This design ensures that theoretical model development is empirically informed while empirical analysis is conducted within a clearly defined conceptual framework.

The first stage of the study consisted of a structured literature review aimed at mapping the field of technology transfer process modelling in universities and research organisations. The objective of this stage was to identify dominant conceptual approaches, reconstruct their analytical logic and determine their explanatory limitations. Literature searches were conducted in three international databases with complementary coverage: Scopus, Google Scholar and Elsevier ScienceDirect. In the Scopus database, 537 documents published between 1974 and 2026 were identified. A Google Scholar search covering the period 2020-2026 returned approximately 6,000 results. In ScienceDirect, the keyword phrase 'university technology transfer process' produced 24 publications, while the broader term 'university technology transfer' yielded 814 publications. The discrepancy between these results indicated that while technology transfer constitutes a broad research field, explicit modelling of transfer processes represents a significantly narrower analytical subdomain requiring targeted selection strategies.

Literature selection followed a 'top-N' approach prioritising peer-reviewed sources with high citation impact, clear theoretical contributions and analytical relevance to technology transfer process structures. Beyond citation metrics, studies were evaluated according to their ability to explain process stages, actor configurations, transition mechanisms between stages and defined transfer outcomes linked to commercialisation performance. After removing duplicates and applying thematic filtering, 1,210 records were retained for screening. Title and abstract screening excluded 990 studies that addressed technology transfer solely as a policy instrument, focused exclusively on firm-level innovation processes or lacked analytical relevance to transfer process architecture. Full-text assessment was conducted for 220 publications, from which 70 studies were included in the final analytical synthesis. The selected literature was analysed using a structured coding matrix capturing five analytical dimensions: entry conditions and starting points of the transfer process, process architecture, institutional and organisational instruments, intermediary mechanisms and categories of transfer outcomes. This approach enabled the creation of a comparable analytical corpus for typologising technology transfer models and developing a conceptual synthesis.

In parallel with the theoretical analysis, a comparative analysis of international cases was conducted to reconstruct dominant institutional architectures of technology transfer systems, including governance structures, policy instruments and critical success factors across comparable innovation environments (Braslina et al., 2026). In addition, a comparative international case analysis was conducted to reconstruct dominant institutional architectures and governance mechanisms of technology transfer systems, drawing on insights from leading university ecosystems such as Stanford, MIT, Cambridge and Oxford (Braslina et al., 2025a). This comparative perspective provided an empirically informed benchmark for the Latvian case study and enabled assessment of the transferability of internationally recognised technology transfer governance models to the context of a small national innovation system.

The empirical component of the study was based on a qualitative research design combining semi-structured expert interviews with institutional document analysis. The interviews aimed to evaluate the applicability of theoretical models to the Latvian institutional context, identify structural bottlenecks in technology transfer processes and reconstruct decision mechanisms influencing commercialisation outcomes. In total, 53 experts were interviewed, including representatives of public administration, university and research institution leadership, technology transfer professionals, industry representatives and international experts with practical experience in technology commercialisation systems. Respondents were selected using purposive sampling based on institutional role, decision-making authority and practical involvement in technology transfer activities to ensure analytical relevance and depth of information.

The empirical analysis included an in-depth examination of twelve Latvian scientific institutions. The institutions were selected to represent the main organisations within the Latvian public research system engaged in technology commercialisation activities, thereby ensuring coverage of the dominant institutional structures of the national innovation system. This institutional analysis focused on governance structures, organisational arrangements and operational practices of technology transfer systems within universities and public research organisations.

Document analysis complemented the interview data and served as a triangulation mechanism. The analysed materials included institutional regulations, strategic development plans, performance indicator systems, public policy documents and internal materials provided by experts. This allowed reconstruction of the institutional configuration of the technology transfer system and enabled comparison between formally established governance frameworks and operational practices reported by interview participants.

Empirical data were analysed using a structured thematic analysis conducted in three sequential stages. The first stage involved open coding, identifying

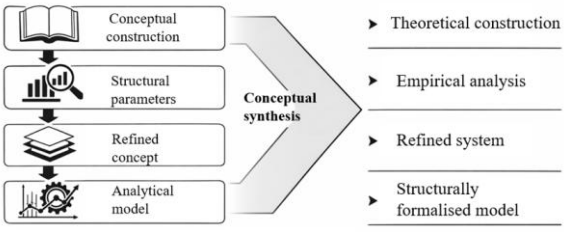
thematic units related to governance structures, allocation of responsibilities, decision regimes, market validation mechanisms, portfolio management practices and incentive systems. The second stage involved axial coding, in which thematic units were grouped into broader analytical categories and their interrelationships were examined. The third stage involved selective interpretation focusing on systemic patterns explaining the effectiveness, institutional permeability and reproducibility of technology transfer outcomes. Coding was guided by the initial conceptual framework while remaining open to the emergence of additional analytical parameters not anticipated in the theoretical model. Attention was given to critical decision points within the transfer process, namely moments when strategic choices are made regarding technology continuation, resource allocation or project termination. Analytical triangulation was ensured by comparing interview findings with document analysis and theoretical insights from the literature.

The validation framework combined several mechanisms of conceptual verification. Preliminary results were discussed with experts as part of iterative model refinement. Findings were also presented in academic conferences as a platform for scholarly discussion, while preparation of peer-reviewed publications provided an additional external review of the theoretical argumentation.

The methodological logic of the study integrates theoretical construction, empirical analysis and conceptual modelling in a sequential research design. Based on the methodological framework illustrated in Figure 1, the following section presents the empirical findings and discusses their implications for the development of a systemic model of technology transfer.

Figure 1

Methodological framework for the development of the systemic technology transfer model



The analysis contributes to understanding how institutional configurations of technology transfer influence innovation capacity in small innovation systems and supports the strengthening of regional innovation capabilities (Braslina et al., 2020a), including rural development contexts where many scientific institutions are located.

Results and Discussion

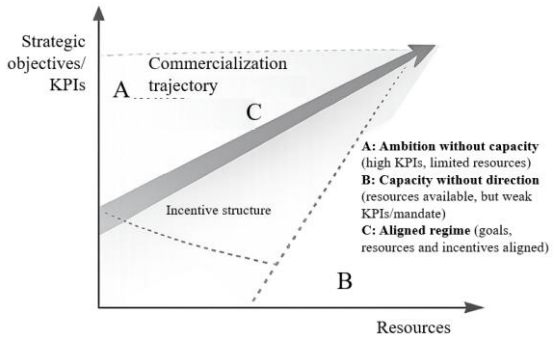
The empirical and theoretical analyses converge on a central finding: high-performance technology transfer systems cannot be adequately explained through a linear sequence of procedural actions such as disclosure, intellectual property protection and licensing. Although such processual descriptions remain operationally useful, they are analytically insufficient, because they fail to capture the structural conditions that determine whether a technology transfer process can generate commercialisation outcomes in the first place (Markman et al., 2005; Siegel et al., 2003). Across the reviewed international models and the empirical assessment of Latvian scientific institutions, technology transfer performance emerges not as the output of procedural formalisation alone, but as a function of systemic capacity shaped by strategic orientation, institutional stability and organisational competence (Bradley et al., 2013; Braslina et al., 2025b; McAdam et al., 2017).

This finding is consistent with broader innovation theory. Diffusion theory suggests that innovation uptake depends not only on invention but on socially mediated adoption mechanisms (Rogers, 2003). Helix models demonstrate that innovation outcomes are produced through patterned interaction among universities, industry and government, rather than through isolated institutional activity (Etzkowitz & Leydesdorff, 2000). Absorptive capacity theory further shows that the ability to recognise, internalise and exploit knowledge is itself a precondition of innovation performance (Cohen & Levinthal, 1990; Zahra & George, 2002). Open innovation and ecosystem approaches reinforce this logic by highlighting that the permeability of organisational boundaries, the density of partnerships and the presence of market integration mechanisms are decisive for innovation outcomes (Adner, 2017; Chesbrough, 2003). Taken together, these perspectives support a shift away from procedural reductionism towards a systemic interpretation of technology transfer as an institutionalised capability.

On this basis, the study identifies three interdependent structural pillars of technology transfer performance. The first is the strategic framework. The comparative analysis indicates that high-performing systems are characterised by an explicit commercialisation mandate embedded in institutional mission, development strategy or national innovation policy. In such systems, technology transfer is not treated as an auxiliary administrative service but as a formally recognised institutional function with a defined purpose, measurable outcomes and long-term direction. Strategic orientation is expressed through quantified performance indicators, including licensing revenues, spin-off creation, industry engagement intensity or broader societal impact. Equally important, strategy is materially underpinned by dedicated budgets, professional staffing and, in many cases, early-stage translational funding instruments. Without such alignment between declared priorities and resource allocation, commercialisation remains symbolic rather than operational. The analysis

therefore suggests that strategic direction functions as a vector: it shapes not only whether technology transfer occurs, but what kind of commercialisation is pursued, measured and institutionally rewarded.

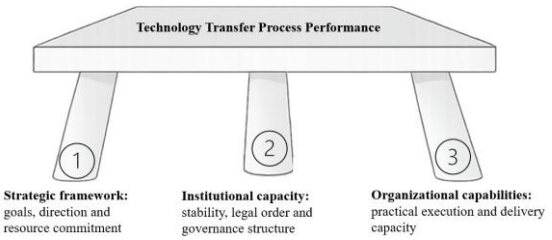
Figure 2
Strategic vector of technology commercialisation: alignment of objectives, resources and incentives



The second pillar is institutional capacity, understood not merely as the formal existence of regulation, but as a functioning stabilisation structure that ensures legal certainty, organisational continuity and reproducibility of transfer processes. The empirical assessment shows that high-performance systems are characterised by clearly defined intellectual property ownership regimes, mandatory invention disclosure procedures, rights assignment mechanisms, revenue-sharing arrangements, conflict-of-interest rules, standardised contractual infrastructure and traceable case management systems. These elements jointly reduce transaction costs, prevent information loss and stabilise the allocation of rights, risks and responsibilities. Importantly, institutional capacity also includes public accessibility of the commercialisation pathway for external actors through technology catalogues, contact points and cooperation guidelines, thereby lowering search costs for industry and increasing system permeability. In this respect, institutional capacity does not function as the 'engine' of technology transfer, but as its enabling architecture: it creates the legally secure and organisationally predictable environment within which innovation objects can be captured, protected and transferred at scale. Where this layer is weak, transfer processes become dependent on informal arrangements and individual discretion, making outcomes fragile and non-reproducible.

The third pillar is organisational competence, which constitutes the practical execution capacity of the system. The comparative analysis suggests that even where strategic direction and formal institutional order are present, commercialisation performance may remain weak if the organisation lacks the capability to operationalise transfer as a disciplined and repeatable practice. The study identifies four core competences. First, the organisation must be able to open and capture an invention as a formal innovation object before it is dissipated through publication, informal interaction or premature disclosure (Batraga et al., 2018). Second, it must possess the capacity to filter, assess and stabilise incoming opportunities by distinguishing between scientifically interesting results and commercially viable cases. This includes technical assessment, market relevance testing and disciplined 'continue-or-stop' selection logic. Third, the system must be able to iterate, redirect or terminate projects without institutional paralysis. In technology transfer, failure is not exceptional but inherent; system performance therefore depends not on avoiding failed cases, but on managing them through structured review, repositioning and socially acceptable archiving mechanisms. Fourth, the organisation must be able to mobilise complementary capabilities, including legal expertise, industry partners, investors, translational finance and implementation teams. This competence is particularly important because it differentiates systemic performance from 'heroic' performance, where isolated successes depend on exceptional individuals rather than on institutionalised routines.

Figure 3
Three structural pillars of technology transfer performance



These three layers together lead to a further conceptual refinement: technology transfer capacity alone is insufficient unless it is activated through an operational translational architecture capable of moving a concrete invention towards implementation. The analysis shows that high-performing systems do not rely on ad hoc activity chains or informal contact networks. Instead, they deploy a structured and traceable project logic that transforms a technology from latent potential into a legally and commercially realisable outcome. This operational layer is analytically distinct from the competence layer. Competences describe what the institution can do in general; the translational architecture describes how a particular innovation object is moved through a documented implementation pathway.

Across the empirical material, five recurrent operational functions can be identified. The first is case activation: the invention is formally transformed into a project with an assigned owner, resource regime, status and decision structure. The second is specification: the technology is translated into an actionable technical-economic proposition through preliminary feasibility analysis, identification of possible use cases, risk assessment and development pathways. The third is market coupling: external signals from industry,

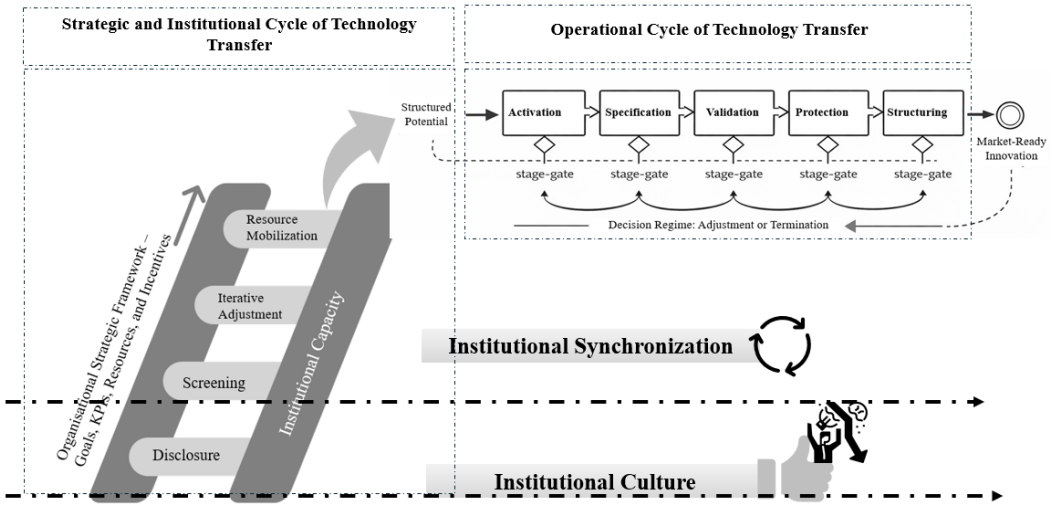
investors or public demand are integrated early in order to test applicability, adoption pathways and implementation actors. The fourth is the operational execution of intellectual property protection through patenting, confidentiality measures, publication control and rights consolidation. The fifth is deal structuring and transition to an implementing actor, whether through licensing, spin-off creation, collaborative development or another institutionalised transfer format. In addition, the empirical analysis strongly indicates that these functions are not truly linear. High-performing systems embed them in a stage-gated logic with decision thresholds, feedback loops and the possibility of redirection or termination. This decision discipline is essential, because it preserves both quality and selectivity: projects do not advance by inertia, but only if they withstand technical, market and legal scrutiny.

The main analytical contribution of the study is therefore the development of an improved model of technology transfer in which performance is determined not by isolated tools or procedures, but by the coherence of four dimensions: strategic direction and resource concentration, institutional stability and legal certainty, organisational competence for selection and mobilisation, and operational translation as the project-specific implementation mechanism. This model helps explain an important paradox identified in both the comparative and Latvian analyses: even when institutions adopt internationally recognised 'good practice' elements, performance may remain limited if those elements are not systemically aligned. In other words, failure in technology transfer often does not arise from errors in one procedural step, but from dissonance between strategic aims, institutional order, practical capabilities and operational execution.

This systemic interpretation is particularly relevant for small and medium-capacity innovation ecosystems such as Latvia. In such contexts, fragmented mandates, weakly synchronised support mechanisms and dependence on individual initiative can significantly reduce the capacity of scientific institutions to transform research into scalable economic value (Braslina et al., 2020b). Conversely, a coherent architecture can strengthen not only institutional commercialisation outcomes but also broader regional innovation capacity, including rural development contexts where scientific and higher education institutions often function as anchor organisations in territorially dispersed knowledge ecosystems. Thus, the proposed model should not be read as a procedural manual, but as a metamodel for diagnosing system viability: it identifies the structural preconditions under which technology transfer processes become reproducible, scalable and developmentally consequential.

Figure 4

Improved systemic model of technology transfer integrating strategic, institutional, organisational and operational dimensions



Taken together, the results suggest that reforms focused solely on process mapping or bureaucratic refinement are structurally insufficient. What is required is the strengthening of system fundamentals: explicit strategic orientation, stable institutional architecture, professionalised organisational competence and disciplined operational translation. Only under such conditions can technology transfer evolve from a fragmented administrative activity into a sustained mechanism of knowledge commercialisation and regional value creation.

From a theoretical perspective, the study contributes to the literature on university technology transfer by shifting the analytical focus from procedural descriptions of transfer stages towards a systemic interpretation of technology transfer as an institutional capability. While existing research has extensively examined individual components of transfer processes

– such as intellectual property management, organisational structures or collaboration mechanisms – these elements are often analysed in isolation. The systemic model proposed in this study integrates these dimensions within a coherent analytical architecture linking strategic orientation, institutional stability, organisational competence and operational translational mechanisms. In doing so, this study contributes to the conceptualisation of technology transfer systems by demonstrating that systemic performance is not a function of isolated instruments, but rather an emergent property of the structural alignment between institutional frameworks, organisational competencies, and the broader dynamics of the innovation ecosystem.

Conclusions

1. The study demonstrates that technology transfer systems in scientific institutions are best conceptualised as systemic capabilities rather than linear procedural sequences centred on disclosure, intellectual property protection and licensing. Instead, technology transfer outcomes emerge from the systemic interaction of strategic, institutional, organisational and operational factors.
2. The analysis demonstrates that high-performing technology transfer systems are characterised by three mutually reinforcing structural pillars: a clearly articulated strategic orientation for knowledge commercialisation, a stable institutional framework ensuring legal certainty and process reproducibility, and organisational competences enabling disciplined evaluation, selection and mobilisation of innovation projects.
3. Empirical evidence from Latvian scientific institutions indicates that weaknesses in any of these structural pillars significantly limit the capacity of research organisations to transform scientific results into commercially viable innovation outcomes.
4. The study further identifies the importance of an operational translational architecture that enables individual technologies to move through a structured implementation pathway, integrating technological readiness assessment, intellectual property management, market validation and capital mobilisation.
5. On this basis, the research develops an improved systemic model of technology transfer that conceptualises commercialisation not as a procedural sequence but as an institutional capability embedded within organisational routines, governance structures and innovation ecosystem interactions.
6. The findings suggest that reforms focused solely on administrative procedures or formal technology transfer instruments are insufficient. Sustainable improvement requires systemic alignment between strategic priorities, institutional frameworks, organisational competences and operational project execution.
7. The proposed model provides an analytical framework that can support scientific institutions and policymakers in strengthening knowledge commercialisation capacity and improving the contribution of research organisations to regional competitiveness and innovation-driven development, particularly in small and regionally distributed innovation systems.

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ANALYSIS OF THE INSTITUTIONAL FRAMEWORK FOR HUMAN CAPITAL DEVELOPMENT IN THE BALTIC SEA REGION

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Abstract
In the context of structural transformation of national economies, human capital is considered a key factor in sustainable economic development. The effectiveness of its formation and accumulation is largely determined by the institutional environment, including legal regulation in education, the labor market, and social protection. In this context, legal and regulatory mechanisms act not only as instruments of state regulation but also as economic institutions that create incentives for investment in human capital and influence the dynamics of socioeconomic indicators. In this regard, it is necessary to understand the institutional and legal mechanisms for human capital development in the Baltic Sea region, focusing on their economic impact. The study examines key regulatory frameworks in education, employment, and social policy, and analyzes their relationship with human capital accumulation and economic development. The empirical part of the study is based on a comparative analysis of macroeconomic, institutional, and educational indicators for the period 2015–2023. The methodological approach combines elements of institutional analysis, economic statistical methods, and econometric modeling, allowing us to assess the relationship between the quality of the institutional environment, human capital development, and economic performance. The study's findings demonstrate that countries with more stable and coherent institutional regulatory environments in education and the labor market are characterized by higher human capital indicators and more favorable economic outcomes. The identified institutional constraints and regulatory imbalances - including those in Latvia - highlight the need for further improvement of the legal framework for human capital development as an important element of economic policy.
Keywords: human capital development, institutional framework.

Introduction

In the context of profound transformation of the global economy, human capital is increasingly seen as a key factor associated with qualitative development. Endogenous growth models assume that the accumulation of knowledge, competencies, and skills represents European technological progress and long-term economic growth (Lucas, 1988; Romer, 1990). Within the framework of classical concepts of human capital, education and training are interpreted as investments that contribute to increased labor productivity and overall economic efficiency (Schultz, 1961; Becker, 1964). Empirical studies confirm this relationship: in particular, Barro (2013) found a significant positive relationship between the level of education of the population and the rate of economic growth in a cross-country analysis.

Contemporary scientific literature expands the traditional understanding of the role of human capital, going beyond assessment solely through GDP indicators. For example, Ma et al. (2025) demonstrate that investment in higher education influences not only economic growth but also the broader concept of 'high-quality development', which includes innovation, environmental sustainability, and social progress. Using panel data for 31 Chinese provinces for 2000–2020, the authors identify a robust positive effect of educational investment on a comprehensive development index and emphasize the complementarity between the level of accumulated human capital and the effectiveness of educational investment. Similar results were obtained in the study by Uddin et al. (2025), who, using panel data for BIMSTEC countries, confirmed the significant impact of human capital on economic growth, accounting for structural characteristics and the institutional environment. These findings are consistent with the extended neoclassical Mankiw–Romer–Weil model (Mankiw et al., 1992), which views human capital as an independent factor of production alongside physical capital.

At the same time, the process of human capital accumulation cannot be considered outside of the institutional context. From the perspective of institutional economics, formal rules, legal norms, and enforcement mechanisms are fundamental factors determining the trajectory of economic development (North, 1990). The quality of institutions—including the stability of legislation, the predictability of regulation, and the protection of property rights—creates a system of incentives for investment in education and skills development (Acemoglu & Robinson, 2012). Hall & Jones (1999) show that differences in the institutional environment largely explain cross-country differences in productivity and income levels.

Thus, government regulation in education, the labor market, and social policy should be viewed not only as an administrative mechanism but also as an economic institution that creates conditions for the accumulation and effective use of human capital. A predictable and stable legal environment reduces uncertainty, promotes long-term investment in education, and fosters sustainable expectations among economic agents.

Despite a significant amount of research devoted to the relationship between education, human capital, and economic growth, the institutional and legal dimensions of this interaction remain insufficiently systematized, particularly within the context of regional comparative analysis. Most empirical studies focus either on quantitative indicators of educational

investment or on aggregate indices of institutional quality, without exploring the specific legal regulation mechanisms that shape incentives for human capital accumulation.

The Baltic Sea region offers a robust and analytically productive platform for studying the institutional and legal mechanisms of human capital development. On the one hand, the countries of the region operate within the unified institutional architecture of the European Union, which implies a certain degree of harmonization of legislation in the areas of education, the labor market, and social policy. European integration processes have facilitated the convergence of formal regulatory rules and the formation of a common economic space (European Commission, 2023; Rodrik, 2007). In this sense, the countries of the region have comparable historical and economic preconditions for integration and participation in Pan-European institutions.

On the other hand, formal normative convergence does not eliminate institutional heterogeneity. Differences in regulatory quality, governance effectiveness, and the predictability of the legal environment persist. According to the concept of institutional divergence (Acemoglu & Robinson, 2012; North, 1990), even with similar formal rules, differences in institutional quality can lead to different trajectories of economic development. Empirical evidence supports this notion: variations in the institutional environment explain a significant portion of cross-country differences in productivity and income levels (Hall & Jones, 1999).

International governance indicators (World Bank's World Governance Indicators, 2023b) demonstrate persistent differences between the Nordic countries and the Baltic states in such areas as regulatory quality, government effectiveness, and rule of law. Similar differences are observed in labor market regulation (OECD Employment Protection Indicators) and social protection models (Eurostat Social Protection Expenditure Database).

Thus, the Baltic Sea Region combines institutional commonality—driven by the common EU legal framework—with structural heterogeneity, stemming from differences in the quality of implementation and regulation. This creates unique conditions for comparative analysis. The combination of formal convergence and variability in institutional quality allows for an examination of how the characteristics of the legal architecture and the level of regulatory predictability influence human capital accumulation and macroeconomic dynamics. Unlike studies based on global cross-country samples, a regional approach reduces the influence of exogenous factors and focuses on institutional differences in a relatively homogeneous economic environment.

In this regard, it is necessary to understand the institutional and legal mechanisms for human capital development in the Baltic Sea region countries, focusing on their economic impact. This study aims to identify the relationship between the characteristics of legal regulation and the dynamics of macroeconomic and educational indicators over the period 2015–2023. The study's underlying hypothesis is that countries with more consistent, stable, and predictable legal systems regulating education and the labor market are characterized by higher levels of human capital and more favorable economic outcomes. This study contributes to the literature by providing a comparative panel analysis of the relationship between human capital, institutional quality, and economic development in the Baltic Sea region.

Materials and Methods

The empirical analysis is based on panel data for countries of the Baltic Sea region. The study includes eight countries: Denmark, Germany, Estonia, Latvia, Lithuania, Poland, Finland, and Sweden. These countries share broadly similar institutional and economic conditions related to their integration into the European economic space. At the same time, they exhibit certain differences in economic structure, education systems, and institutional models of labour market regulation. This combination of similarities and differences makes the Baltic Sea region a suitable empirical setting for analysing the relationships between the institutional environment, human capital development, and economic performance.

The study covers the period 2015–2023. The selection of this time interval is determined by the availability of comparable statistical data for all countries included in the analysis. As a result, a balanced panel dataset consisting of 72 observations (8 countries over 9 years) was constructed.

Data for the analysis were obtained from international statistical sources that ensure cross-country comparability of indicators. Indicators of economic development and labour productivity were taken from the World Development Indicators database of the World Bank (World Bank, 2023a). Data on education and human capital were obtained from the Eurostat statistical database (Eurostat, 2023). Indicators of the institutional environment were drawn from the Worldwide Governance Indicators (WGI) developed by the World Bank, which reflect various dimensions of governance quality and institutional performance (Kaufmann et al., 2010).

The empirical analysis employs variables representing economic development, the level of human capital, and the quality of the institutional environment.

The dependent variable is GDP per capita, measured in U.S. dollars. This indicator is widely used in economic research as a proxy for the level of economic development of a country. To reduce distributional asymmetry and improve the interpretability of regression coefficients, the variable was transformed using the natural logarithm.

The key explanatory variable is labour productivity, measured as gross domestic product per hour worked (GDP per hour worked) and expressed in U.S. dollars. This indicator reflects the efficiency of labour

utilisation and is considered one of the main drivers of economic growth.

To capture the level of human capital, the analysis uses the tertiary education attainment rate, measured as the percentage of the population with completed tertiary education. This indicator is widely applied in macroeconomic research as an approximate measure of the accumulated stock of human capital in the economy.

The institutional environment is characterised using indicators from the Worldwide Governance Indicators (WGI) database. Three indicators are included in the analysis: regulatory quality, reflecting the ability of the government to formulate and implement sound economic policies and regulations; rule of law, capturing the extent to which agents have confidence in and abide by the rules of society, particularly the quality of contract enforcement and the legal system; and government effectiveness, reflecting the quality of public services and the effectiveness of policy implementation. These indicators are measured on a scale ranging from −2.5 to +2.5, where higher values correspond to better institutional quality.

The inclusion of institutional indicators makes it possible to assess the influence of governance quality and the regulatory environment on the processes of human capital formation and economic development across countries.

To analyse the relationships between human capital, institutional factors, and economic development, panel econometric methods were employed. Panel data allow the researcher to simultaneously account for both cross-country differences and temporal dynamics, which improves the reliability of estimates compared with purely cross-sectional or time-series approaches (Baltagi, 2021).

The econometric specification used in this study:

$$ln(GDP_{it}) = \beta_0 + \beta_1\, ln(Productivity_{it}) + \beta_2\, HumanCapital_{it} + \beta_3\, RegulatoryQuality_{it} + \beta_4\, RuleOfLaw_{it} + \beta_5\, GovernmentEffectiveness_{it} + \varepsilon_{it}$$

Where i denotes the country and t represents the year of observation.

The dependent variable $ln(GDP_{it})$ is the natural logarithm of GDP per capita. Labour productivity $ln(Productivity_{it})$ is measured as GDP per hour worked and reflects the efficiency of labour utilisation. The variable $HumanCapital_{it}$ represents the share of the population with tertiary education and serves as a proxy for human capital.

The institutional environment is captured by three indicators from the Worldwide Governance Indicators database (WGI, 2023b): regulatory quality, rule of law, and government effectiveness, which measure different aspects of institutional quality. The coefficients β1–β5 represent the estimated effects of the explanatory variables on economic development, while ε_{it} is the error term.

The model was estimated using the random effects (RE) estimator, which allows unobserved country-specific heterogeneity to be incorporated into the model under the assumption that these effects are randomly distributed across countries. The choice between fixed effects and random effects specifications was determined using the Hausman test, which is commonly applied in panel data analysis to assess the consistency of estimators (Hausman, 1978).

To ensure the robustness of the estimated results, several diagnostic checks were conducted. In particular, potential multicollinearity among the explanatory variables was assessed using the Variance Inflation Factor (VIF), which evaluates the degree of correlation between regressors and its possible influence on the stability of coefficient estimates (Gujarati & Porter, 2009). In addition, robust standard errors were employed to account for possible heteroskedasticity.

All calculations were performed in the R statistical environment using the plm package, which is specifically designed for the estimation of panel data models.

Results and Discussion

Descriptive statistics for the variables used in the empirical analysis are presented in Table 1. The results reveal substantial differences in the level of economic development among the countries of the Baltic Sea region. GDP per capita ranges from 22,543 to 78,914 USD, reflecting the gap between the more economically developed Nordic countries and the Baltic states.

Table 1

Descriptive Statistics of human capital data in BSR

Variable	Mean	Std.Dev	Min	Max
GDP per capita (World bank data)	47327.6	13564.7	22543.9	78913.7
Productivity (World bank data)	62.39	19.15	32.28	103.84
Human capital (Eurostat data)	37.55	5.48	26.5	48
Regulatory Quality (WGI data base)	1.47	0.34	0.72	1.89
Rule of Law (WGI data base)	1.37	0.51	0.38	2.05
Government Effectiveness (WGI data base)	1.30	0.49	0.25	2.02

Labour productivity also exhibits considerable variation, ranging from 32.28 to 103.84 USD per hour worked. These differences reflect variations in technological development, economic structure, and the efficiency of labour utilisation across the countries included in the analysis.

The human capital indicator, measured as the share of the population with tertiary education, varies between

26.5% and 48%, with an average value of approximately 37.5%. This suggests a relatively high level of educational attainment in the region, although noticeable cross-country differences remain.

Institutional indicators derived from the Worldwide Governance Indicators database also show relatively high average values, reflecting generally strong governance institutions in the Baltic Sea region. However, the observed variation indicates differences in regulatory quality, the rule of law, and government effectiveness across countries.

The correlation matrix presented in Table 2 provides preliminary insights into the relationships between the variables included in the econometric model.

Table 2

Correlation Matrix of Economic and Institutional Variables

	Gdp_pc	*Productivity*	*Reg_quality*	*Rule_law*	*Gov_ effectiveness*
GDP per capita	1				
Productivity	0.98	1			
Regulatory quality	0.64	0.69	1		
Rule of law	0.68	0.75	0.95	1	
Government effectiveness	0.64	0.72	0.92	0.97	1

The strongest positive correlation is observed between GDP per capita and labour productivity (0.98). This result reflects the fundamental role of productivity as one of the key determinants of economic development. Higher levels of labour efficiency are generally associated with higher levels of economic output per capita.

Human capital shows a moderate positive correlation with GDP per capita (0.35), suggesting a potential relationship between the educational attainment of the population and economic performance. Similar moderate correlations are observed between human capital and institutional indicators.

Institutional variables also demonstrate a noticeable positive relationship with economic development. The correlation coefficients between GDP per capita and the institutional quality indicators range from 0.64 to 0.68, indicating a positive association between institutional quality and economic performance.

At the same time, a relatively high degree of correlation is observed among the institutional indicators themselves. This pattern is typical for variables derived from the Worldwide Governance Indicators framework, as they capture closely related dimensions of governance quality. To assess the potential impact of multicollinearity on the regression results, Variance Inflation Factor (VIF) statistics were calculated.

To provide a more in-depth analysis of the relationship between human capital, the institutional environment, and economic development, a panel regression model was estimated. The results are presented in Table 3.

Prior to estimating the model, a Hausman test was conducted to determine the most appropriate panel model specification. The obtained p-value (0.22) exceeds the conventional significance level of 0.05, indicating that the random effects specification is preferable. Therefore, the subsequent analysis was conducted using the Random Effects model.

The regression results show that labour productivity has a strong and statistically significant effect on economic development. The coefficient for ln(Productivity) equals 1.039 and is significant at the 1% level, indicating that increases in labour productivity are associated with higher GDP per capita. This finding is consistent with classical economic growth theories emphasizing the central role of labour efficiency in economic development (Baltagi, 2021).

Table 3

Regression Results for Human Capital and Institutional Factors

Variable	Coefficient	Std. Error	Significance
ln(Productivity)	1.039	0.0387	***
Human capital	0.0046	0.0022	*
Regulatory quality	0.106	0.056	.
Rule of law	-0.023	0.049	
Government effectiveness	-0.138	0.0416	**
Constant	6.362	0.118	***

The human capital variable also demonstrates a positive and statistically significant effect on economic development. The coefficient is 0.005 and is significant at the 5% level, confirming the hypothesis that higher levels of educational attainment contribute to economic growth. This result is consistent with human capital theory, which suggests that investments in education and skill development increase labour productivity and support long-term economic development (Becker, 1964; Schultz, 1961).

The institutional indicators show more mixed results. The variable regulatory quality has a positive coefficient and is statistically significant at the 10% level, indicating that improvements in regulatory quality may contribute to a more favourable economic environment. In contrast, the rule of law variable does not exhibit a statistically significant effect in the model. The coefficient for government effectiveness is

negative and statistically significant, which may be related to the high correlation among institutional variables and the presence of multicollinearity.

Despite these mixed institutional results, the model demonstrates strong explanatory power. The coefficient of determination ($R^2 = 0.963$) indicates that the included variables explain a substantial share of the variation in GDP per capita across the countries in the sample.

Additional diagnostic tests confirm the robustness of the estimated results. The Variance Inflation Factor (VIF) test indicates a relatively high correlation among institutional indicators, which is expected when using variables derived from the Worldwide Governance Indicators framework. Furthermore, the use of robust standard errors confirms the statistical stability of the main model coefficients.

In addition, the logarithmic specification of the model allows the coefficients to be interpreted in elasticity terms. In particular, the coefficient of 1.039 for ln(Productivity) indicates that a 1% increase in labour productivity is associated with approximately a 1.04% increase in GDP per capita, holding other factors constant. This result highlights the central role of productivity growth in explaining differences in economic performance across countries.

The coefficient for human capital (0.005) suggests that an increase in the share of the population with tertiary education is associated with a gradual improvement in economic outcomes. Although the magnitude of this effect is relatively moderate, it reflects the long-term contribution of education and skills to economic development.

Overall, these findings support the theoretical assumption that productivity, human capital, and institutional conditions jointly influence economic performance, reinforcing the importance of investments in education and improvements in the institutional environment.

The above results provide empirical support for the importance of human capital development and institutional quality in shaping economic outcomes in the Baltic Sea region.

Conclusions

1. The results of the panel regression analysis indicate that labour productivity is one of the most important determinants of economic development in the Baltic Sea region. A strong positive relationship was found between productivity growth and GDP per capita, confirming the central role of efficient labour utilisation in explaining differences in economic performance across countries.
2. The findings also highlight the significant role of human capital in economic development. Higher levels of educational attainment contribute to improved labour productivity, greater innovation capacity, and enhanced economic competitiveness. These results are consistent with human capital theory, which emphasizes the importance of investments in education and skills for long-term economic growth (Becker, 1964; Schultz, 1961).
3. The analysis of institutional variables suggests that regulatory quality has a positive association with economic development, indicating that effective regulatory frameworks can contribute to the creation of favourable economic conditions. Simultaneously, other institutional indicators did not demonstrate a consistently significant effect within the estimated model, which may be related to the strong correlation among governance indicators.
4. Overall, the results underline the importance of a comprehensive approach to human capital development, combining investments in education with improvements in the institutional environment. For the countries of the Baltic Sea region, this implies the need to further strengthen policies in the areas of education, labour markets, and economic regulation.
5. From a policy perspective, the findings highlight the importance of long-term institutional strategies aimed at supporting investments in human capital. This is particularly relevant for transition economies, including Latvia, where improvements in the education system and institutional governance may become key drivers of sustainable economic growth.
6. Despite the empirical findings, the study has several limitations. The analysis relies on a limited set of macroeconomic and institutional indicators and covers a relatively short time period. Future research may benefit from incorporating additional indicators of human capital and institutional development, as well as applying alternative econometric approaches.

Overall, the study confirms that human capital development, supported by effective institutional frameworks, plays an important role in shaping long-term economic development in the Baltic Sea region.

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SUSTAINABLE FOOD PACKAGING INDICATORS

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Abstract
Sustainability is one of the most widely used concepts today, particularly in the context of packaging. The European Union has introduced multiple regulatory requirements, such as PPWR, the Single-Use Plastics Directive, and food contact regulations, alongside retailer standards and growing consumer demand, all of which have significantly increased the need for sustainable packaging. However, due to inconsistent and unclear information, it remains difficult to define what sustainable packaging is and how it can be evaluated. The concept is relatively new and lacks a clear, precise, and universally accepted definition. Moreover, the term 'sustainability' itself has over 300 definitions, and interpretations of 'sustainable packaging' vary across contexts (Jestratijevic et al., 2022; Boz et al., 2020). This lack of clarity creates challenges for both consumers and manufacturers in distinguishing sustainable packaging from less sustainable alternatives. The aim of this study is to identify a clear set of criteria and indicators for assessing sustainable packaging in the food production sector. Using monographic and secondary data analysis methods, as well as public databases, a literature review was conducted. As a result, ten key indicators were identified and grouped according to the three traditional sustainability dimensions: environmental, social, and economic. These indicators provide a structured framework to better understand and evaluate sustainable packaging.
Keywords: sustainable packaging indicators, key indicators packaging, sustainable packaging design, food packaging indicators.

Introduction

Sustainable packaging has become an increasingly important topic in both academic research and industry practice, driven by growing environmental concerns and changing consumer expectations. According to Meredith Leahy, sustainable packaging can be understood as packaging that reduces environmental impact by replacing less sustainable alternatives. Although the terms 'sustainable' and 'eco-friendly' are often used interchangeably, they are not identical; however, the use of more sustainable materials in packaging development is widely considered to contribute positively to environmental protection.

Packaging plays a critical role not only in protecting and preserving products but also in influencing consumer perceptions. Research by N. D. Steenis and Ellen van Herpen highlights that the visual appearance of packaging can significantly affect how consumers evaluate its sustainability (Steenis et al., 2017). Therefore, sustainable packaging should communicate environmental responsibility through its design and materials. At the same time, packaging must fulfill several essential functions, including containment, protection, preservation, identification, information provision, and market appeal, as emphasized by P. Betancur-Muñoz and M. A. Pascall (Betancur-Muñoz et al., 2014; Pascall et al., 2022).

A widely recognized definition describes sustainable packaging as packaging that incorporates smart design principles, promotes the use of recycled or renewable materials, and is intended for reuse, recycling, or composting, with clear user guidance. Furthermore, it should support broader system-level solutions, such as reuse and refill models, and contribute to the development of recycling and composting infrastructure (Sustainable Packaging Coalition).

In addition, four key variables are essential in evaluating sustainable packaging: cost, sustainability performance (including recyclability, compostability, and reusability), functional performance, and effective sorting or waste management. These criteria demonstrate a clear link to the three traditional dimensions of sustainability – environmental, economic, and social – highlighting the multidimensional nature of sustainable packaging.

Given the diversity of definitions and approaches, this article aims to: (1) clarify the terminology related to sustainable food packaging, (2) identify relevant indicators for its assessment and (3) classify these indicators into main groups aligned with the environmental, social, and economic dimensions of sustainability.

Materials and Methods

This study applies a monographic research approach combined with a structured literature review and qualitative content analysis to examine sustainable food packaging and develop a conceptual framework of sustainability indicators. The research consisted of four sequential stages: (1) a structured literature review; (2) critical analysis of identified indicators and research gaps; (3) development and classification of the proposed indicator framework and (4) interpretation of the findings.

The literature review was conducted between September 2024 and January 2026. To ensure the relevance of current developments in sustainable packaging, only scientific publications published from 2020 onwards were included. Searches were performed using the keyword combination *'sustainable food packaging indicators'* together with related terms. More than 140 publications were initially identified, screened for relevance, and analysed using predefined selection criteria.

The review revealed that most studies focus on waste management, intelligent packaging, bio-based materials, packaging composition and pH indicators. In contrast, limited research defines comprehensive

sustainable packaging indicators or proposes systematic approaches for evaluating sustainable food packaging. Furthermore, sustainable packaging is often associated with eco-design principles, although it represents a broader concept encompassing environmental, economic, and social dimensions.

The indicator selection process followed a structured literature review approach. Scientific publications indexed in Scopus and Web of Science, together with European Union policy documents and internationally recognised sustainability frameworks, were analysed. Indicators were selected according to four criteria: (1) relevance to food packaging sustainability, (2) applicability to the meat industry, (3) measurability and (4) representation of environmental, economic and social sustainability dimensions. Similar and overlapping indicators were consolidated into broader categories, resulting in the synthesis of 28 initial criteria into a conceptual framework comprising 10 key sustainability indicators.

Results and Discussion

Sustainable packaging and its indicators

Sustainable packaging is increasingly analyzed through the Triple Bottom Line (TBL) approach, integrating economic, social, and environmental impacts across the entire life cycle of packaging—from raw material extraction to end-of-life management (Dörnyei & Uysal-Unalan, 2023). In the literature, sustainable packaging is often associated with terms such as eco-friendly, green, or climate-friendly packaging. It is commonly defined as packaging that minimizes harm to people and the environment throughout its life cycle, meets functional and economic requirements, and supports closed-loop systems through recycling or reuse (Dörnyei & Uysal-Unalan, 2023). However, many definitions remain narrowly focused on waste reduction and pollution prevention, lacking a broader, multidisciplinary perspective.

Indicators are therefore essential tools for evaluating sustainability, as they provide measurable and structured information. In the context of packaging, sustainability is often linked to three key aspects: environmental impact, packaging-related food loss and waste (FLW), and circularity (Pauer et al., 2019). The environmental dimension includes direct impacts from production and disposal, indirect impacts such as food waste, and recyclability (Pauer et al., 2019). Given the significant environmental footprint of packaging systems, improving their sustainability has become a critical priority (Flanagan et al., 2007).

Various frameworks define sustainable packaging through functionality, efficiency, circularity, and environmental performance. These include reducing waste, improving resource efficiency, enabling reuse and recycling, and minimizing emissions and toxicity (Lewis & Fitzpatrick, 2007; Sustainable Packaging Coalition, 2011). Packaging must also meet core functions such as protection, preservation, and communication while supporting circular material flows **(**Brgant, 2022; Santi et al., 2022).

From the literature review, 28 initial criteria describing sustainable packaging were identified and later consolidated into 10 key indicators. These include aspects such as material, design, recyclability, functionality, resource efficiency, cost, innovation, and social responsibility. The indicators were grouped into environmental, social, and economic sustainability dimensions, forming a structured framework for further analysis.

Material and properties

Material is one of the most critical indicators of sustainable packaging and often serves as the primary criterion in packaging selection (Boesen et al., 2019; Hvězdová et al., 2023). Consumers frequently rely on material labeling as a simple and accessible guide for evaluating sustainability (Herbes et al., 2020; Eberhart & Naderer, 2017; Magnier & Crié, 2015; Lindh et al., 2016). Materials such as paper, cardboard, glass, metal, and certain bioplastics are commonly perceived as more sustainable, although interpretations vary (Kachook, 2024; World Packaging Organisation et al., 2020).

Material properties strongly influence consumer perception, as sensory characteristics such as texture and appearance are associated with naturalness and sustainability (Steenis et al., 2017; Karana, 2012). At the same time, widely used materials such as plastics (PET, HDPE, LDPE, PP) remain dominant due to their functional and economic advantages (Ceflex, 2020).

A key principle in sustainable packaging design is the preference for mono-material solutions, which improve recyclability. Where multi-material solutions are necessary, they should be easily separable to avoid recycling challenges (McTigue Pierce et al., 2019; Association of Plastic Recyclers (n.d.)). Composite packaging, often used for functional purposes such as extended shelf life, remains problematic due to its limited recyclability (Turos et al., 2019).

Another important consideration is the proportion of recycled versus virgin material. Reducing the use of virgin materials and increasing recycled content is a major goal in sustainable packaging development (Ellen MacArthur Foundation, 2019, 2023; Jacobi et al., 2018). Studies also confirm that material recyclability significantly influences consumer purchasing decisions (Lindh et al., 2015).

Design and structure

Packaging design plays a crucial role in both functionality and consumer perception. While manufacturers often prioritize visual appeal, sustainable design requires a broader perspective that considers the entire life cycle and environmental impact (Brgant, 2022).

Research shows that approximately 80% of consumers evaluate packaging sustainability based on labeling and visual cues (Herbes, et al., 2020). Elements such as color, transparency, and print coverage strongly

influence perceptions. Natural colors (green, brown, earth tones) and minimalistic designs are commonly associated with sustainability (Seo & Scammon, 2017; Wood & Robinson, 2018). Lower ink usage and transparent materials are preferred, as they enhance recyclability and reduce environmental impact (Scott & Vigar-Ellis, 2014; Szaky, 2019).

Labels, adhesives, and coatings also affect recyclability. Incorrect labeling or excessive coverage can interfere with sorting technologies and contaminate recycling streams (Leahy, 2020). Therefore, design decisions must consider compatibility with recycling systems and material recovery processes (Jestratijevic et al., 2022).

Ultimately, sustainable design must balance aesthetics, functionality, and environmental performance. Transparent and light-colored materials are particularly valuable in recycling systems, while darker or heavily colored plastics often have lower recycling value (Hahladakis & Iacovidou, 2018).

Recyclability and circular economy

Recyclability and circularity are central to sustainable packaging. Packaging should be designed to enable reuse, recycling, or composting, reducing waste and supporting closed-loop systems (Kachook, 2024; World Packaging Organisation et al., 2020; European Parliament & Council of the European Union, 2024). Materials such as glass, aluminum, and certain plastics (PET, HDPE) are widely recyclable and can be reintegrated into production cycles (Matos et al., 2024; Sikra & Szaky, 2019).

However, recyclability depends not only on material design but also on infrastructure, market demand, and consumer participation. Factors such as collection systems, sorting efficiency, and availability of end markets significantly influence actual recycling outcomes (Sikra & Szaky, 2019).

Increasing the use of post-consumer recycled (PCR) materials and ensuring that packaging is fully reusable, recyclable, or compostable are key industry goals (Ellen MacArthur Foundation, 2015). At the same time, packaging design must avoid materials that are difficult to recycle or rarely processed, as these increase costs and reduce efficiency (Turos & Szaky, 2019; Hahladakis & Iacovidou, 2018).

Circularity also requires a system-level perspective, considering not only materials but also logistics, infrastructure, and life cycle impacts (Jestratijevic & Vrabič-Brodnjak, 2022).

Optimization: resources, weight, form, and size

Resource optimization is a fundamental principle of sustainable packaging. Reducing material use, minimizing weight, and improving design efficiency contribute to lower environmental impact and reduced costs (Kachook, 2024).

Lightweight packaging is a major trend, enabling reduced resource consumption and lower transportation emissions. For example, plastic packaging, although widely used, represents only 17% of total packaging weight in Europe, with significant reductions achieved in recent years (European Parliament & Council of the European Union, 1994).

Packaging size and shape also influence sustainability. Efficient shapes, such as stackable or square designs, improve logistics and reduce transportation impacts (Magnier & Crié, 2015; Ellen MacArthur Foundation, 2023). At the same time, packaging must be appropriately sized to avoid overpackaging and unnecessary material use.

Optimization must balance environmental and functional requirements, ensuring that packaging remains effective in protecting products while minimizing resource use.

Performance and functionality

Packaging performance is essential for maintaining product quality, safety, and shelf life throughout the supply chain (Meherishi et al., 2019). Sustainable packaging must achieve these functions while minimizing environmental impact.

Life Cycle Assessment (LCA) is a key tool for evaluating the overall environmental performance of packaging systems, considering all stages from production to disposal (Kachook, 2024). Materials such as glass and metal may have higher initial impacts but offer advantages in recycling and long-term use.

Sustainable packaging aims to reduce the overall footprint by optimizing material use, improving durability, and supporting circular systems (Matos et al., 2024). Importantly, sustainability does not imply zero impact, but rather reduced impact compared to conventional alternatives (Cays, 2024).

Biodegradability and compostability

Biodegradability and compostability are often associated with sustainable packaging, as they allow materials to break down naturally and reduce environmental impact (World Packaging Organisation et al., 2020). However, these properties must be carefully managed to avoid contamination of recycling streams.

Packaging should not be considered sustainable solely based on biodegradability. Functional performance and system compatibility remain critical factors (Sustainable Packaging Coalition, 2011).

Social and environmental responsibility

Sustainable packaging also includes social aspects such as worker safety, ethical production, and societal well-being (Jestratijevic et al., 2022). This involves fair labor practices, local sourcing, and responsible supply chains (Herbes et al., 2020).

Consumers and businesses must consider the broader social impact of packaging, including production conditions and environmental responsibility.

Health and safety

Health and safety are essential indicators of sustainable packaging. Packaging must not pose risks to consumers, workers, or the environment (Herbes et al., 2020). It plays a critical role in protecting food from contamination and reducing food waste (Guillard et al., 2018).

However, certain materials may pose risks through

chemical migration into food. Studies highlight concerns related to metals and chemical substances used in packaging, emphasizing the need for safe material selection and minimal use of additives (Deshwal & Panjagari, 2020). Consumer awareness of these issues remains limited, reinforcing the need for clearer communication and classification systems (Brgant, 2022).

Expenses and economic factors

Economic feasibility is a key dimension of sustainable packaging. Packaging must be cost-effective, functional, and scalable to ensure widespread adoption (Sangroniz et al., 2019).

Materials such as plastics remain dominant due to their low cost, durability, and efficiency, despite environmental concerns (Khandeparkar et al., 2024).

Balancing cost with sustainability requires innovation and efficient resource use.

Innovation and communication

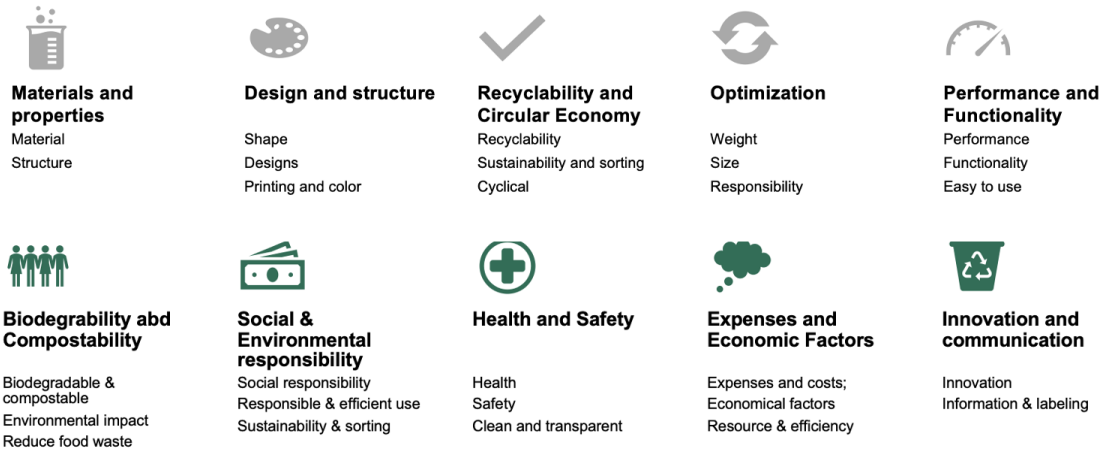
Innovation plays a crucial role in advancing sustainable packaging through new materials, technologies, and systems **(**Sustainable Packaging Coalition, 2011). Trends include mono-material solutions, reusable packaging, and simplified designs.

Effective communication and information sharing are essential for improving understanding and adoption of sustainable packaging. Collaboration between producers, manufacturers, and consumers can enhance knowledge and support more sustainable choices.

Figure 1 illustrates the proposed conceptual framework of sustainable food packaging indicators. The framework presents the ten key sustainability indicators together with the principal packaging core assessment elements, that characterise each indicator and define its scope within the overall sustainability assessment.

Figure 1

Sustainable packaging indicators& packaging core assessment elements



As sustainable packaging is inherently linked to the three dimensions of sustainability, the identified packaging indicators were classified according to their primary sustainability contribution. This classification provides a structured understanding of how individual indicators support environmental, social, and economic sustainability.

Table 2 presents the classification of the proposed sustainable food packaging indicators according to the environmental, social and economic dimensions of sustainability. The classification reflects the primary sustainability focus of each indicator while recognising that several indicators may contribute simultaneously to multiple sustainability dimensions. Overall, the results demonstrate that sustainable food packaging is a multidimensional concept.

Despite extensive research, there is still no unified set of criteria for evaluating sustainable packaging. The main challenges are unclear definitions and limited knowledge among stakeholders.

This study identified 28 criteria and grouped them into 10 indicators and broader sustainability dimensions—environmental, social, and economic. These indicators provide a structured framework for understanding sustainable packaging and addressing both academic and practical gaps.

The findings highlight that all indicators are interconnected and rooted in sustainability principles. A holistic approach is therefore essential, integrating environmental impact, social responsibility, and economic feasibility.

Future research should focus on developing standardized frameworks and practical tools that support decision-making and enable consistent evaluation of sustainable packaging across industries.

Conclusions

Sustainable packaging remains a complex and evolving concept within the broader context of sustainability and business development. Although its importance continues to grow, there is still no single, universally accepted definition, which creates challenges for both

researchers and practitioners. This study addressed this issue by identifying and systematizing key indicators of sustainable packaging, with a particular focus on the food production sector. Through a comprehensive literature analysis, the research developed a structured framework of indicators and classified them according to the three traditional sustainability dimensions: environmental, social, and economic.

Table 2

Classification of Sustainable Food Packaging Indicators According to Sustainability Dimensions

Environmental Sustainability	Social Sustainability	Economic Sustainability
Indicators that emphasize ecological conservation, resource efficiency, and waste reduction.	*Indicators that prioritize human health, societal well-being, and ethical responsibilities.*	*Indicators that ensure cost-effectiveness, financial feasibility, and innovation while maintaining sustainability.*
Material and Properties: Focuses on the use of sustainable raw materials, lightweight materials, and eco-friendly options.	**Social and Environmental Responsibility**: Combines ethical accountability and actions that benefit both society and the environment.	**Design and Structure**: Efficient designs minimize costs while meeting functionality and aesthetic goals.
Recyclability and Circular Economy: Supports a closed-loop system that reduces waste and promotes reuse.	**Health and Safety**: Ensures that packaging materials and designs do not pose risks to human health or safety.	**Expenses and Economic Factors**: Relates directly to affordability, production costs, and resource optimization.
Biodegradability and Compostability: Highlights materials that break down naturally, reducing environmental harm.	**Innovation and Communication**: Includes transparency (e.g., labeling), accessibility, and advancements that benefit society.	**Optimization**: Ensures that the packaging is durable and effective, reducing waste and costs.

The findings reveal that current approaches to evaluating sustainable packaging are fragmented and inconsistent. Different stakeholders apply diverse criteria, making it difficult to distinguish sustainable packaging from conventional alternatives. This highlights the need for a unified and standardized system that would simplify decision-making processes and improve communication between stakeholders. Furthermore, the study emphasizes the importance of practical tools, such as indicator-based frameworks, which can support both consumers and manufacturers in assessing packaging sustainability.

The research also underlines the limited availability of educational resources and structured knowledge in the field of packaging sustainability. Strengthening awareness and providing clear guidance systems would contribute to more informed choices and promote sustainable practices. Overall, the study confirms that sustainable packaging indicators are interconnected and rooted in common sustainability principles, reinforcing the need for a holistic approach.

1. The research aim was achieved by identifying and classifying sustainable packaging indicators into a structured framework aligned with environmental, social, and economic dimensions.
2. The concept of sustainable packaging remains unclear and inconsistently defined, creating challenges for its practical application.
3. A lack of standardized criteria complicates the evaluation and comparison of packaging solutions across different stakeholders.
4. There is a need for unified guidelines and practical assessment tools to support decision-making and improve transparency.
5. Sustainable packaging indicators are interrelated and require a holistic approach to effectively evaluate and implement sustainable solutions.

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ENVIRONMENTAL PRACTICES IN TOURISM AND TOURISTS' PRO-ENVIRONMENTAL BEHAVIOUR AS DRIVERS OF SUSTAINABLE RURAL DEVELOPMENT IN UKRAINE

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Abstract
The article investigates how the synergy between environmental practices in rural destinations and tourists' pro-environmental behaviour supports the sustainability of Ukraine's rural territories. The study's relevance is underpinned by Ukraine's European integration trajectory, the growing role of domestic tourism as an instrument of socio-environmental resilience under wartime conditions, and the need to align the tourism sector with European Union principles of sustainable development. The aim of the research is to empirically identify and interpret the relationship between tourists' perceptions of environmental practices in rural tourism destinations and their pro-environmental behaviour. The methodological foundation comprises a questionnaire survey of 128 respondents who had visited rural tourism destinations in Ukraine within the last 12 months. Data analysis employed descriptive statistics, the aggregation of indicators into composite indices, Spearman's rank correlation analysis, and linear regression modelling. The findings indicate a high level of tourists' pro-environmental orientation and, overall, a favourable perception of destinations' environmental practices. Statistically significant positive associations were found among perceived environmental practices at rural destinations, tourists' pro-environmental behaviour, and tourism's contribution to the long-term sustainability of rural regions. Demographic characteristics exerted a limited effect, whereas institutional and contextual determinants of tourism organization played a decisive role. The results substantiate that the combination of environmentally responsible destination management and conscious tourist behaviour creates important preconditions for the economic, social, and environmental resilience of rural communities. The study's practical recommendations may inform the development of policies for sustainable rural tourism in Ukraine in the context of post-war recovery and European integration.
Keywords: sustainable rural development, environmental practices in tourism, tourists' pro-environmental behaviour, green tourism practices, rural destinations.

Introduction

Progress toward the Sustainable Development Goals is closely linked to conditions in rural areas, particularly their capacity to support environmental stewardship, social cohesion, and economic diversification (Suárez-Roldan et al., 2023; Sun et al., 2024). The significance of rural tourism as a strategic tool for the long-term viability of countryside regions continues to grow, as it bridges the gap between local economic prosperity and the protection of indigenous cultural traditions alongside ecological preservation. At the same time, the growth of tourist activity in rural destinations heightens the need to implement environmental practices and to foster tourists' pro-environmental behaviour (PEB) as key factors for minimizing adverse impacts and ensuring long-term development resilience (Baloch et al., 2023; Lane et al., 2022).

Rural tourism is increasingly recognised as an important driver of sustainability, with the potential to integrate the economic, social, and environmental dimensions of regional development (Li & Ye, 2025; World Tourism Organization, 2020; Kyryliuk et al., 2026). When guided by effective governance and environmental limits, rural tourism can support economic diversification and employment opportunities while promoting heritage conservation and responsible resource use. Scholars argue that sustainable rural tourism development is feasible only through a comprehensive approach that balances economic efficiency, social cohesion, and environmental responsibility (An & Alarcón, 2020).

The importance of rural tourism as an instrument of sustainable development is also reflected in European Union policy documents. In particular, the European Committee of the Regions (2024) notes that tourism should be an integrated component of long-term rural development strategies and serve as a mechanism to strengthen the resilience, competitiveness, and adaptability of rural areas to socio-economic challenges. In this context, European standards and initiatives, such as the European Charter for Sustainable Tourism, the EU Ecolabel, Blue Flag, and Green Key, are crucial, as they encourage eco-conscious operations in the tourism industry, effectively harmonizing financial growth with the imperatives of nature conservation.

Contemporary discourse on rural development has undergone a substantial transformation – from a paradigm centred on the economic exploitation of natural resources to the concept of regenerative tourism. From this perspective, both tourists' PEB and the consistent application of environmental measures serve as fundamental catalysts for ensuring that tourism-dependent regions remain durable and sustainable in the long run (Iddawala & Lee, 2025).

Environmental practices entail adopting measures to minimize tourism's negative environmental impacts. These include waste sorting and reduction, improvements in energy efficiency, water conservation, support for local products and producers,

and restrictions on single-use materials. Empirical studies show that implementing such practices not only reduces tourism's environmental footprint but also enhances destination attractiveness for tourists with high levels of environmental awareness (Burak & Sorokina, 2025).

The theoretical foundations of research into PEB were established through the definition advanced by scholars who conceptualize it as deliberate behaviour aimed at minimizing the negative impacts of human activity on the natural and built environment (Kollmuss & Agyeman, 2002). Contemporary empirical evidence indicates that the development of such behaviour is strongly shaped by levels of environmental awareness, risk perceptions, and social norms (Chen et al., 2023).

The evolution of academic interest in tourists' PEB has been examined in detail by researchers (Carvajal-Trujillo et al., 2024). In their bibliometric analysis covering the period 1999–2023, the authors systematically mapped the theoretical landscape of this field and documented a shift from foundational models of environmental awareness towards multidimensional approaches integrating concepts from sustainable development, destination management, and behavioural economics. This shift has contributed to growing scholarly attention to the determinants of consumers' pro-environmental behavioural intentions within tourism and hospitality (Gao et al., 2021).

Researchers demonstrate that the principal drivers of tourists' PEB are internal factors, including personal norms, moral obligations, environmental values, and emotional attachment to the destination (Prawira et al., 2024). At the same time, PEB is not confined to the environmental dimension alone; it also encompasses intangible aspects of sustainability, such as respect for local residents, traditions, and culture (Kock et al., 2019). The evidence suggests that tourists' PEB is shaped through the dynamic interaction of internal determinants and external conditions, including destination policies, the availability of eco-infrastructure, social pressure, technological support, emotional engagement, and the broader sociocultural context (Prawira et al., 2024).

Several studies also confirm the important role of destination image in shaping tourists' attitudes and behaviour. Drawing on the cognitive appraisal theory of emotion, researchers have confirmed that destination branding significantly bolsters tourist confidence and contentment. Such dynamics are essential for maintaining the steady and balanced growth of the rural tourism sector (Rao et al., 2022).

Despite the growing scholarly interest in sustainable tourism, the contemporary literature still contains a limited number of empirical studies that comprehensively examine the simultaneous effects of destination environmental practices and tourists' PEB on the sustainable development of rural areas. This relationship remains particularly under-explored in crisis and post-crisis contexts shaped by military conflict. For Ukraine – currently enduring a full-scale war while pursuing a European integration – rural areas assume a distinctive role as spaces of socio-economic resilience, community recovery, and recreational renewal. Accordingly, investigating the relationship between environmental practices in tourism and tourists' PEB is especially pertinent for developing models of sustainable rural development in Ukraine under wartime conditions and in the context of post-war transformation.

The primary objective of this paper is to identify and interpret the role of environmental practices in rural tourism destinations and tourists' PEB in shaping the preconditions for the sustainable development of rural areas in Ukraine.

In pursuit of this aim, the study outlines several key objectives:

1. To characterize the level and principal manifestations of tourists' PEB during trips to rural tourism destinations in Ukraine, based on empirical data collected through an original questionnaire.
2. To analyse tourists' perceptions of environmental practices implemented in rural tourism destinations.
3. To identify and empirically validate the relationship between tourists' perceptions of destinations' environmental practices and tourists' PEB, as interrelated elements in the formation of preconditions for sustainable rural development.
4. To interpret the findings through the lens of sustainable rural development and Ukraine's European integration context, and to develop practical recommendations for their implementation.

In light of the above, it is appropriate to elaborate on a conceptual approach that enables a systematic explanation of the interaction between environmental practices in tourism and tourists' PEB as interrelated drivers of sustainable development in rural areas of Ukraine.

Materials and Methods

To address the research questions, a quantitative design was implemented, involving the collection of first-hand data through a dedicated questionnaire survey. This approach enabled an empirical examination of the determinants of tourists' PEB and an assessment of how environmental practices in rural tourism destinations shape the preconditions for the sustainable development of rural territories in Ukraine. The research is descriptive-analytical, combining the profiling of respondents' behavioural characteristics with an explanation of the relationships among the key variables.

Empirical data were collected in January 2026 via an online survey administered through Google Forms. In total, 200 questionnaires were received. Following an initial screening for completeness, internal consistency of responses, and compliance with the inclusion criterion (experience of visiting rural tourism destinations in Ukraine within the previous 12 months), 128 questionnaires were retained for further

analysis. The remaining questionnaires were excluded due to the absence of relevant tourism experience or incomplete completion of the instrument.

The sample was constructed using convenience sampling, a common and methodologically defensible practice in tourism and consumer behaviour research, particularly in exploratory studies. The selection of this sampling approach was driven by the absence of an accessible and comprehensive sampling frame of tourists who had visited rural destinations in Ukraine during the preceding 12 months, which rendered probability-based sampling methods infeasible. Furthermore, sample relevance was strengthened through the application of a screening criterion, whereby only respondents with recent experience of rural tourism travel in Ukraine were included in the analysis. This procedure enhanced the analytical validity of the empirical data and ensured close alignment between the sample composition and the study objectives. Given the study's objectives and its focus on identifying relationships between destinations' environmental practices and tourists' PEB, this sample size is sufficient for conducting correlation and regression analyses. The sample structure spans diverse age groups, educational levels, and travel frequencies, providing the necessary data variability and enhancing the analytical value of the findings.

The questionnaire was developed and adapted to the purpose of the study and comprised four blocks:

1. respondents' socio-demographic profile and tourism experience (age, gender, education, travel frequency and duration, and types of rural tourism);
2. perceptions of environmental practices in destinations (environmental friendliness of infrastructure, waste management, energy and resource efficiency, and informational support for environmental initiatives);
3. tourists' pro-environmental behaviour (waste reduction, resource conservation, and the choice of responsible services);
4. environmental awareness and behavioural intentions.

To evaluate the constructs in blocks 2–4, a 5-point Likert-type scale was employed, ranging from 'strongly disagree' (1) to 'strongly agree' (5), which allowed for a precise quantitative assessment of the primary research variables.

To operationalize the core concepts, composite indices were constructed. The Environmental Practices Index (EPI) was calculated as the arithmetic mean of five items measuring tourists' perceptions of environmental practices in rural destinations. The Pro-Environmental Behaviour Index (PEBI) was computed as the mean of five items capturing tourists' environmentally responsible behaviour during travel. The Sustainable Rural Development Perception Index (SRDPI) was formed as the mean of five items assessing tourism's economic, social, cultural, and environmental impacts on rural areas. Each index was measured on a scale of 1 to 5, where elevated scores reflect a higher degree of consensus among the participants.

The processing of data involved both descriptive and inductive statistical methods. To examine associations between variables, Spearman's rank correlation was used, given the ordinal measurement scale and the absence of normality assumptions. To quantify the effect of age on tourists' PEB, a linear regression model was estimated with the composite PEBI score as the dependent variable and respondents' age as a continuous numeric predictor. By applying regression modelling, it became possible to evaluate both the orientation and intensity of how demographic factors influence the development of eco-conscious behaviour among visitors.

Participation in the survey was voluntary and anonymous. Respondents were informed about the study's scientific purpose and the confidentiality of data processing. No personally identifiable information was collected.

Limitations of the study include the use of convenience sampling and self-reported data, which may restrict the generalizability of the results. Nevertheless, the adopted methodology is appropriate for identifying key relationships and for formulating practice-oriented recommendations for the sustainable development of rural tourism in Ukraine.

Results and Discussion

Rural tourism in Ukraine has traditionally played an important role in preserving ethnocultural heritage and meeting the population's recreational needs through authentic experiences, local gastronomy, and environmentally oriented leisure activities. However, the challenges posed by the COVID-19 pandemic and the consequences of the Russian federation's full-scale invasion have transformed the sector's functional remit.

At present, under martial law, rural tourism has ceased to be merely an economic sector and has increasingly assumed the features of a strategic instrument for socio-psychological rehabilitation and for strengthening territorial resilience. Contemporary research on community recovery emphasises that the development of rural destinations simultaneously supports psychological restoration, social integration, and the economic adaptability of local communities (Romanova & McGinley, 2025). Time spent in natural environments and physical distance from active combat zones and intense urban pressures contribute to reductions in stress levels, depressive symptoms, and manifestations of post-traumatic stress disorder. At the same time, rural tourism fosters social cohesion through interaction between host communities and internally displaced persons (IDPs), while creating opportunities for self-employment and alternative economic activities under constrained resource conditions.

Against the backdrop of heightened societal sensitivity to issues of safety, health, and quality of life, responsible tourism is increasingly shifting from a form of leisure to a mode of conscious consumption and support for territorial viability. Environmental

practices implemented in rural destinations establish the necessary institutional and behavioural preconditions for tourists' PEB, oriented towards minimising negative environmental impacts and conserving local natural resources. Collectively, these dynamics amplify tourism's contribution to achieving sustainable development goals in rural areas.

The growing demand for domestic rural tourism during martial law reflects a shift in consumer priorities – from seeking entertainment to seeking safety, emotional stabilisation, and an ecologically clean environment. This transformation creates the conditions for new models of sustainable development, within which tourists' PEB becomes an integral element of conserving natural capital and supporting the country's long-term recovery.

In view of the theoretical propositions outlined above, the subsequent section analyses the results of an empirical survey of tourists to identify the characteristics of their pro-environmental behaviour and assess their perceptions of environmental practices implemented in rural tourism destinations in Ukraine.

The synthesis of the socio-demographic characteristics of the 128 respondents enabled the development of a generalised profile of contemporary tourists visiting the country's rural areas. The key sample parameters are presented in Table 1.

The gender distribution of respondents indicates a predominance of women, who constitute 64.1% of the sample, whereas men account for 33.6%; a further 2.3% of participants preferred not to disclose their gender. This structure aligns with patterns reported in prior studies of tourist behaviour, in which women more frequently engage in environmentally oriented leisure.

In terms of age, the most strongly represented group comprises respondents under 25 years (34.4%), suggesting high levels of youth participation in rural and nature-based tourism. At the same time, the sample covers all major age cohorts, providing sufficient variability for subsequent analyses of behavioural characteristics.

With respect to educational attainment, respondents with higher education dominate (51.6%), which is particularly pertinent for research on tourists' PEB, as educational level is commonly associated with environmental awareness and a greater propensity for responsible consumption of tourism services.

The analysis of travel characteristics shows that most respondents prefer short trips of 2–3 days' duration (42.2%), consistent with the domestic rural tourism format as a form of recreational and psychological 'reset'.

Regarding preferences for rural tourism types, the nature-based segment (mountains, forests, protected areas) is predominant, selected by 60.2% of respondents. This corroborates the idea that direct contact with natural environments is a key motive for visiting rural destinations in Ukraine and that these destinations provide conditions conducive to the development of tourists' pro-environmental behavioural patterns.

Table 1

Socio-demographic profile of the survey respondents (n = 128)

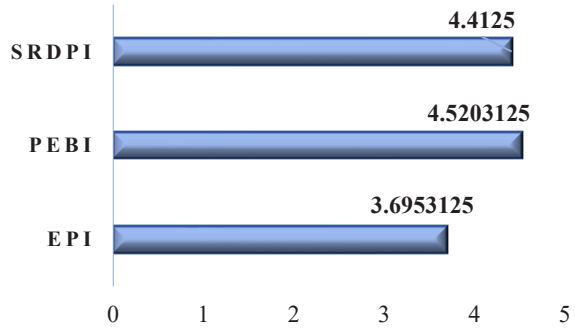
Category	Count (n)	Percentage (%)
Gender		
Female	82	64.1
Male	43	33.6
Prefer not to say	3	2.3
Age		
Up to 25 years	44	34.4
26–35 years	22	17,2
36–45 years	23	18.0
46–55 years	26	20.3
over 55 years	13	10.1
Education		
Secondary	25	19.5
Vocational	14	10.9
Higher education	66	51.6
Academic degree	23	18.0
Travel frequency		
Once a year	49	38.3
2–3 times a year	50	39.1
4 or more times a year	29	22.6
Trip duration		
1 day	46	35.9
2–3 days	54	42.2
4–7 days	23	18.0
More than a week	5	3.9
Preferred type of rural tourism		
Rural green homesteads	37	28.9
Eco-farms / farm enterprises	13	10.1
Nature-based tourism (mountains, forests, protected areas)	77	60.2
Other	1	0.8

The next stage of analysis involves assessing the integrated measures reflecting perceptions of destinations' environmental practices, the level of tourists' pro-environmental behaviour, and their views on tourism's contribution to sustainable rural development. To this end, the relevant composite indices (EPI, PEBI, and SRDPI) were calculated, and their mean values are presented in Figure 1.

The results indicate a relatively high level of respondents' pro-environmental orientation. The highest mean value is observed for the Pro-Environmental Behaviour Index (PEBI = 4.52), suggesting that tourists are willing to comply with environmental norms, use resources sparingly, minimise waste, and support local products when

travelling to rural destinations. This points to the presence of well-established behavioural dispositions oriented towards the responsible consumption of tourism services.

Figure 1
Mean values of indicators of environmental practice perception, tourists' PEB, and the impact of tourism on sustainable rural development



The mean level of perceived tourism contribution to sustainable rural development (SRDPI = 4.41) is also high. Respondents largely agree that tourism supports community economic development, job creation, the preservation of cultural heritage, and the protection of the natural environment. This indicates that tourists recognise the broader socio-economic role of tourism in the development of Ukraine's rural areas.

At the same time, the index capturing perceptions of destinations' environmental practices (EPI = 3.70) is moderately high but lower than the indices for behaviour and perceived sustainable development impacts. This divergence may signal a gap between tourists' environmental readiness and the actual extent to which environmental solutions are implemented in rural tourism destinations. In other words, there is a mismatch: tourists appear to demonstrate a higher degree of environmental responsibility than the destination's current infrastructure and management practices can accommodate.

The imbalance highlighted above underscores the need for more proactive implementation of environmental practices at the level of rural destination governance, as such practices can reinforce and institutionalise tourists' existing pro-environmental dispositions.

The next stage of the analysis aimed to test the statistical relationships between perceptions of destinations' environmental practices, the level of tourists' PEB, and assessments of tourism's contribution to sustainable rural development. To this end, Spearman's rank correlation analysis was applied, and the results are presented in Table 2.

Spearman's rank correlation analysis was used to assess the relationships between EPI, PEBI, and SRDPI. The results indicate statistically significant positive associations among all variables ($p < 0.01$). In particular, a moderate positive relationship was observed between perceptions of environmental practices in destinations and tourists' pro-environmental behaviour ($\rho = 0.38$), suggesting that the more favourably tourists evaluate the extent to which environmental measures are implemented in a destination, the more actively they exhibit environmentally responsible behaviour during travel.

A positive association was also identified between perceptions of environmental practices and assessments of tourism's contribution to sustainable rural development ($\rho = 0.42$). This finding implies that destinations' environmental orientation strengthens tourists' perceptions of tourism's economic, social, and environmental benefits to local communities.

Table 2
Spearman's rho correlation coefficients for the analyzed constructs

Variables	1	2	3
1. Perceived destination environmental practices	1.000		
2. Tourists' pro-environmental behaviour	0.38**	1.000	
3. Perceived tourism contribution to sustainable rural development	0.42**	0.44**	1.000

Note: Statistical significance is indicated as follows: *$p < 0.05$; **$p < 0.01$. Values where $p \geq 0.05$ are considered statistically non-significant.

The strongest correlation was observed between tourists' pro-environmental behaviour and their perceived contribution to sustainable development ($\rho = 0.44$). This result supports the notion that tourists with higher levels of environmental responsibility tend to evaluate tourism's contribution to rural development more positively, including in terms of employment, cultural preservation, and environmental protection.

To quantify the effect of age as a potential determinant of tourists' pro-environmental behaviour, a linear regression model was estimated. The dependent variable was PEBI (scale 1–5), and the independent variable was respondents' age, coded as a numeric predictor based on age categories (Table 1).

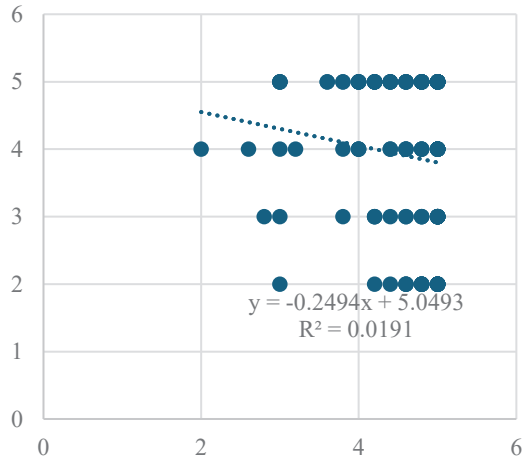
The regression results indicate that the model has low explanatory power ($R^2 = 0.019$) and is not statistically significant ($F(1,126) = 2.45$; $p = 0.120$). The coefficient for the 'age' variable is negative ($B = -0.077$), suggesting a slight tendency for PEB to decrease as age increases; however, this effect does not reach statistical significance ($p = 0.120$).

To visualise the results, a scatterplot with an overlaid linear regression line was constructed (Figure 2), showing a weak linear trend between respondents' age and their pro-environmental behaviour.

The findings indicate that, within the studied sample, age is not a decisive factor in shaping tourists' PEB. Only around 2% of the variance in PEBI is explained by age-related characteristics, confirming the limited role of this demographic determinant. This conclusion

is consistent with contemporary research in sustainable tourism, which emphasises that tourists' PEB is increasingly driven not by socio-demographic attributes, but by cognitive and contextual factors – particularly environmental awareness, value orientations, and perceptions of destinations' environmental practices (Han, 2015; Kang, 2022). As Han argues, it is the configuration of attitudes, norms, and perceived behavioural control that shapes tourists' readiness to engage in environmentally responsible behaviour far more strongly than age or gender (Han, 2015).

Figure 2
Relationship between tourists' pro-environmental behaviour and age



In the context of Ukraine, experiencing a full-scale war and anticipating post-war reconstruction, these results acquire additional strategic significance. The recovery of rural areas is increasingly understood not merely as an infrastructural endeavour, but as a socio-environmental task. Tourism can act as a catalyst within this process, stimulating economic activity, safeguarding natural capital, and strengthening local community identity. Under such conditions, tourists' pro-environmental orientation is shaped less by age and more by the extent to which destinations embed sustainability principles in post-war development models and effectively communicate them to visitors.
Accordingly, fostering tourists' PEB during Ukraine's recovery period requires systematic institutional action. This entails an active role for national authorities and local self-government in mainstreaming 'green recovery' standards into tourism policy, expanding environmental infrastructure, strengthening environmental education for tourists, supporting local initiatives, and engaging communities in the governance of natural resources. Coordinated efforts by the state, business, and territorial communities can transform rural tourism into a vehicle not only for economic recovery, but also for the ecological modernisation of rural areas in the post-war period.

Conclusions

The study substantiates the role of environmental practices in tourism and tourists' pro-environmental behaviour as strategic determinants of sustainable development in rural areas of Ukraine. It demonstrates that, under crisis transformations triggered by war, sustainable rural tourism constitutes not only an economic priority but also an instrument of socio-environmental resilience and post-war community recovery. The empirical evidence confirms that sustainable rural tourism cannot be understood solely as an outcome of managerial or infrastructural decisions; rather, it depends substantially on tourists' behavioural patterns and on how they perceive the environmental orientation of destinations.

1. A high level of pro-environmental orientation among contemporary tourists visiting rural destinations in Ukraine was identified. The calculated Pro-Environmental Behaviour Index (PEBI) indicates respondents' established readiness for prudent resource use and for supporting local ecosystems. This suggests that Ukraine already possesses behavioural potential that can be used as a basis for the sustainable development of rural tourism.
2. The results show that tourists assess tourism's contribution to sustainable rural development positively, associating it with the economic activation of communities, the preservation of cultural heritage, and the protection of natural resources. At the same time, the Environmental Practices Index (EPI) was lower than the level of tourists' behavioural readiness. This points to a gap between tourists' environmental intentions and the actual extent to which environmental solutions are implemented in rural destinations in Ukraine.
3. Statistically significant positive relationships were empirically confirmed between perceived destination environmental practices, tourists' PEB, and assessments of tourism's contribution to sustainable rural development. This indicates that environmentally oriented destination governance not only affects environmental outcomes directly but also shapes tourists' behavioural patterns, which, in turn, amplify the effects of sustainable development at the community level.
4. The regression analysis challenges the stereotype of age-determined environmental responsibility, as demographic characteristics explain only around 2% of the variance in PEBI. This supports the view that environmental responsibility in tourism is increasingly shaped not by age, but by cognitive, motivational, and contextual factors—particularly by how destinations implement and communicate their environmental practices.

Within the context of Ukraine's Green Recovery, rural tourism is conceptualised as a mechanism of socio-environmental modernization. The strategic success of reconstruction depends on integrating environmental

standards into local governance and on creating institutional conditions that enable and sustain local environmental initiatives. The findings can be utilized by public authorities when designing regional development programmes that combine economic revitalization with the conservation of natural capital and the strengthening of local identity.

Future research should focus on the spatial differentiation of pro-environmental behavioural patterns across Ukraine's regions and on assessing the influence of digital eco-tools on the transformation of tourists' behaviour in the post-war period.

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SUSTAINABILITY COMMUNICATION: FROM SMALL ENTERPRISES TO STRONG COMMUNITIES IN THE REGIONS OF LATVIA

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Abstract
Sustainability communication has emerged as a critical tool for organizations seeking not only to strengthen their market positioning but also to engage meaningfully with society. Enterprises are increasingly expected to demonstrate responsible business practices, yet translating sustainability commitments into tangible actions at the local level remains a significant challenge. However, the effectiveness of such commitments largely depends on how well sustainability communication is implemented and coordinated across all stakeholders. Despite its growing importance, research examining how companies, particularly small and medium-sized enterprises (SMEs) in Latvia, implement sustainability communication in local contexts is limited. Addressing this gap is essential for understanding how businesses can move beyond symbolic efforts to achieve meaningful, community-oriented outcomes. Integrating sustainability into engagement with local communities enables companies to build long-term relationships that foster trust and enhance competitiveness, stimulating innovation and facilitating access to new markets and critical resources to strengthen regional development. Therefore, sustainability communication plays a crucial role in translating sustainability commitments into meaningful local engagement. This research aims to investigate how small and medium-sized enterprises in Latvia's regions implement sustainability communication at the local level. The study used mixed methods. The study demonstrates that fragmented responsibility across supply chains results in an inconsistent approach to sustainability communication. This lack of centralized accountability not only hampers the development of a shared understanding of sustainability but also constrains the implementation of coordinated practices across different actors.
Keywords: sustainability, SMEs, stakeholder management, local communities.

Introduction

The European Union (EU) purposefully implements a holistic approach that contributes to a sustainable and resilient future. The 17 Sustainable Development Goals (SDGs) of the United Nations (UN) 2030 Agenda are integrated into policies of the EU and the core development strategies of its Member States. These goals are reflected in both the European Green Deal and long-term budget planning (European Commission, 2026). Although significant progress has been achieved (Eurostat, 2026), starting in 2026, the EU has increasingly focused on the green and digital transition, promoting economic growth, social progress, and environmental protection, while striving to make substantial progress in reducing inequalities and ensuring decent work (European Commission, 2026). Within this EU policy context, there is a growing need in Member States to integrate the SDGs not only at the national or regional level, but also at the business level - including small and medium-sized enterprises (SMEs), and within local communities.

Understanding sustainability principles and communicating sustainability can often be challenging for SMEs, as it may also impose an additional burden in ensuring the provision and reporting of sustainability data. It is therefore not surprising that in the summer of 2025, the European Commission adopted a standard for voluntary sustainability reporting specifically for SMEs. SMEs can use this framework to improve their access to sustainable finance, enhance competitiveness, and better understand sustainability-related indicators (European Commission, 2025). At the same time, it should be recognized that implementing these practices will require additional resources and capacities from SMEs.

The Latvian National Development Plan for 2021-2027 (Cabinet of Ministers, 2023) and the Sustainable Development Strategy of Latvia for the planning period up to 2030 (Cabinet of Ministers, 2026) define entrepreneurship as part of the key sectors in the context of sustainable development. The sustainable use of resources is one of the preconditions for competitive entrepreneurship, while social responsibility and productivity are essential prerequisites for business activity, promoting balanced regional development in the country. Entrepreneurship within the framework of these two planning documents is linked to sustainability in relation to the labour market, innovation, productivity, exports, and capital. Unfortunately, Latvia's competitive weaknesses include a low level of innovation and low business sophistication, which are lacking, for example, in the implementation of competitive marketing practices and thus in integration into global value chains (Ministry of Economics, 2018; Think factory LV PEAK of University of Latvia, 2025). Sustainability is viewed as the implementation of new opportunities, new business models and practices, ultimately leading to the development of innovative approaches and innovations. Sustainability communications serve as an instrument that helps not only to transform these business models but also to build a link with other stakeholders, including society at large. Sustainability communication is closely integrated with the fields of economics and management, yet it is developed on the principle of long-term success (Bittner-Fasseler & Weicht, 2020).

This research aims to investigate how small and medium enterprises in Latvia's regions implement sustainability communication at the local level. The study seeks to answer the following research

questions: 1) How are the concept and essence of sustainability communication understood in theory? 2) How do small and medium-sized enterprises in Latvia's regions currently implement sustainability communication in practice? The following hypothesis was formulated: the conceptualization and strategic framing of sustainability communication within SMEs are determined at the managerial level, whereas operational execution is delegated to specialized communication practicioners.

Materials and Methods

To achieve the aim and answer the research questions, a mixed-method research design was chosen for data collection.

In the qualitative part of the research, four in-depth interviews with SME representatives and two expert interviews were conducted. The selection of information was carried out taking into account the size of the company and its turnover.

A total of 200 SMEs from Latvia's five planning regions participated in the survey in 2025. Most respondents represent sectors, such as agriculture, forestry and fisheries, as well as manufacturing, construction and trade. Of the 200 SMEs, 190 stated that they implement sustainability communication; therefore, the analysis includes and is based on the responses of these 190 enterprises. In the data collection and analysis process, adherence to the fundamental principles of research ethics was observed by all participants, and the anonymity of survey respondents was ensured.

Theoretical explanation of sustainability communication

When evaluating the three main dimensions of sustainability in the context of business, the authors also refer to the concept of the 'Triple Bottom Line', introduced by John Elkington to expand the traditional view of business beyond profit indicators to a broader approach that balances economic, social, and environmental aspects. This concept relates to the assessment of corporate sustainability performance using the following criteria: people (social dimension), planet (environmental dimension), and profit (economic dimension) (Salimi & Vrauwdeunt, 2024; Elkington, 2004).

Overall, Corporate Social Responsibility (CSR) is a voluntary business practice that promotes ethical and sustainable operations, as well as positive impact on society and the environment, including cooperation with stakeholders and adherence to international standards, as explained on the website of the Ministry of Welfare. As highlighted in research, the development of this model is closely linked to a country's specific economic situation, social needs, and cultural characteristics (Lenssen et al., 2014).

In countries with strong social security systems and regulated labour markets, companies more often cooperate with governments and civil society organizations. In contrast, in countries with more liberal economies, initiatives more frequently originate from entrepreneurs themselves and other market participants. Addressing sustainability issues requires cooperation among various stakeholders in society.

The Environmental, Social, and Governance (ESG) model has evolved from the Corporate Social Responsibility (CSR) model and emphasizes a stakeholder-oriented approach, and values, such as integrity, transparency, and purposefulness in 'making money'. At the same time, it evaluates a company's impact on the environment and society through the lenses of risk, profit, and investment (Fenwick et al., 2022). This model contributes to enhancing companies' long-term competitiveness. Within this framework, SMEs, by collaborating with larger organizations, can develop a sustainable competitive advantage.

Meanwhile, Michael E. Porter and Mark R. Kramer propose the concept of 'creating shared value', whereby companies generate economic value while simultaneously creating value for society. The authors explain that this is a strategic approach that integrates social and environmental considerations into a company's core business activities. Within this framework, value chains play a significant role, aiming to improve competitiveness while simultaneously supporting the development of local communities by rethinking products and markets in line with societal needs. In essence, the idea suggests that 'doing good is good for business, not simply because it is expected' (Porter & Kramer, 2011).

In summary, the authors conclude that stakeholders, values, and processes play a crucial role when implementing sustainability. The interaction of these elements shapes the modern understanding and practice of sustainability in companies, where values become a catalyst for corporate sustainability, which, in turn, determines a company's focus on risk and process management.

To ensure sustainable development, it is necessary to actively invest in communication that explains the benefits of sustainability and promotes public understanding. Sustainability cannot be achieved solely through political declarations or academic research; rather, it is a long and complex process that requires changes in both societal behaviour and business practices (Primoži, 2022; Elkington, 2004).

The concept of sustainability communication is multidimensional, and its interdisciplinary nature highlights the complexity of its theoretical framework. To explain the concept of sustainability communication, the theoretical framework will be based on J. Grunig's Excellence Theory, R. E. Freeman's Stakeholder Theory, and Sustainability Management Theory (Grunig, 2023).

Today, sustainability communication is seen as a value creation process (Johansson et al., 2018). Essentially, this approach integrates both human resource management and corporate social responsibility principles, becoming a strategic tool (Bittner-Fesseler

& Weicht, 2020). In this context, employees act as change agents, helping to implement the organization's sustainability objectives. Public relations form a smaller part of this strategic sustainability communication, which enables organizations to gain an 'outside-in' perspective, adapting their strategies to the needs of stakeholders and thereby incorporating societal values into their operations (Steyn & Niemann, 2014).

Research shows that media attention to sustainability issues increases in response to major events – such as scandals, significant policy decisions, or global trends – resulting in fluctuating, wave-like patterns of attention (Barkemeyer et al., 2009). The problem is that interest and attention spike following major events, but if no ongoing communication follows, relevance, attention, and public interest quickly decline. In this context, sustainable communication requires the regular integration of content into daily interactions to maintain engagement and awareness.

Companies that, for example, become the focus of media attention due to 'greenwashing' face the risk of reputation damage, which can even affect their financial performance (Slutskiy et al., 2024) and result in a loss of stakeholder trust.

Companies need to ensure transparent and honest communication, thereby fostering corporate openness and stakeholder trust at both the community level and the broader societal level.

The role of sustainability communication by small and medium-sized enterprises (SMEs) in regional development

Previous research has concluded that SMEs are an important driving force for regional development, as they implement regional economic and sustainability strategies, providing benefits to local communities (Salimzadeh & Courvisanos, 2015). To implement sustainability practices, SMEs need to establish close collaboration with stakeholders, which may include sustainability training, networking with local communities, and effective cooperation with other stakeholders (Smith et al., 2022). Research has shown that sustainability practices are influenced differently by various stakeholders, such as legislators, environmental groups, financial institutions, suppliers, local community representatives, and the social responsibility awareness of SME (Saveanu et al., 2021). SMEs still struggle to integrate social and environmental considerations into their business practices, facing challenges such as limited understanding of sustainability impacts and benefits, as well as constraints in time and resources (Journeault et al., 2021). Although SMEs often encounter these difficulties, studies indicate that they regularly support culture, education, youth, sports, and other local initiatives in their regions, driven by the sense of responsibility to communities in which they operate. Unlike larger corporations, whose actions tend to be more formalized and strategically planned, SMEs often employ more informal strategies to address sustainability in their local contexts (Derecskei et al., 2024).

This study will provide a better understanding of sustainability communication by SMEs in Latvia, highlighting both the benefits and challenges they face.

Results and Discussion

Communication in organizations should generally be viewed in the context of organizational intelligence and integration processes (Genc, 2017). It becomes a system that transforms the organization's intellectual and social capital, creating shared expectations and understanding of the messages being conveyed. By communicating its core values and sustainability goals to its employees, an organization ensures that these principles are more likely to guide its interactions with external stakeholders and its practical business practices. Thus, implementation largely depends on employees' understanding. In this context, the implicit and explicit attitudes of management and employees become highly significant. For example, management may publicly support sustainability initiatives, but unconsciously prioritize short-term gains and new market opportunities, such as attracting 'green consumers', without making changes to internal organizational processes. As a result, this can conflict with long-term sustainability goals. Understanding these dynamics is crucial for developing effective internal communication, creating more targeted external communication practices, and identifying discrepancies between the organization's publicly stated values and actual sustainability actions. This, in turn, promotes bigger changes not only within the organization, but also in consumer behaviour (Elving, 2020). The study focuses on specific employee roles, each with a distinct function in sustainability communication. The results reflect respondents' opinions on which employees in SMEs best understand sustainability communication. The data indicates that 35.5% of respondents perceive the company manager as possessing a 'comprehensive understanding' of sustainability communication (Table 1). Empirical findings indicate that 32% of respondents perceive deputy managers as possessing a 'comprehensive understanding' of sustainability communication. Notably, communication specialists received the highest proportion of affirmative responses, with 37% of participants selecting 'fully agree', metric. This disparity likely reflects the specialized professional competencies and functional responsibilities inherent to the latter role.

Based on respondents' evaluations, certain employee groups were identified as having a lower understanding of sustainability communication. These groups are hierarchically further from company management (Table 1). Overall, consistent with findings elsewhere, the central tendency indicates 'partially understands' (Mdn=3.00), representing a moderately positive level of understanding.

Table 1

Employees' Understanding of Sustainability Communication in SMEs, N=190

Survey statements	Mdn	IQR	%				Mdn		U
			1	2	3	4	Small enterpr.	Medium enterpr.	
Company Manager	3	1	2.5	8	49	35.5	3	3	4106.00
Deputy Manager	3	1	2	8	53	32	3	3	4112.50
Communication Specialist	3	1	6	9	43	37	3	3	3992.50
Human Resources Specialist	3	1	6	14.5	50	24.5	3	3	3908.00
Production Specialist/Manager	3	1	6.5	9.5	50	29	3	3	3940.50
Procurement Specialist/Manager	3	1	6.5	14.5	49.5	24.5	3	3	4010.00

Note: $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.*

Table 2

Employee-implemented Sustainability Communication, N=190

Survey Statements	Mdn	IQR	%				Mdn		U
			1	2	3	4	Small	Medium	
Company Manager	3	1	4.5	14.5	36.5	39.5	3	3	4170.00
Deputy Manager	3	2	9.5	19	40	26.5	3	3	3782.00
Communication Specialist	3	2	10.5	19	31.5	34	3	3	3524.50**
Human Resources Specialist/Manager	3	1	19	18	37	21	3	3	3340.50**
Production Specialist/Manager	3	2	18	16	36	25	3	3	3729.50
Procurement Specialist/Manager	3	2	19.5	14.5	36	25	3	3	4200.00

Note: $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.*

A more detailed examination of responses shows that both company groups similarly assessed employee understanding, maintaining the same central tendency (Mdn=3.00). The interquartile range (IQR=1) indicates a relatively consistent level of agreement, meaning that responses are clustered around the central tendency 'partially understands'. No statistically significant differences were found, suggesting that the level of understanding of employees in SMEs is relatively uniform.

In the context of sustainability, sustainable communication also gains significance. Its essence is not merely formal information exchange, but rather the development and maintenance of long-term relationships (Bittner-Fesseler & Weicht, 2020), while sustainability communication conveys values, risk, and process management to stakeholders. Policymakers and regulators also play an important role in the implementation of sustainability, as they play a decisive role in promoting sustainable business through regulatory and economic instruments. A balanced approach must be applied here by combining the 'carrot-and-stick' (taxes-subsidies) approach. There is a significant difference between passive reporting of sustainability efforts and active sustainability communication. While the ESG model is primarily relevant to the state and policymakers, other stakeholders (employees, consumers, etc.) are more effectively engaged through information communicated in a way that is understandable to them; within companies, this ultimately translates into sales performance. In order to further explore how such engagement is reflected in practice, this study examines differences in sustainability communication practices in SMEs. Respondents were asked to assess how frequently the employees listed in the survey implement sustainability communication within their company. According to respondents, company managers are most frequently involved in implementing sustainability communication, with 39.5% indicating 'often', and 36.5% indicating 'sometimes'. Deputy managers show slightly lower activity, with 26.5% rating 'often' and 40% 'sometimes'. Evaluating extremely negative responses ('never'), it is evident that the proportion of such answers increases gradually as one moves further from the company manager position. These results indicate that, in respondents' views, management involvement in sustainability communication is the most active, reflecting the implementation of sustainability communication at the strategic level of the company. Communication specialists were assessed as the second most active employee group in sustainability communication implementation, with 34% of respondents indicating 'often', which is understandable given the specific nature of their professional role in sustainability communication.

At the operational level, employees' implementation of sustainability communication received similarly positive evaluations. Both production and procurement specialists – including their respective

managers - were rated as 'often' engaged by 25% of the respondents. For Human Resources specialists, the lowest fully positive rating ('often') was observed with only 21% of respondents, which may indicate an incomplete understanding of the HR specialists' potential role in implementing sustainability communication within the company (Table 2).

The data indicate a moderate central value of 'sometimes' (Mdn=3.00) across all statements. Different interquartile ranges (IQR=1 and IQR=2) were observed, suggesting that employees in SMEs do not implement sustainability communication uniformly, and its regularity varies (Table 2).

The interquartile range shows that a more consistent perception of sustainability communication among employees exists only for the company manager and the Human Resource specialist, as evidenced by the small spread of responses clustered around the mean value (IQR=1). For the remaining employees, the evaluation of sustainability communication shows a more uneven spread of responses (IQR=2), indicating greater differences of opinion among respondents and a lower consensus regarding the sustainability practices carried out by these employees. For communication specialists, statistically significant differences were observed ($U=3534.50$, $z= -1.97$, $p< .05$), though very close to the threshold. This indicates that there is a likely, but small, difference between groups' opinions regarding how this employee implements sustainability communication. Similarly, statistically significant differences were found for Human Resources managers/specialists ($U=3340.50$, $z= -2.52$, $p< .01$). Here, the difference between groups is more pronounced, providing greater confidence that respondents' evaluations or experiences regarding sustainability communication implementation vary significantly.

The engagement of employees and other target audiences within the context of stakeholder management is essential for the implementation of sustainability communication.

Socially responsible organizations actively seek to establish this connection with society before making decisions, which subsequently results in competitive advantages, greater employee engagement, stronger reputation, and improved crisis prevention. Moreover, a key aspect of engagement is not addressing 'society as a whole', but rather identifying those segments of society that are directly affected by the organization's decisions, products, and services. By addressing the problems of one such 'small' community, a contribution is made to society as a whole (Grunig, 2023). It is also important to note that, according to Grunig, crises in organizations are more often caused not by external influences but by management decisions that have either not been communicated at all or have been poorly communicated to the targeted audience.

Often, lower-level employees in companies do not understand how to involve stakeholders in sustainability communication, and sustainability communication is interpreted simply as building relationships with customers and collecting feedback, which can hinder the improvement of competitiveness and full integration of sustainability dimensions in small and medium-sized enterprises.

Overall, the study underscores the necessity for SMEs to internalize sustainability frameworks in a manner that ensures organizational alignment without compromising operational efficiency or market competitiveness. This requires reviewing internal organizational processes and balancing all dimensions of sustainability, rather than focusing solely on the economic dimension.

Conclusions

1. Sustainability, including sustainability communication, is a necessity, not a choice, not only within the framework of EU policy, but also for small and medium-sized enterprises, although it often creates additional administrative and resource burdens.
2. The role of sustainability communication: it is no longer just information, but a strategic tool that helps transform business models and build connections with society, based on the principles of long-term success.
3. The study found that the involvement of the company's management in the implementation of sustainability communication is critically important and determines the company's strategic approach, while lower-level employees ensure its practical implementation in the company's daily processes, emphasizing and implementing sustainability communication in the team as a whole.
4. Employee awareness and implementation of sustainability communication are closely related to stakeholder engagement, in which the most active roles should be taken by managers of small and medium-sized enterprises, communication specialists, and procurement specialists. It should be noted that medium-sized enterprises in Latvia demonstrate a greater understanding of sustainability communication and its importance, including within the internal environment of the company, than small enterprises.
5. Medium-sized companies in Latvia better understand the role of employees at all levels in implementing sustainability communication, thus better using the opportunity to convey the company's values and sustainability principles internally, while strengthening the company's reputation. Such an approach promotes a unified corporate culture and more sustainable business development, as well as creates advantages in the labour market, especially in attracting younger generations of employees.

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POWER RELATIONS IN SENIOR CARE: COMMUNITY-BASED AND LONG-TERM CARE SOLUTIONS

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Abstract
Senior care takes place under conditions of increasing population ageing, the deinstitutionalization of services, and resource constraints, which foreground the analysis of power relations. In the care process, older adults often find themselves in a vulnerable position due to health problems, functional limitations, and social dependence. The aim of the study is to explore power relations in senior long-term care and community-based solutions in home care. The research questions examine manifestations of 'power over' and 'power with' in long-term care institutions and home care settings, and explore the factors shaping power relations in senior care provision. The research results reveal how power relations in senior care may emerge as 'power over' where one individual exerts power over another, resulting in unequal relationships between the caretaker and the caregiver, and as 'power with', where power relations are formed among senior as caretaker and caregivers based on principles of equality in decision-making. This study focuses on rural areas of Latvia outside Riga. Home care services are financially, administratively, and organizationally dependent on local communities. Therefore, community-based solutions largely determine the nature, scope, and organization of these services. Furthermore, because of the deinstitutionalization process in Latvia, institutional social care services are increasingly being brought closer to a home-like environment. Although long-term care institutions remain a form of institutional care, they are progressively incorporating elements associated with community-based initiatives, including person-centered approaches, greater social participation, and stronger links with local communities. Community-based solutions are potential mechanisms for balancing power in senior care.
Keywords: senior care, power relations, vulnerability, risks, community-based services.

Introduction

In the 21st century, rapid changes in society require attention to the potential of an ageing society and how to treat this age group more respectfully. Increasing importance is being placed on how to address people who exceed a certain age limit more respectfully, without emphasizing their biological age (Amundsen, 2022). This is particularly important for seniors receiving long-term social care services at home (for 12 months or longer), hereafter referred to as **home care**, as well as for seniors receiving care in long-term care institutions (hereafter referred to as **LTCIs**). **Seniors** are understood the people who have reached the old-age pension age, in accordance with the Latvian retirement age, which is 65 years (On State Pensions, 1995; State Social Insurance Agency, 2025). Seniors as caretakers need not only social care services, but also the company of peers and communication with them (Tripathi, 2014). Vulnerability of seniors is linked to necessity to adapt to the new circumstances, to change their previous life. As people age, their needs change, which may also increase the need for care provision at a certain age. The article focuses on issues of power relations in senior care, which is provided by local communities (municipalities) through the provision of home care services, as well as through the provision of care services in LTCIs. These services in Latvia are the responsibility of local, municipal governments, as their implementation varies from county to county. The European Expert Group on the Transition from Institutional to Community-based Care (EEG) provides expertise on the transition to family- and community-based support. Such a transition requires changes to institutional practices whereby residents are isolated from the wider community and are unable to choose with whom they live. It also requires addressing situations in which residents do not have sufficient control over their own lives or over decisions that affect them (EEG, 2023).

Community-based solutions include a wide range of services and support systems designed to help seniors live autonomously for as long as possible in their home or more independently in LTCIs. The municipal services can include voluntary activities, transportation, meal delivery, health care and social activities, all of which are tailored to the unique needs of seniors (Siegler et al., 2015; Li et al., 2024; Lindén & Trætteberg, 2025). In Latvia, senior LTCIs are also the responsibility of municipalities, so in this article we focus on both social care at home and in institutions, but not health care.

Rural areas in Latvia are generally defined as territories outside the capital city of Riga, its surrounding region, and other major cities.

Social care is necessary to ensure a full life for those seniors who have difficulty meeting their basic daily needs. Social care is a socially constructed phenomenon, the provision of which can involve violations of moral and ethical boundaries (Phillips, 2007; Arjama et al., 2024), when individual human needs collide with the risks of power relations created by the limited possibilities of providing care services. When characterizing social care at home or in LTC institutions, the challenge is how and who will provide care, maintaining a certain degree of independence for seniors 65+, for as long as possible (Phillips, 2007; Gurung & Chaudhury, 2025; Moilanen et al., 2025). This indicates that care can also be seen as an element of power and resistance to this power would mean giving up the opportunity to receive care (Fox, 1993; Andersson et al., 2017). This means that receiving care services is usually associated with the willingness to obey certain rules, to fulfil requirements, because

otherwise care services will not be available. For example, by refusing the opportunity to receive care services at home, there is a risk of becoming even more dependent on the social care providers. In Latvia, seniors entering LTCIs usually have to part with their pets and familiar furniture, adapt to having a roommate(s), and adjust to the institution's strict routines.

In this article, we will analyze power relations in social care at home (at the place of residence), which is provided by the municipality or organization selected by it, as well as in social care in LTCIs. The aim of the study is to explore power relations in senior long-term care and community-based solutions in home care. As a community-based service, home care varies by municipality, utilizing local NGOs, volunteers, and municipal caregivers. The research questions are: 1) How are power relations exercised in LTCIs and home care?; 2) What are the differences in manifestations of ʿpower over' and 'power with' between LTCI and home care?; 3) What are examples of ʿpower with' in senior care within LTCI and home care settings?; 4) What factors shape ʿpower with' and ʿpower over' relationships in senior care provision?

The research tasks are: 1) theoretically interpret power relations in senior care; 2) to describe possibilities of community-based services in senior home care and LTCI; 3) to identify power-related issues in senior home care and LTCI and explore how community-based solutions could be applied.

French researcher of social power relations Michel Foucault argues that power is everywhere (Foucault & Faubion, 2000). Power relationships arise when one person or group of people with greater social influence, through social, cultural or institutional superiority, can influence the actions of another person or group of people, even if this action does not correspond to the wishes of the other party (Foucault, 1978).

When examining the relationship between service providers and recipients, authors focus on two distinct power dynamics: first, where the caregiver holds the dominant power over the senior; and second, where the dynamics reverses, giving the senior greater leverage over the caregiver.

'Power over' and 'power with' are associated with Foucault's idea of the directions of dominance and resistance of power. The authors explain 'power over' as control and the ability to determine the limits of the actions of others, which are often based on hierarchical relations and institutional mechanisms. 'Power with' is interpreted as a form of collaborative influence and shared participation in decision-making processes, where goals are achieved in partnership, using shared knowledge, resources and responsibility (Foucault, 1980; Tew, 2006; Karim, 2023; Charfe, 2026).

'Power over' in the context of social care for seniors is often exercised by institutions (such as LTCIs, municipal services or home care organizations) and their employees over seniors, determining daily routines, access to resources and services, as well as decisions about the type and extent of social care. Institutional rules and procedures can reproduce seniors' dependence on care providers, for example by limiting their ability to make independent decisions about their daily lives. **'Power over'** is expressed through direct control over time, freedom of movement and daily activities. Seniors' autonomy is possible if seniors are provided with access to information about their rights, support for the implementation of these rights, and real participation in decision-making.

'Power with' in social care for the seniors means that decisions about care are made in collaboration between the seniors, caregivers, family members, and policymakers. It could take the form of joint working groups where seniors and staff agree on adjustments to the daily routine bring together different perspectives to achieve better results. Collaborative partnerships can be formed between seniors and care staff to achieve better living conditions, but they can also be formed between management and staff to maintain the existing order by limiting the influence of seniors (Meagher & Szebehely, 2013). Unlike 'power over', 'power with' offer alternative models of power that can reduce dependency and promote autonomy in social care for seniors (Tew, 2006).

Materials and Methods

The research is based on case study approach applying statistical analysis and qualitative semi-structured interviews with nine seniors (S), nine caregivers (CG), nine social workers (SW), and seven organizers of community-based social care services (SO) (34 semi-structured interviews). Data saturation was achieved after the first 28 semi-structured interviews. However, to ensure the validity of the findings, six additional interviews were conducted. The temporal boundaries of the case cover the period from 2016 to 2026. The first five years (2016–2020) were devoted to the exploratory phase of the study, while the following five years (2021–2026) comprised the main research phase.

The spatial borders of case are seven rural counties from four Latvia regions. The purposive sampling covered rural areas in four regions in Latvia outside of Riga and major cities. The study was based on seven case studies conducted in rural municipalities across four administrative regions of Latvia: Vidzeme (V1–V3), Zemgale (Z1), Kurzeme (K1), and Latgale (L1–L2). The case studies primarily focused on the manifestations of 'power over' and 'power with' in the provision of care for seniors in home care and long-term care institutions (LTCIs). Community-based solutions provided the context for exploring these power relations, including home care services and the incorporation of community-based elements into LTCIs as part of the deinstitutionalization process.

These research participants joined the study on a voluntary basis with written informed consent. The thematic data analysis is performed from the perspectives of sociology and social work.

Results and Discussion

According to Central Statistical Bureau of Latvia (CSB, 2026a) data, at the end of 2024, there were 110 LTCIs for adults where social care is provided for seniors. Compared with 2020, the number of residents of LTCIs in the municipal sector increased by 2024, which indicates a growing demand for long-term social care services at the municipal level (Table 1). The care level is indicated by numbers from 1 to 4. A higher level of care (e.g., care level 4) indicates that a senior requires a broader and more intensive range of services. Since 2020, there has been a continuous increase in the number of seniors assigned to care levels 3 and 4. In contrast, the number of people at care level 1 is decreasing, indicating that long-term social care is increasingly provided to individuals with severe functional impairments. This indicates that municipal LTCIs are mostly provided to seniors who need more intensive care and cooperation with medical service providers. Power relations are also related to the possibilities of financial autonomy, the ability to pay for the necessary care. An analysis of the average old-age pensions of seniors shows that a large proportion of seniors who require social care services cannot afford them, as the costs of these services are continuously increasing, both for home care and LTCIs. The provision of necessary social care services for seniors, especially long-term social care delivered through home care or LTCIs, requires significant financial resources. This places a financial burden on the municipality, on seniors themselves, on their relatives, and on society.

Table 1

Senior distribution by care levels in municipal Long-Term Care Institutions (LTCIs)

Year	Care Level 1	Care Level 2	Care Level 3	Care Level 4
2020	430	1383	3033	1981
2021	263	1145	3237	1991
2022	258	1063	3545	2146
2023	247	1041	3618	2206
2024	239	1016	3697	2298

*****_Distribution of seniors by care levels in the provision of long-term social care and social rehabilitation services, 2020–2024 (as of 31 December) in municipal and other organizations' institutions._

Source: Compiled by the authors based on Ministry of Welfare of the Republic of Latvia (2026a, 2026b, 2026c; 2026d, 2026e).

Table 2

Overview of Home Care Service Provision in Rural Municipalities in Latvia

Care Level	Municipality of Vidzeme Region (V1)	Municipality of Vidzeme Region (V2)	Municipality of Vidzeme Region (V3)	Municipality of Zemgale Region (Z1)	Municipality of Kurzeme Region (K1)	Municipality of Latgale Region (L1)	Municipality of Latgale Region (L2)
Care Level 1	up to 12 hours per month	up to 16 hours per month	up to 16 hours per month	up to 16 hours per month	up to 16 hours per month	up to 10 hours per month	up to 16 hours per month
Care Level 2	up to 16 hours per month	up to 24 hours per month	up to 24 hours per month	up to 24 hours per month	up to 32 hours per month	up to 20 hours per month	up to 24 hours per month
Care Level 3	up to 22 hours per month	up to 32 hours per month	up to 32 hours per month	up to 48 hours per month	up to 48 hours per month	up to 30 hours per month	up to 32 hours per month
Care Level 4	the social service may decide to grant other services	up to 40 hours per month (excluding weekends)	up to 48 hours per month (excluding weekends)	up to 96 hours per month	up to 64 hours per month	up to 40 hours per month	up to 48 hours per month

In 2025, the average old-age pension in Latvia ranges from 625 to 673 euros, with men receiving 724 euros and women 645 euros. The median old-age pension in Latvia is between 500 and 600 euros. There are noticeable regional differences in pension amounts: in rural municipalities further from Riga, the average is 515 euros, while in the Greater Riga area it reaches 780 euros (Open data portal, 2025; CSB, 2026b). The offer of social services is not uniform across Latvian municipalities, as each municipality has its own regulations and funding options. This makes it difficult for service recipients to make choices, for example when moving from one municipality to another. A case study of Latvian rural municipalities reveals the functioning of social care organizations under conditions with limited resources. The demand for services is increasing due to the rapid ageing of the population and changes in the structure of society, especially in rural areas. The analysis covers the impact of financial and administrative conditions on the organization of social care for seniors, where manifestations of 'power over' and 'power with' can be identified in social care for seniors at home and in LTCIs.

There is a shortage of specialists in the field of social care, which can be explained by the low prestige of care specialties, which is mainly determined by low pay, lack of health insurance and social guarantees, while at the same time, for example, for caregivers it is physically and emotionally hard work, which was

confirmed by both caregivers and organizers of community-based social care services in their interviews.

After re-reading the interview data and considering the theoretical framework, two main themes were identified for the analysis: 'power over' and 'power with'. The **'power over'** theme encompasses administrative power, administrative structure, administrative barriers and hierarchy, the financial framework, and service provision procedures. The **'power with'** theme includes relationship-based collaboration, peer relationships, participation in care planning, and empowering the autonomy of seniors.

1. Expressions of 'power over' in social care for seniors at home and in LTCIs in the regions of Latvia are primarily expressed through administrative regulation and the control of financial resources. This form of power influences whether services are accessible to seniors and whether the provision of these services is financially secured.

Administrative Power

In the Latvian social care system, regional municipalities play a central role, acting as intermediaries between state organizations and residents. The participation of municipalities in the provision of social care for seniors is important not only by providing financial support, but also by ensuring specialists and appropriate infrastructure. Referring to interviews with organizers of community-based social care services and social workers, in each region, the identification of lonely seniors and obtaining information about them takes place differently and not always all lonely seniors are identified; if they are not clients of social services, then they may remain unobserved. There are general guidelines about criterions for social care recipients from central government (Social Services and Social Assistance Law, 2002), but determining the scope of the service (hours, levels, intensity) each regional municipality in Latvia may have a different procedure. There are also variations in service fees, municipal co-financing, and the procedures for providing social services. As one source noted: 'Each municipality does as it pleases. This creates conflict situations. People get very angry; they come in, bang their fists on the table, and shout asking why we don't offer something that another municipality does. For years, we have been talking within the Union of Local Governments about the need to change the law to have the same payment procedure and number of hours at each level of care' (SW1 Z1).

Information regarding how to access these services is not readily available on all municipal websites, and the scope of the information provided varies significantly. Furthermore, because Latvian regional municipalities currently lack a unified service basket for home-based social care, the availability and quality of care remain highly unequal. The quality of the service may also vary. Analyzing the regulations of Latvian regional municipalities on social care at home, the authors conclude that in some regional municipalities, a senior may be denied the opportunity to stay in his or her home if the care level 4 is needed (Table 2). Such regulatory frameworks well characterize the influence of 'power over' on social care for seniors.

Structural Factors Affecting Senior Care Provision

The **geographical location** of seniors' place of residence and distance from the service provider can limit access to social care services, but statistics on seniors who live alone, in places without basic amenities or live outside cities are currently not available, and there is also no unified system for recording such seniors.

The provision and accessibility of services are largely determined by **municipal funding mechanisms** and **administrative procedures**, which regulate eligibility criteria, service allocation, and the scope of care provided. As a result, professionals and institutions exercise a degree of control over the distribution of resources and the organization of care services. This administrative framework shapes the options available to seniors, influencing whether support is provided in the home environment or through placement in a LTCIs.

The data presented in Table 1 indicate an increasing demand for more intensive institutional care; however, the capacity of institutions is limited. Therefore, the structure of administrative power may prevent the adequate provision of seniors' needs.

In **home care services** are primarily provided to seniors with care level 1 and 2 needs, who require lower to moderate levels of assistance with activities of daily living (Table 1). Unlike, **LTCIs** typically serves seniors with care level 3 and 4 needs, who require more intensive and continuous support due to more severe health conditions and reduced functional capacity (Table 1). Municipalities in Latvia are responsible for organizing and providing home care services for seniors. Home care services for seniors in Latvia are essentially community-based services, as responsibility for their provision lies with local municipalities and communities. The level of care provided and the financial conditions under which services can be ensured depend on decisions made at the local community level. Furthermore, the organization of home care services is also determined by local community decisions. The provision of these services may involve NGOs, volunteers, or caregivers funded by the local community. This, to some extent, limits seniors' ability to make autonomous choices about social care services: 'Then there are no other options, because in our community… and if the person does not have the means to pay for this service privately, then yes - unfortunately, (there is no option for home care services…)' (SW3 V2).

Consequently, municipalities organize home care services according to their capabilities, using their own resources or purchasing home care services from other providers, calculating the service basket. This reflects the exercise of 'power over' in the provision of social

care services. Social workers noted in the interviews that opportunities to provide social care for seniors are determined by decisions made by local communities, which are based on the understanding and allocation of local resources. Some municipalities finance only one hour of home care per week, while others consider senior home care a priority and provide up to 24 hours of care per week. Local communities decide which seniors receive publicly funded services and which must pay for services themselves.

When municipalities are unable to provide certain services themselves, they must purchase them from NGOs or external service providers. However, not all municipalities have sufficient financial resources to do so. 'Power over' is exercised in the assessment of seniors' needs while considering decisions made by the local community. **Inequality in power relations** depends on each senior's individual resources and the decisions of the local community.

The differences in power relations between home care and LTCIs are mainly related to the degree of control over daily life and environment. In home care, the senior mostly retains greater autonomy, as he/she lives in his/her usual environment and retains greater control over daily decisions, such as daily routine, meals or social contacts. The seniors remain in their familiar living environment while maintaining contact with relatives and friends. Autonomy may be reduced when a senior becomes dependent on assistance with medical care, personal hygiene, and nutrition.

The 'power over' of social workers in this situation is more often manifested at an administrative and coordinating level, for example, when making decisions about the provision of a service or organizing the provision of care services. In LTCIs, however, 'power over' is more often manifested through structural and organizational control over seniors' daily lives. In LTCIs, 'power over' is exercised through institutional rules, daily routines, staff availability, and organizational procedures, which may limit seniors' individual choices. The findings of the study support the theoretical conceptualization of power relations proposed by Karim (2023).

Thus, in institutional settings, the 'power over' exercised by social workers and caregivers in organizing seniors' daily lives is more pronounced than in home care, where seniors often retain greater independence and the ability to influence their everyday life. For example, a shortage of specialists and financial resources limits seniors' recovery after a stroke. As one caregiver noted, 'There is not enough money for quality rehabilitation programs' (CG1 L2). As a result, seniors in LTCIs often do not receive adequate post-stroke rehabilitation. Although rehabilitation specialists and caregivers try to support seniors as much as possible, limited time and staff make it difficult to provide rehabilitation at the level and intensity required.

Long waiting lists for placement in LTCIs represent another issue at the administrative level of the care system, as illustrated by one social worker who explained, 'six are waiting in line, lying in hospitals; there is nowhere to place them' (SW2 V3). As the number of seniors requiring placement in LTCIs increases, the limited capacity of regional institutions creates additional pressure on the system. Consequently, municipalities must cooperate with LTCIs in other regions to ensure placement.

Administrative Barriers and Hierarchy

The administrative framework requires strict documentation of daily service provision. This documentation process includes reporting systems, social care journals, records, risk assessment questionnaires, and other administrative documents, which transform social care relationships into data units. While this contributes to transparency in the provision of social care services, it also reflects the manifestations of 'power over'. A social worker noted that this system increases distance and shifts decision-making away from the senior, leaving less time for personal contact: 'Reports provide a clear order, but the feeling is that the document is more important than the person himself' (SW4 V3). The digitalization of the Latvian social care system improves transparency but also strengthens monitoring as a form of 'power over'. As one social worker explained: 'To minimize paperwork, an electronic system has been introduced. Of course, papers are not left anywhere, so are journals, reports' (SW6 Z1).

Hierarchy represents a clear manifestation of 'power over'. The central government delegates responsibilities to municipalities, which in turn pass them on to social services and care providers. As a result, seniors as service recipients become dependent on these institutions. Social services monitor and assess which residents qualify to receive social assistance.

Financial Framework

Financing models for rural municipal home care services and LTCIs are not uniform. Part of the funding for home care services and LTCIs is provided by municipalities, with the level of co-payment determined by municipal council decisions according to the assigned care level. Persons officially recognized as needy are exempt from co-payments, whereas low-income persons are required to cover part of the co-payment. In both home care and LTCIs, seniors' financial situation influences their ability to pay for and financially access social care services. In some home care situations, seniors must privately hire caregivers for an additional fee, while in other cases assistance is provided on a voluntary basis without financial compensation. Financial criteria determine access to social care services. As a result, seniors' economic capacity functions as a structural instrument of 'power over'.

Service Provision Procedures

Bureaucracy is manifested through complex procedures and documentation requirements, which often delay decision-making and require additional

time from both social care providers and service recipients. As one social worker acknowledged: 'Sometimes it seems that more time is spent filling out paperwork than actually working with the person' (SW2 V2). For example, access to social care services requires a medical assessment of the senior's health condition and the submission of bank statements from the senior and their close relatives for income verification.

The provision of social care services may also be hindered by the relationship between the seniors and their relatives. For example, relatives may refuse to provide information about their income or to pay for the service, and although such cases may take years to resolve in court, the service is often needed immediately.

'Power over' in LTCI often appears when the individual needs of seniors do not align with the institution's set daily routine or offered activities. Although activities are organized with the aim of maintaining the seniors' physical and mental health, they do not always match their interests and desires. For example, a senior living in a municipal LTCI says: 'I'm not going to go and squeeze those little balls! But there are social workers who force you to sit there... Activities should be for everyone separately, individually' (S3 V2). The senior's words illustrate resistance to forced activities and highlight manifestations of 'power over' in the LTCI, imposed by institutional order, thereby limiting the seniors' autonomy. 'Power over' can also arise during hygiene procedures both in home care and in LTCIs. For example, a senior may not want to be bathed on a particular day (S6 L1) in such instances, caregivers admit that power is exercised. Similar situations where 'power over' seniors in institutional care are exercised include issues regarding roommates, mealtimes and menus, daily routines, quarantine restrictions, transfers from one care center to another, and the choice of clothing. In home care, on the other hand, 'power over' is expressed through determining when and for how long a senior is visited, whether the caregiver engages in conversation with them, and whether the senior can request additional services (such as eyeglass repairs, bringing books or medicine, cooking a favorite meal, etc.). For example, one senior shared her disappointment: 'I have the third care level, and the caregiver is supposed to come every day to help in the kitchen, but she often skips visits and only comes every other day' (S2 V1).

2. Expressions of 'power with' in social care at home and in LTCIs for seniors in rural municipalities are primarily expressed through collaborative relationships between seniors, caregivers, and social workers. This form of 'power with' promotes cooperation, participation, and mutual trust, enabling seniors to maintain autonomy and actively participate in decisions and activities related to their care and everyday life.

Relationship-based collaboration

'Power with' in social care for seniors at home and in LTCIs in rural areas of Latvia is closely related to the quality of relationships between seniors and caregivers. They also depend largely on the social worker's ability to build a trusting relationship with the senior. In some cases, seniors allow only certain people to provide care at home. In other cases, trust becomes so strong that the social worker is trusted to accompany the senior to an LTCI. This reflects a collaborative approach in which social workers, caregivers, and seniors work together in decision-making. These findings are consistent with discussion of power within relationship-based practice, which emphasizes that the ability of professionals to exercise 'power with' and develop collaborative relationships is shaped by organizational and structural constraints (Chrafe, 2025).

Community-based care is reflected through the involvement of volunteers, neighbors, and librarians. For municipalities, it is more cost-effective to hire local caregivers; being community-based, they operate according to their own local resources and capabilities.

Peer relationships

Relationships with peers are very important for seniors living in LTCIs. For example, establishing contact with a roommate plays an important role in everyday life. In cases where such contact is not established, roommates may be changed. 'Power with' in LTCIs is manifested in seniors' ability to form relationships with peers, express opinions as a group rather than as separate individuals and develop a sense of belonging within the institution.

Participation in Care Planning

'Power with' may also be exercised in a supportive manner, for example by helping seniors navigate the care system, ensuring access to necessary services, and defending their interests. In the context of care planning, professionals may use their position to involve seniors in decision-making and support their participation in planning the services they receive.

Empowering the Autonomy of Seniors

Social workers support seniors' autonomy by encouraging their active participation in decision-making. For example, specialists seek to involve seniors in decisions about the services they receive while respecting their wishes and abilities. They emphasize that it is important not only to provide assistance but also to support seniors' ability to remain independent in everyday life for as long as possible. Social care planning therefore considers each senior's individual needs, health status, life experiences, and personal preferences.

In LTCIs, 'power with' is also expressed through seniors' participation in **daily activities**. When seniors show interest in what is happening in the LTCI, they are given opportunities to participate in various activities. Seniors are encouraged to participate in decision making regarding leisure activities, including

the choice of artists and other specialists they wish to meet, as well as the people with whom they would like to interact and establish social relationships. Such opportunities promote autonomy and reflect manifestations of 'power with'. These practices also illustrate the incorporation of community-based elements into LTCIs as part of the deinstitutionalization process, emphasizing social participation and person-centred care.

Conclusions

1. Power relations in senior social care are exercised through both 'power over' and 'power with'. 'Power over' is expressed through administrative regulations, financial arrangements, service provision procedures, and organizational control, whereas 'power with' is reflected in collaborative relationships between seniors, caregivers, family members, social workers, volunteers, and local communities.
2. The differences between home care and LTCIs are reflected in the degree of organizational control over seniors' everyday lives. Home care generally enables greater autonomy by allowing seniors to remain in their familiar environment and retain greater influence over daily decisions, whereas LTCIs are characterized by stronger institutional regulation of daily routines, activities, and care provision.
3. 'Power with' is expressed through seniors' participation in care planning, shared decision-making, peer relationships, and collaboration with caregivers, family members, volunteers, and local community representatives. Community-based services and person-centred approaches create opportunities for seniors to participate more actively in decisions regarding care, daily routines, leisure activities, and social relationships.
4. Power relations in senior care are shaped by administrative and financial regulations, municipal organization of services, local resource availability, and relationship-based collaboration. Although common national guidelines for needs assessment exist, municipalities differ in how they organize and finance services, resulting in unequal access to social care and varying opportunities to exercise both 'power over' and 'power with'.
5. The findings demonstrate that both 'power over' and 'power with' are evident in senior social care in rural municipalities of Latvia. While administrative and financial structures shape access to services and create inequalities between municipalities, collaborative and community-based approaches strengthen seniors' autonomy, participation, and person-centred care.

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INSTITUTIONAL AND REGIONAL INEQUALITY IN LONG-TERM SOCIAL CARE PROVISION IN LATVIA: IMPLICATIONS FOR RURAL DEVELOPMENT

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Abstract
The aim of the study is to analyse the provision of long-term social care services in Latvia during the period from 2018 to 2023, examining territorial disparities and identifying institutional and financial constraints that contribute to inequality. The research problem is grounded in the territorial fragmentation of the long-term social care system in Latvia, where service availability depends on place of residence, the financial capacity of municipalities, and differing demographic and socio-economic factors, thereby creating structural inequalities between municipalities and regions, particularly in rural areas and sparsely populated municipalities. The study combines secondary data analysis of official statistical databases with findings from expert interviews and focus groups involving municipal representatives, service providers, and care recipients from different administrative territories of Latvia. The results reveal significant disparities between municipalities, indicating that inequality is determined by the uneven distribution of service providers, differences in municipal financial capacity, and the financial resources of clients. The findings highlight the need to give greater attention to the territorial dimension in social policy planning, strengthen the institutional and financial capacity of municipalities, and improve financing mechanisms for long-term social care. At the same time, the results also outline directions for further research, particularly in analysing the impact of municipal fiscal capacity, institutional resources, and the availability of human resources on service accessibility and on the potential for reducing regional inequalities.
Keywords: long-term social care, regional inequality, service accessibility, rural development.

Introduction

Latvia, similarly to other European countries, is experiencing demographic changes characterised by population decline, an increasing old-age dependency ratio, and rising life expectancy. Projections by the European Commission (EC) indicate that Latvia's population is projected to decrease from 1.89 million in 2022 to 1.26 million in 2070, while the old-age dependency ratio will increase from 36% to 61%. At the same time, life expectancy is expected to increase substantially, from 70.3 to 82.5 years for men and from 79.8 to 88.4 years for women (EC, 2024).

Population ageing will increase the proportion of older people and consequently raise the demand for long-term care, healthcare, and both institutional and home-based care services. In particular, the need for specialised care for people with chronic diseases and functional impairments is expected to become increasingly significant. At the same time, public expenditure on long-term care in Latvia remains among the lowest in the European Union (EU), accounting for only 0.4% of GDP, while out-of-pocket payments for healthcare considerably exceed the EU average (EC, 2024).

Pronounced demographic differences can be observed across Latvian municipalities. In 2023, the proportion of residents above working age ranged from 9.7% in Mārupe Municipality to 24.7% in Krāslava Municipality and 24.6% in Valka Municipality. Comparatively lower shares are also observed in Ropaži Municipality (14.5%), Ķekava Municipality (15.2%), and Ādaži Municipality (15.6%) (RAIM, 2026b). These differences indicate more pronounced population ageing in peripheral territories compared with demographically younger municipalities.

Territorial disparities are also evident in the prevalence of disability. The proportion of adults with disabilities ranges from 2.23% in Mārupe Municipality to 10.76% in Balvi Municipality and 9.18% in Ludza Municipality. Relatively low proportions are also observed in Ādaži Municipality (2.56%) and Ķekava Municipality (3.29%) (Latvia Open Data Portal, 2026a; RAIM, 2026a).

In addition to demographic differences, Latvia is characterised by significant income inequality. The income of the wealthiest twenty percent of the population exceeds that of the poorest twenty percent by more than six times. In 2021, 26.1% of the population were at risk of poverty or social exclusion. Among people aged sixty-five and over, this share reached 44.6%, representing the highest level in the European Union. Particularly high risks are observed among single-parent households, people with disabilities, and residents of rural areas. However, public expenditure on long-term care is among the lowest in the European Union (EC, 2023).

Projections indicate that the proportion of potentially dependent people in the total population will increase from 31.7% in 2019 to 56.7% in 2050. At the same time, the share of the population experiencing serious difficulties in performing self-care or household activities in Latvia exceeds the European Union average (EC, 2023).

These trends highlight the importance of ensuring the sustainable development of social protection, healthcare, and long-term care systems, particularly from a regional perspective. The increasing proportion of older people, combined with territorial and socio-economic disparities, emphasises the need for a more in-depth analysis of care accessibility and service provision in Latvia.

The objective of the study is to analyse the provision of long-term social care services in Latvia during the period from 2018 to 2023 by mapping territorial

disparities and identifying institutional and financial constraints that contribute to inequality. The research problem is related to the pronounced territorial fragmentation of the long-term social care system in Latvia, where access to services depends on place of residence. Consequently, structural inequalities emerge between municipalities and regions, particularly in rural and sparsely populated areas.

Public expenditure on long-term care in Latvia is increasing, creating additional challenges for the financial sustainability of the system. At the same time, the long-term care financing strategy remains insufficiently developed, which may result in difficult-to-predict expenditures in the future (Spasova et al., 2018; EC, 2021). The availability of long-term social care services in Latvia largely depends on the financial capacity of municipal budgets, which varies significantly across the country, including between Riga and many regional municipalities, thereby creating disparities in service provision (EC, 2021).

Regional differences may also be related to the governance and regulatory structure of long-term care services. In different countries, the organisation of services and quality assurance is implemented at national, regional, or municipal levels, which may lead to geographical differences in service accessibility and quality (Cès & Coster, 2019; Seimuskane & Sloka, 2025). Significant disparities in the availability and quality of social care services between regions are also evident, and in many countries, care infrastructure is typically more developed in urban areas than in rural regions (Oliveira Hashiguchi & Llena-Nozal, 2020). Limited availability of institutional care and restricted access to home-based care, particularly for people living alone or in rural areas, may further constrain access to necessary long-term social care services (OECD, 2023). Moreover, the cost of long-term care in many countries can be very high and often exceeds the average income of older people, creating substantial financial risks when care is required (Oliveira Hashiguchi & Llena-Nozal, 2020).

Materials and Methods

The analysis of the study is based on administrative, statistical, and qualitative data obtained from various public institutions covering the period from 2018 to 2023. The quantitative analysis relies on secondary data from the Latvia Open Data Portal on the provision of social services and long-term social care services, as well as data from the Regional Development Indicator Module (RAIM), including demographic indicators and municipal budget expenditures (Latvia's Open Data Portal, 2026a, 2026b; RAIM, 2026a, 2026b, 2025c).

The analysis of the normative and institutional framework is based on national legislation and policy planning documents in the field of long-term social care services, as well as national and international research studies. These sources provide a broader analytical context for interpreting the empirical findings within the framework of social policy and welfare policy.

The qualitative analysis is based on forty-seven semi-structured interviews and three focus group discussions. Participants were selected purposively and included representatives of the legislature and national-level policymakers, municipal decision-makers and social service representatives, public and private service providers, non-governmental organisations and social partners, as well as service recipients, their family members, and informal carers. The sample covered a range of long-term social care service types, regions across Latvia, including both urban and rural areas, as well as different financing models. The group of service recipients included children, working-age adults, and older people with varying levels of care needs. This sample structure enabled the analysis of long-term social care services from the perspectives of multiple stakeholder groups.

An inductive thematic approach was applied in the analysis of qualitative data, enabling the identification of analytical conclusions regarding the accessibility of long-term social care services, financing mechanisms, and institutional differences. The interview and focus group transcripts were coded using an open coding method and subsequently organised into thematic categories. The study was conducted in accordance with research ethics principles. Informed consent was obtained from all participants, and data confidentiality and anonymisation were ensured.

The study integrates quantitative and qualitative analysis in order to ensure data triangulation and the validity of the results. Quantitative data were systematised, harmonised, and analysed using comparative and descriptive statistical analysis, as well as through the search for relationships among variables relevant to the provision of long-term social care services, demographic indicators, and the fiscal capacity of municipalities. Data comparability over time was ensured by adjusting the information to the municipal structure established following the administrative-territorial reform.

Results and Discussion

Municipal expenditure on the social sector, including long-term social care services, gradually increased during the analysed period. In 2023, 3.7% of the total municipal budget was allocated to social services, the majority of which was related to long-term social care services. Overall, during the analysed period, funding for social services increased at a faster rate than funding for long-term social care; however, long-term care maintained a dominant role in the structure of municipal social service expenditure. In 2023, long-term social care services accounted for 78.9% of total social service expenditure, representing an increase of 6.1 percentage points compared with 2018 (Table 1).

At the same time, the overall share of municipal budgets allocated to the social sector remained relatively low, which may further reinforce territorial

disparities in service accessibility. Qualitative data from the study indicate that municipalities are facing increasing difficulties in ensuring the necessary volume of long-term social care services. The findings reveal a growing mismatch between demand and available financial resources, driven by population ageing, increasing care needs, and rising service costs.

Table 1

Share of social and long-term social care expenditure in total local government expenditure, (%), (2018–2023)

Indicators	2018	2019	2020	2021	2022	2023
Local government expenditure on social services	2.7	2.9	3.1	3.4	3.5	3.7
Local government expenditure on long-term social care services, excluding boarding house and respite care services	2.0	2.2	2.4	2.7	2.7	2.7

Source: Authors' construction and calculation based on the Latvian Open Data Portal database 'Reports on social services and social assistance in municipal and city local governments' and on the RAIM database 'Total local government budget expenditure' (Latvia's Open Data Portal, 2026b; RAIM, 2026c).

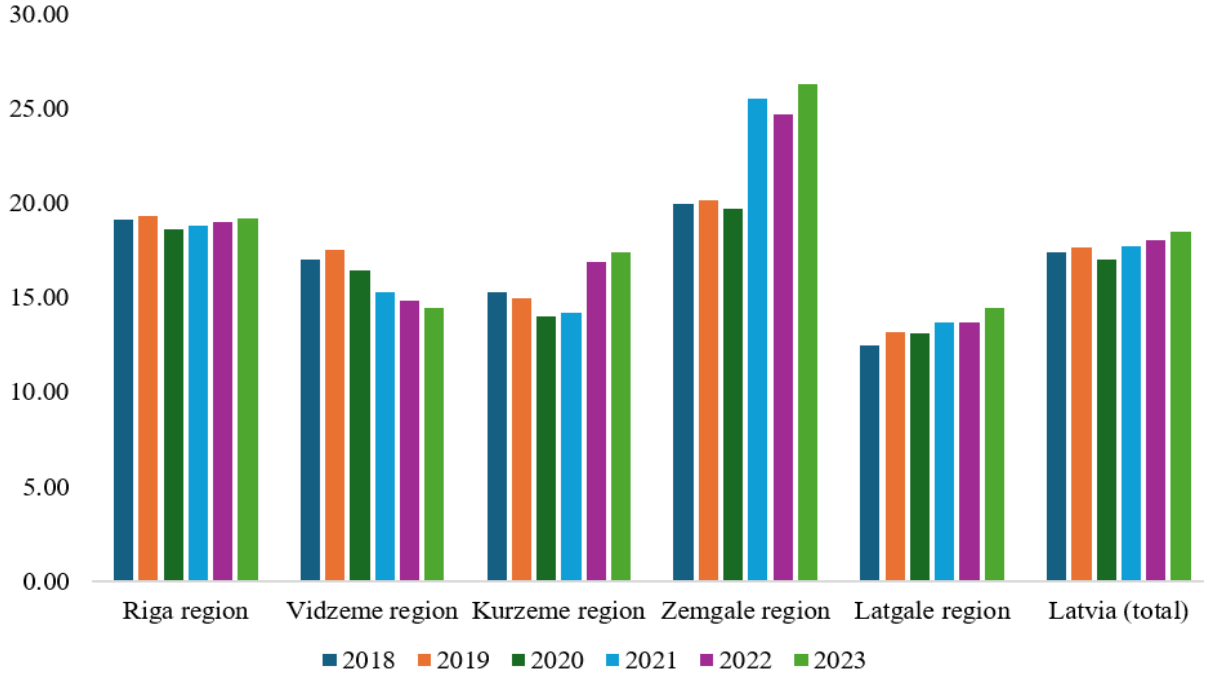
The number of long-term social care services per 1,000 inhabitants in Latvia increased overall from 17.4 to 18.5 between 2018 and 2023 (Figure 1). However, the national average for the analysed period (17.73) conceals considerable regional differentiation.

At the regional level, the volume of services differed substantially. In the Zemgale region, it reached 22.72 services per 1,000 inhabitants, whereas in the Latgale region it amounted to 13.44. The indicators in the Vidzeme (15.93) and Kurzeme (15.46) regions were below the national average, while the Riga region (19.01) recorded a slightly higher level.

These findings indicate persistent regional differentiation, with a substantial gap between the highest and lowest indicators in both absolute and relative terms. Moreover, this differentiation intensified over time: the difference between the maximum and minimum regional indicators increased from 7.5 services per 1,000 inhabitants in 2018 to 11.8 services in 2023, indicating a strengthening trend of uneven regional development.

Figure 1

Number of long-term social care services per 1,000 inhabitants by region (2018-2023)



Source: Authors' construction and calculation based on the Latvian Open Data Portal database 'Reports on social services and social assistance in municipal and city local governments' and on the RAIM database 'Total population' (Latvia's Open Data Portal, 2026b; RAIM, 2026a).

The high indicator observed in the Zemgale region is particularly noteworthy given the large share of rural territories in the region. This suggests that the intensity of long-term social care services is not determined solely by the level of urbanisation or population density. At the same time, the lower indicators observed in Latgale, Vidzeme, and partly in Kurzeme, where extensive rural areas also dominate, indicate that the rural dimension alone is not the decisive factor. Rather, the availability of services is determined by the

interaction of several structural factors, including the fiscal capacity of municipalities, the organisational model of service provision, and the level of development of institutional care infrastructure.

The qualitative data from the study complement the quantitative analysis by highlighting significant differences between municipalities, as well as between urban and rural territories, in the accessibility and provision of long-term social care services. In urban areas, particularly in Riga, the availability of services and financing opportunities is broader. In contrast, in rural territories, accessibility is constrained by the distance to service provision locations, shortages of specialists, and the quality of infrastructure. Low population density further complicates the provision of services in each territory, thereby reinforcing structural differences in the accessibility of long-term social care services between regions.

In this context, territorial constraints are particularly evident in the organisation of specific services. In rural areas, the provision of long-term social care services is often more complex due to large distances, lower population density, and limited service infrastructure. For example, in the case of day care centers, the distance to the service location can significantly restrict service use, particularly in situations where the availability of public transport is not aligned with the operating hours of the service or where transport provision creates an additional financial burden for the municipality or service provider.

Similar barriers are also observed in the provision of home care services. In rural territories, accessibility is limited by shortages of care workers and difficulties in reaching clients' places of residence due to long distances and insufficiently developed transport infrastructure. These factors may reduce the regularity and intensity of service provision and may also influence the choice of care arrangements. As a result, institutional care is sometimes selected even in situations where appropriate home-based care could potentially be provided, but infrastructure and human resource constraints limit this option.

The dynamics of the unit cost of long-term social care services between 2018 and 2023 demonstrate a substantial increase and pronounced regional differentiation. In Latvia overall, the cost per service unit increased from 1,166.26 EUR in 2018 to 2,354.51 EUR in 2023, representing an increase of approximately 102% (Figure 2). In the Riga region, the cost level throughout the period exceeded the national average by 10–20%, and the growth rate reached 115%, thus surpassing the overall national trend. This indicates both a higher initial cost level and a more rapid increase in costs during the analysed period.

Figure 2

Regional Differences in Long-Term Social Care Service Unit Costs in Latvia, 2018–2023 (EUR)



Source: Authors' construction and calculation based on the Latvian Open Data Portal database 'Reports on social services and social assistance in municipal and city local governments' (Latvia's Open Data Portal, 2026b).

In the other regions, the cost level remained significantly below the national average. In 2023, the cost per service unit reached approximately 60% of the national average in Kurzeme, 56% in Vidzeme, 63% in Zemgale, and 76% in Latgale. At the same time, the rate of cost increase varied considerably between regions: 52% in Kurzeme, 53% in Vidzeme, 35% in Zemgale, and 24% in Latgale. These differences

indicate that the dynamics of service costs are influenced not only by general economic trends but also by regional differences in service organisation, labour market conditions, and the development of institutional care infrastructure.

Qualitative data from the study indicate that the prices of long-term social care services are typically reviewed no more than once a year to ensure predictability for municipalities, clients, and their relatives. At the same time, cost dynamics are also influenced by external economic factors, such as increases in energy prices. Service prices are differentiated according to the intensity of care and the specific needs of clients.

Between 2018 and 2023, the total expenditure on long-term social care services in Latvia more than doubled (Figure 3). While in 2018 total funding amounted to slightly below EUR 100 million, by 2023 it had exceeded EUR 220 million, reflecting a substantial fiscal expansion of the sector over a relatively short period of time.

The structure of expenditure growth across funding sources was uneven. State funding increased by 69%, while municipal funding grew by 164%, indicating a considerable increase in the financial burden at the local level. An even faster increase was observed in client co-payments (+256%), representing the highest growth rate during the analysed period. Financial contributions from relatives increased by 85%, while other funding sources rose by 19%.

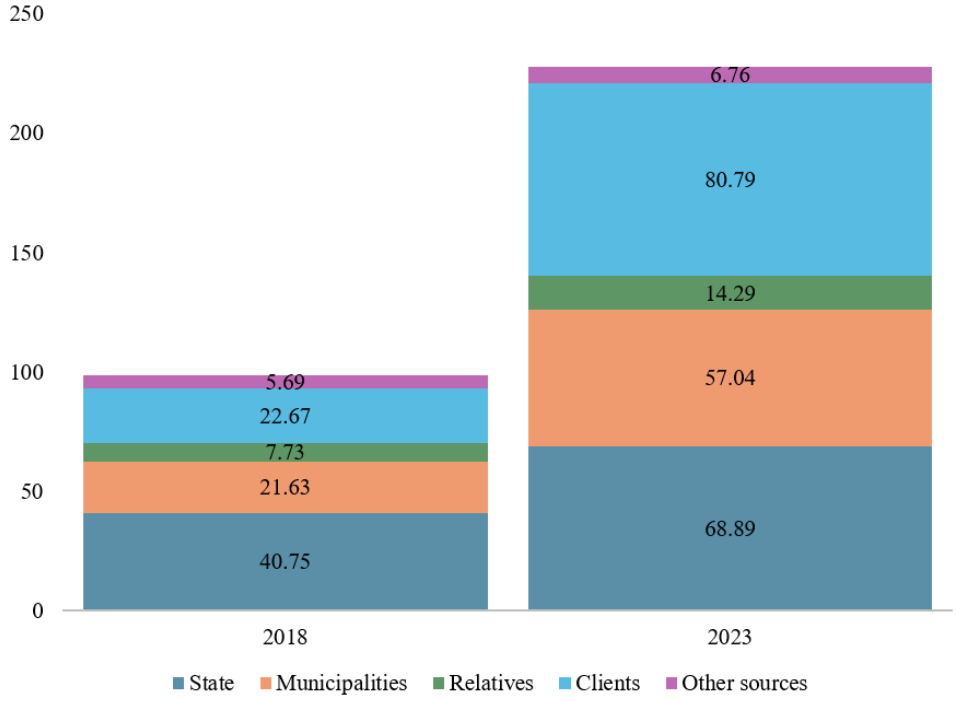
A comparison of the funding structure shows that in 2023, both state and municipal contributions increased significantly in absolute terms. However, proportionally, the fastest growth was observed in the private participation component, namely client payments. This indicates a shift in the financing structure, with a growing share of direct household payments.

The dynamics of these changes highlight important aspects related to the long-term sustainability of long-term social care financing, particularly given the high risk of poverty among older people. A rapid increase in client contributions may affect service accessibility for different socio-economic groups.

Qualitative analysis further demonstrates that the growing demand for long-term social care services, together with rising costs, is creating an increasing financial burden for both public budgets and households. The limited financial capacity of clients and their relatives often makes it difficult to cover the costs of services, thereby increasing the financial burden on municipalities and limiting the financial accessibility of services.

Figure 3

Financing of Long-Term Social Care Services by Funding Source in Latvia, 2018 and 2023 (million euros)



Source: Authors' construction and calculation based on the Latvian Open Data Portal database 'Reports on social services and social assistance in municipal and city local governments' (Latvia's Open Data Portal, 2026b).

The results of the study indicate that the availability and volume of long-term social care services in Latvia differ significantly across territories, highlighting the importance of territorial and institutional factors in the provision of care. A person's place of residence – urban or rural – acts as a structural factor influencing both the range of services available and the actual opportunities to access them. In urban environments, the infrastructure of social services is generally more developed, supported by higher population density,

greater availability of specialists, and stronger institutional capacity. In contrast, municipalities with extensive rural territories often face lower demand density, greater distances, and more complex service organisation, which may limit both the availability and diversity of services (Dūdele et al., 2025).

Territorial constraints are particularly evident in the organisation of specific services. In rural and remote areas, access to care services is hindered by long distances, low population density, and areas that are more difficult to reach. This may limit access to community-based services, as reaching the service location is more difficult. Similar challenges can also be observed in the provision of home care, as service delivery in rural and remote areas is more difficult. Under such conditions, territorial disparities in effective access to long-term social care services may be further exacerbated (Spasova et al., 2018).

In addition to territorial factors, the financial capacity of municipalities plays a significant role in determining service availability. Municipalities in Latvia differ considerably in terms of financial resources and institutional capacities; therefore, the availability and quality of long-term social care services are not uniform across territories. The results of the study show that service costs vary substantially between regions, which may influence municipalities' ability to provide the required volume of services. Moreover, growing demand for long-term social care services may place an additional burden on municipal budgets in the future. At the same time, funding decisions are often made within the limits of available budgets rather than based on a systematic assessment of population needs, which may further reinforce regional disparities in service provision (EC, 2021; Dūdele et al., 2025).

An important factor influencing access to long-term social care services is the financial capacity of service recipients and their relatives. Low income among some service recipients limits their ability to fully cover the cost of services, thereby increasing the financial burden on municipalities. A particularly high risk of poverty and social exclusion persists among lower-income groups, which may further reduce their ability to co-finance the necessary care services. At the same time, service providers often maintain relatively low service prices, taking into account the limited purchasing power of clients and the budget constraints of municipalities. This may restrict opportunities to improve service quality, attract additional staff, and ensure competitive remuneration (EC, 2023; Dūdele et al., 2025).

The availability of long-term social care services in Latvia is therefore shaped by the interaction of several structural factors. Territorial structure, municipal fiscal capacity, availability of human resources, and the financial capacity of service recipients together create a situation in which service provision and care organisation differ significantly between municipalities. The analysis of the number of services per 1,000 inhabitants and the dynamics of service costs across regions indicates that the provision of long-term social care services in Latvia is uneven and varies considerably between territories.

These findings highlight the need to systematically consider the territorial dimension in the development of long-term social care. Strengthening municipal institutional capacity, improving service accessibility in rural areas, and promoting a more sustainable financing model are essential steps towards addressing these disparities. At the same time, the results indicate that service accessibility is strongly linked to the institutional and financial capacity of municipalities, which varies significantly across territories. The growing demand for care services, together with increasing service costs, underscores the need to ensure sustainable financing of the long-term social care system.

Consequently, future policy planning and research should place greater emphasis on institutional and financial mechanisms that could improve access to long-term social care services and reduce territorial inequalities between municipalities. Overall, the results demonstrate that the availability of long-term social care services in Latvia is significantly influenced by territorial, institutional, and financial factors, which together create an uneven structure of care provision across municipalities.

Conclusions

1. Demographic changes in Latvia significantly increase the demand for long-term social care services. Population ageing, rising life expectancy, and the increasing share of potentially dependent people indicate the growing importance of long-term care within the social protection system.
2. Long-term social care services constitute the dominant share of municipal social service expenditure. During the analysed period, their proportion within the structure of social service expenditure increased, reaching nearly four-fifths of total social service expenditure in 2023, although the overall share of municipal budgets allocated to the social sector remained relatively low.
3. The provision of long-term social care services in Latvia is territorially uneven. Regional differences in the number of services per 1,000 inhabitants are substantial, and this differentiation increased during the analysed period.
4. Service accessibility is strongly influenced by territorial and institutional factors. In rural territories, service provision is constrained by greater distances, lower population density, limited transport infrastructure, and shortages of human resources, which reduce service accessibility.
5. The cost of long-term social care services increased significantly during the analysed period, while pronounced regional differences persisted. The cost per service unit more than doubled, with the highest cost levels observed in the Riga region, whereas the

rate of cost increase varied considerably between regions.

6. During the analysed period, the share of client co-payments increased significantly within the financing structure of long-term social care, thereby increasing the financial burden on households.

7. Differences in the financial resources of municipalities affect their ability to ensure the necessary volume of long-term social care services in accordance with population needs and to provide equal access to services across the country.

8. The results highlight the need to strengthen the sustainability and accessibility of the long-term social care system. Future system development should take into account the territorial dimensions by strengthening municipal institutional capacity, improving service accessibility across municipalities, and promoting a more balanced financing model between state, municipal, and client resources. At the same time, the identified territorial disparities and increasing demand for care services indicate the need to reassess the current financing approach and consider potential reforms in long-term social care financing.

9. Further research should focus on a more in-depth analysis of the impact of municipal fiscal capacity, institutional resources, and the availability of human resources on the provision of long-term social care services to better understand the causes of territorial inequalities and the possibilities for reducing them.

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SOCIAL IMPLICATIONS OF THE SILVER ECONOMY IN RURAL REGIONS OF LATVIA

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Abstract
Population ageing is one of the most significant demographic and social challenges in rural regions of Europe. Statistical data and research on rural areas of Latvia highlight issues related to both high emigration and the increasing proportion of seniors, pointing to territorial and social inequality and rural viability. In this context, ageing is often perceived primarily as a social and economic problem. However, the silver economy concept offers an alternative perspective where seniors are perceived not only as recipients of social care, but also as active participants in economic and social life – promoters of economic development. The aim of the article: to analyse the social implications of the silver economy in rural regions of Latvia, combining a conceptual approach with an analysis of available secondary statistics and a qualitative analysis of documents. The conceptual framework of the silver economy reveals the differences between narrow, market-based definitions and broader approaches that integrate both economic and social aspects. In the context of Latvia, the analysis focuses on the demographic structure, the proportion of residents aged over 65, employment, the risk of poverty, and the availability of services in rural regions of Latvia. It is concluded that although the ageing of the population in rural Latvia is associated with significant social challenges, the silver economy approach offers an important framework for recognizing the social potential of seniors and enhancing the quality of life. Integrating the principles of the silver economy into rural development policies can promote social inclusion and sustainable development of rural areas.
Keywords: silver economy, population ageing, rural development.

Introduction

Population ageing has become a critical process in modern society, driven by a combination of demographic, economic and social factors. It particularly affects rural regions, where ageing rates are significantly higher than in urban settings (Eurostat, 2024). Rural regions in Latvia are experiencing not only a decline of the total population but also an increase in the proportion of seniors, which is particularly affected by persistently low birth rates, emigration and general ageing of the population. As a result of these trends, rural regions are often characterised as less socially and economically viable, and, as indicated in the Long-term Vision for Rural Areas, there is a lack of evidence that these territorial inequalities will decrease in the near future (European Union, 2021). In turn, population ageing is mainly perceived as financial and service burden.

The challenges of ageing are integrated into broader policy frameworks, where the focus shifts from the costs of ageing to a rights and needs based, further developed social investment approach, as defined by the European Pillar of Social Rights (European Parliament, 2017). This framework document emphasises the social inclusion of older people and active, healthy ageing. The latest developments have been further strengthened in the Green Paper on Ageing (European Commission, 2021) and the European Care Strategy (European Commission, 2022). The European Union positions demographic ageing not as a cause of recession, but as an opportunity for economic development, as population ageing is not always associated with economic decline. The conceptual development of the silver economy begins with the European Commission's (2015) information report, which highlights the role of markets for senior-friendly healthcare and technology. Today, this policy has become comprehensive, integrating labour market and social inclusion aspects, based on the latest forecasts of the long-term impact of population ageing (European Commission, 2024).

The discussions included in the policy papers have contributed to a growing interest in the silver economy, focusing on the economic and social potential of an ageing society, positioning it as a driver of social cohesion and innovation. The concept of the silver economy is also increasingly and broadly used in academic literature, offering an alternative view on ageing. The silver economy emphasises the role of seniors not only as spenders of public resources, but also views them as active agents in the economy - consumers, labour market participants, entrepreneurs and creators of social capital. This approach allows for the analysis of ageing not as an issue but as a resource for regional development.

The aim of the article is to analyse the social implications of the silver economy in rural regions of Latvia, combining a conceptual approach with secondary analysis of available statistics and qualitative analysis of documents. The article investigates the following research questions: 1) How is the silver economy conceptualised within current literature? 2) What are the manifestations and characteristics of the silver economy in rural regions?

Materials and Methods

The article uses a desk research approach, which is based on the analysis of scientific literature, policy planning documents and official statistics. Articles and studies on population ageing, active ageing, the silver economy, and rural areas as the context in which these processes occur are analysed. Attention is also drawn to documents of the European Parliament, the European Commission, and the OECD, which form the

political framework for the development of the silver economy. The study uses statistical data from the Central Statistical Bureau, Eurostat, OECD, and other publicly available data on processes in rural areas. A descriptive thematic analysis was conducted, searching for the main trends and trying to link theoretical insights with the Latvian rural context.

Results and Discussion

Conceptual Framework of the Silver Economy

According to Eurostat data, the share of older people (aged 65 years and over) in the EU member states at the beginning of 2024 was 21.6% (Eurostat, 2025). In Latvia, it is even higher - 21.35% (CSB, 2024, IRE040). This does not mean just a higher proportion of older people, but requires significant changes in society, not only in the labour market, social and healthcare, but also in most areas of public life.

In response to the ageing of society and its impact, the concept of the silver economy was created. In recent decades, it has become an important analytical framework explaining the influence of population ageing on the economy and regional development. In contrast to the traditional view, where ageing is mainly associated with various challenges and increasing social costs, the concept of the silver economy emphasises population ageing as a potential source of economic growth, innovation and employment. Its roots can be found in Japan, where in the 1970s and 1980s there was a talk of a 'silver market' (European Commission, 2018), which referred to a purely commercial approach - how to sell goods better and more to wealthy elderly people, making more profit. Over time, the understanding has changed and expanded. Several important turning points in the development of the silver economy are noted. In the 1990s, a conceptual expansion took place - a change in emphasis from a narrow market niche to adapting the entire economy to the needs of older adults. 2002 marked the emergence of the active ageing framework, which is associated with a completely new perspective that emphasises participation - seniors are no longer just users of services (a burden), but they are active economic participants, working, solvent consumers. Special attention is paid to the silver economy after 2010, when seniors are viewed not as a burden and a brake on economic growth, but as a labour market resource, co-creators of innovation and growth potential.

The understanding of the age to which the silver economy is attributed is also changing: if in the first documents it is within 50 – 60 years, then in more recent documents – about 65 years and older. Here we can see a transition from concern about the high proportion of pensioners to a longer working life and preservation of functional abilities. Seniors today are older, but 'younger' in their activities.

The transformation from a 'market niche' to a silver economy is not just a change in concepts, but a different vision which acknowledges the importance of older adults in society, while not denying their economic contribution. Data show that the silver economy has enormous importance and holds a significant growth potential - about 100 million people and an estimated turnover of approximately 6 trillion euros in Europe, and it can be considered the third largest economy in the world after the USA and China. Globally, the turnover of the silver economy in 2020 was estimated at 15 trillion dollars (Senior Eco-Nect, 2023).

Despite its impressive macroeconomic performance, the silver economy faces two major challenges: practical implementation and conceptual uncertainty. This is typical of many concepts that attempt to encompass a very wide range of phenomena, as in this case, from high technology to social care and volunteer work. Defining such a broad range of things poses significant difficulties, and the silver economy is no exception. The concept has no clear, generally accepted boundaries, and definitions express political focus or research interest.

Different definitions of the silver economy can be found in scientific literature and policy planning documents; mostly, they talk about the multifaceted nature of the silver economy, emphasising its concentration towards meeting the needs of an ageing society, while also creating opportunities for economic growth and development (Maj-Waśniowska et al., 2018).

In EU policy documents, the concept of the silver economy has evolved from a narrow, market-oriented niche to a comprehensive socio-economic framework. It was initially defined as a set of economic activities that meet the needs of people aged 50 and over (European Commission, 2015), and included initiatives for active ageing, healthcare innovation and labour market participation (European Parliament, 2015). However, more recent perspectives (European Commission, 2018) shift the focus from seniors as passive consumers to an environment in which older adults thrive as active participants and innovators. This redefinition of the concept positions the silver economy not only as a response to the 'costs of ageing', but also as a strategic contribution to social and economic sustainability (European Commission, 2024).

In the scientific literature, the concept of the silver economy is interpreted differently depending on the analytical focus. There is a narrower approach, where the silver economy is defined similarly to policy documents – as a specific market segment; and a broader approach, which covers not only economic, but also social aspects and focuses on participation. It sees older adults as active participants in economic and social life as people involved in the labour market, entrepreneurs, self-employed and carriers of social capital (Walker, 2012). Their skills, experience and knowledge can contribute to economic and social development. This understanding links the silver economy with the idea of active ageing. It is the

broader understanding of the silver economy that is particularly suitable for the analysis of rural regions.

Sociology views ageing not only as a biological process, but as a socially constructed phase of life, the meaning of which is closely related to institutional regulations, social norms and resources accumulated over the course of life (Gilleard, 2025). Consequently, the silver economy is not a neutral economic phenomenon, but rather reflects a certain view of older people as a social group. On the one hand, this concept challenges the traditional perception of seniors as economically passive and dependent on welfare systems, emphasising their consumption capacity, professional experience and potential for longer participation in the labour market (OECD, 2018). On the other hand, there is a risk that the silver economy discourse homogenises the elderly population, ignoring the significant social differences within this group. Actually, a 'third age' can be distinguished, where the focus is on self-realisation and consumption, and a 'fourth age', where the priority is to maintain autonomy and provide specific care technologies (European Commission, 2018).

The silver economy is mostly analysed through an economic lens, focusing on the development of new markets (health, technology, housing) and the inclusion of older adults in the labour market (European Commission, 2018). In rural areas, it is most often manifested in traditional sectors – agriculture, crafts and tourism – where senior self-employment serves not only as a necessary survival strategy (Walker & Maltby, 2012), but also as an essential mechanism for maintaining local identity and social capital (Brown & Schafft, 2018).

From a social perspective, the silver economy resonates with the framework of active and healthy ageing, which places the main emphases on older adults as active civic participants rather than passive recipients of care. In rural areas with limited formal services, the 'ageing in place' approach, which relies on informal support networks and volunteer work, is of critical importance (Wiles et al., 2012). Such social engagement not only reduces the isolation of seniors but also fundamentally strengthens the resilience of the entire rural community against demographic transformations.

Despite all the positive aspects, sociological analysis points to several problematic aspects. For example, the development of the silver economy may result in rural areas being less advantaged, thus increasing territorial inequality (Krzyminiewska, 2019). Not all segments of society benefit either, as both goods and services are often available mainly to more economically secure seniors. The idea of active ageing, which emphasises staying longer in the labour market, lifelong learning and flexible forms of employment, can translate into normative pressure on individuals to age productively, regardless of their health status or work history (Stončikaitė, 2017). Research shows that implementation of active ageing may be an elusive goal for significant segment of older adults, as at the individual level it is preconditioned by health, education, financial stability, and other factors (Jensen, & Skjøtt-Larsen, 2021). In rural regions, seniors are more likely to face limited access to healthcare, social services and digital technologies, which can reduce their opportunities to fully engage in silver economy processes (OECD, 2019). In addition, not all older workers are able or willing to continue working, especially in sectors with high physical or emotional stress, which are often characteristic of lower-paid job segments. The silver economy also affects the dimension of everyday life and social relationships. Technological solutions for older people, such as digital health monitoring systems or smart home technologies, are often presented as promoting well-being and effectiveness (European Commission, 2018); however, this is not entirely clear. It is necessary to analyse the impact of these solutions on autonomy, privacy and the quality of social contacts (van Dyk, 2014). There is a risk that technological solutions replace social care rather than complement it (Abdullayeva, 2025), especially in the context of institutional care. In conclusion, the silver economy as an analytical framework offers an important opportunity to reconsider society's attitude towards ageing and the role of older people. The sociological perspective allows us to analyse this phenomenon not only as a resource for economic growth, but also as a social process that reflects societal values, solidarity mechanisms and the dynamics of social inequality. Combining economic and sociological perspectives in silver economy research and policy-making can promote more socially just and inclusive solutions in an ageing society.

Manifestations and features of the silver economy in the regions of Latvia

In the context of the ageing of society, the WHO's actions and the United Nations Decade of healthy ageing 2021-2023 (Who, 2020), which focuses on the transition from 'active' to 'healthy' ageing, are directly related to the silver economy. The focus of the plan is on maintaining functional abilities, combating discrimination, creating an age-friendly environment, and enhancing the quality of health care services. These priorities are the basis of the silver economy, in which older adults are positioned not as passive recipients of care, but as socially and economically active, integrated members of society.

The silver economy not only in the EU, but also in Latvia and especially in its rural regions is no longer a choice, but a necessity, because according to CSB data, Latvian society is ageing: at the beginning of 2025, the proportion of residents over 65 years of age in Latgale reached 24.4%, but in some regions (Krāslava, Valka) it even exceeded 27% (CSB, 2025). Communities and the countryside are transforming, and rural residents play a vital role in social, economic and environmental aspects (Brown, & Schafft, 2018), and ageing in rural areas is different, it is more related to resilience and

adaptation to existing conditions – 'ageing in place', because older people want to stay in their homesteads and communities, even if there is a lack of services, a sense of identity and existing interaction ties are especially important, neighbourhoods and communities are a practical resource for ageing in place (Wiles et al., 2012). In this context, the silver economy in rural areas does not manifest itself as the consumption of new goods, but rather as the ability of informal social ties and local support networks to ensure the autonomy of a senior in his or her homestead, replacing the missing state or market infrastructure.

The silver economy in rural Latvia is significantly limited by the law income and purchasing power of the population, as well as regional inequality. According to statistical data for 2024, the disposable income of households in rural Latvia per member is lower - 865.19 EUR, compared to cities - 984.87 EUR (CSB, 2024, MIS010). Looking at the regions, there is a large gap between Riga (2,453.78 EUR) and the other regions: in Zemgale the income is 2,009.25 EUR, in Kurzeme 1,759.79 EUR, in Vidzeme 1,757.33 EUR and in Latgale almost half less than in the Riga region - 1,384.21 on average per household (CSB, 2025, MIS030).

Financial poverty directly affects the role of seniors in the silver economy. In the context of EU member states Latvia ranked sixth in terms of the proportion of its population at risk of poverty and social exclusion in 2024 (24.7%), but for the population 65 and over, this indicator is significantly higher - 41.7% (CSB, 2026). Low income levels in rural regions of Latvia significantly limit the 'consumption pillar' of the silver economy, turning seniors from potential market drivers into passive implementers of survival strategies. Under such circumstances, the role of older people in the silver economy changes significantly: they are no longer primarily consumers and recipients of services, but become maintainers of local identity and community viability (Zobena, 2018), replacing the missing market infrastructure with informal social capital.

Employment in rural areas, access to transport, healthcare, and other services are important aspects characterizing the manifestations of the silver economy. Employment after reaching retirement age is one of the central manifestations of the silver economy, which in rural regions of Latvia often serves as a survival necessity and also a way to ensure dignified old age. CSB data indicate that in 2024, 83,156 people over 65 were employed in Latvia, accounting for approximately 10% of the employed (CSB, 2024, EKA031). The employment structure shows sharp regional differences (Table 1).

Table 1
Employed population in the statistical regions of Latvia in 2024 aged over 65

Age	Riga region	Vidzeme region	Kurzeme region	Zemgale region	Latgale region
65–69 years	23022	6869	6389	5369	5294
70–74 years	10437	3050	2780	2218	2436
75–79 years	4235	1340	1179	886	1079
80–84 years	1909	967	649	523	707
85 years and over	669	383	231	211	324
Total	40272	12609	11228	9207	9840

Source: *CSB, 2024, EKA031.*

The data indicate that almost half of the population works in the Riga region, with the lowest activity in the Latgale region, which is related to the job opportunities. In the age group over 65 years, employees dominate (60,767), there are significantly fewer employers (3,444), and the number of self-employed people is significant (18,945) (CSB, 2024, EKA031). This may indicate individual economic activity as a necessary survival strategy. It is also clear that the silver economy has limited development potential in terms of consumption - over 48% of working seniors receive a salary of up to 1,000 euros per month, and this proportion increases with age (CSB, 2025, DSN030m). Despite the substantial increase in the non-taxable minimum for seniors following the tax reform in 2025, the 25.5% personal income tax (PIT) rate continues to exert a significant impact, particularly on lower-income groups. Studies on the potential of silver economy in Latvian regions decision to continue working after reaching retirement age is complex: it is influenced by both financial necessity and the desire for social inclusion and self-realization, while the main inhibiting factor is health status (Seimuškāne, 2025). This duality indicates that silver economy in rural regions is not just a market resource, but a matter of social sustainability.

Paradoxically, at a time when the silver economy and the importance of seniors as a significant resource are emphasized, the labour market situation indicates the opposite. The total number of unemployed people in Latvia is dominated by people over 50 years of age (38.9%), while in the group of long-term unemployed, this age category accounts for as much as 64.3% (including 28.0% of pre-retirement age) (State

Employment Agency, 2026b). In turn, data for the beginning of 2026 indicate a pronounced regional disproportion: while the average registered unemployment rate in Latvia is 5.2 % and in the Riga region 3.8%, in Latgale it is 10.6%), where there is also the largest number of unemployed people over 60 years of age (State Employment Agency, 2026a). The data shows that the regions of Latvia have potential for employment in the context of the silver economy, but it is not currently being used. This is related to both the low mobility of the population and the existing stereotypes in society – they work slowly, lack skills, the employer is not worth investing in because they will retire, health problems; 53% of the surveyed population indicate that they have encountered or been offended because of their age (Kūla, 2024), and the economic and social activity of the population.

The sustainability of the silver economy in rural Latvia is threatened by low public health indicators and problems with the availability of health care services. According to the Latvian report State of Health in the EU 2023, data show that the healthy life expectancy of the population of Latvia at the age of 65 is the lowest in the EU, and a significant proportion is affected by chronic diseases – 37% of women and 29% of men have more than one chronic disease (OECD/EC, 2023). Such a trend contradicts the silver economy and the goals of healthy ageing. No less important aspect is the accessibility of healthcare. Latvian media frequently underscore systemic challenges regarding healthcare accessibility and financing, particularly concerning regional hospitals. Under the Ministry of Health's planned network reorganization, these facilities face significant funding reductions, prompting hospital managers to warn of 'looming risks' to service availability and long-term operational viability (LSM, 2026). For rural residents, whose autonomy within the framework of the silver economy directly depends on their health status and the availability of medical support near their place of residence, these reforms may become a critical obstacle to ageing in place. Thus, in the context of rural Latvia, the potential of silver economy is hampered by a structural inability to provide even basic level services, deepening social inequality.

Social inequalities in public health most clearly affect low-income populations, where the rate of unmet medical needs (13.9%, in dentistry – 15.8%) is more than three times higher than EU average (3.8%). The most significant obstacles cited are financial, geographical or waiting time restrictions, as well as high out-of-pocket spending (OECD/EC, 2024). Overall, it must be concluded that access to healthcare services for older people is limited and rural Latvia is not characterized by healthy ageing, which is also confirmed by the low self-assessment of health status - 22.7% of residents aged 65-74 assess their health status as poor or very poor, rising to 45.8% in the over 75 group (CSB, 2025).

Digital skills are also important in the context of societal development and especially the silver economy, although the results of the Digital Economy and Society Index in the EU rank Latvia only 18th among 27 Member states. 54% of the population in Latvia have acquired digital skills at least at the basic level. A number of projects are being implemented in Latvia to acquire them in adult education and also in schools (DESI, 2022). Statistical data show that in 2025, 77.8% of the population aged 65-74 will regularly (at least once a week) use a computer/internet (CSB, 2025, DLM010). As shown by the study, older people use digital technologies for health-related purposes, or use digital health devices, have heard of e-prescription (Győrffy et al., 2023) and other services to pay bills, search for information, etc. In rural Latvia, residents who do not have a computer/internet connection in their household often use it in schools or libraries. However, data show that due to the optimization of the school and library network, the full use of silver economy services is becoming limited - since 2004, the number of schools has decreased by almost 42% (from 1026 to 596) (CSB, 2024, IZG070), while 13 public libraries have been closed in the last year (CSB, 2024, BIB020). For rural residents, for whom these are the only digital access points, such optimization, although objectively justified, creates additional obstacles to the availability of silver economy services.

A similar trend is observed in cultural consumption and social participation, where seniors show the lowest activity. In Latvia, the Cultural Activity Barometer data show that only 64% of seniors aged 65 to 75 have attended a cultural event in person at least once a year. Participation is influenced by factors such as personal interests, availability and accessibility of cultural services, ticket prices, and health status. Thus, it can be concluded that older people are not active and relatively few – 38% – have participated in any participatory activities in the last year. The most active involvement has been in volunteer work, charity, and local community activities, such as public consultations or discussions (Latvijas Kultūras akadēmija, 2025). It can be concluded that in the context of the silver economy, the offer of cultural accessibility and consumption is not widely used, although potentially involvement in cultural activities and networking could improve the mental, emotional, and physical well-being of older people in the regions of Latvia.

Conclusions

1. Structural inequality as an obstacle to the silver economy: the study analysis confirms sharp regional differences in the age structure of the population, income level and employment. In rural regions of Latvia, especially in Latgale, the development of the silver economy comes up against structural poverty and a high risk of social exclusion (41.7% among seniors), which limits the role of seniors as consumers

and makes the silver economy a matter of survival, not growth.

2. Hierarchical dependence between the silver economy dimensions: the development of the 'narrow' silver economy dimension (market of specific goods and services) in regions directly depends on the quality of the 'broad' dimension. Without targeted support from the state and local governments in the provision of basic services (health, transport, digital infrastructure), the silver economy model in rural areas faces territorial isolation, depriving seniors of the opportunity to implement healthy and independent ageing in their place of residence (ageing in place).

3. Community as the last resort: In the context of negative demographic trends and service network optimisation (closing schools and libraries), older people are becoming a critical resource in maintaining the viability of rural communities. Their resilience and informal social capital replace the missing market infrastructure; however, this resource is limited due to health indicators and low mobility.

4. Unrealised participation potential: Although seniors' involvement in culture, volunteering and local initiatives is an essential prerequisite for emotional and physical well-being, this potential is currently not fully utilised. Silver economy strategies at the regional level should focus not on passive care, but on the active inclusion of seniors in social processes, thus reducing ageism and promoting new socio-economic initiatives in rural areas.

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NGOS IN RURAL SOCIO-ECONOMIC DEVELOPMENT: COMMUNITY RESILIENCE AND SOCIAL INFRASTRUCTURE

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Abstract
This paper examines the role of Non-Governmental Organizations (NGOs) in strengthening community resilience and sustaining social infrastructure in rural regions. Rural communities increasingly face depopulation, limited access to services, demographic change, and recurring social and economic pressures, which affect their capacity to adapt and maintain community well-being. The primary objective of this study is to develop and empirically test a conceptual framework explaining how NGOs contribute to community resilience through institutional capacity, cooperation networks, and investment in social infrastructure. The research applies a dual-methodological approach, combining an integrative literature review with an empirical survey of NGOs operating in rural regions of Latvia. Three composite indices were constructed to measure institutional capacity, cooperation networks, and social infrastructure investment, and their relationships were analysed using Spearman's rank correlation. The findings indicate that rural NGOs report relatively high institutional capacity and strong integration into cooperation networks, while their contribution to social infrastructure is assessed at a more moderate level. The results further suggest that institutional capacity is positively associated with cooperation networks, whereas cooperation networks demonstrate the strongest association with social infrastructure investment. In contrast, no statistically significant direct relationship was found between institutional capacity and investment in social infrastructure. These findings indicate that cooperation networks may function as an intermediary mechanism linking organizational capacity with practical community contributions. The findings highlight the importance of strengthening cooperation among NGOs, local governments, and other local actors to support long-term community resilience and sustainable rural development.

Keywords: non-governmental organizations, rural development, community resilience, social infrastructure, socio-economic development.

Introduction

In the 21st century, rural regions in Europe are increasingly facing challenges, including climate change, economic instability, declining birth rates, the centralization of public services, and institutional changes such as municipal mergers (Flood et al., 2022; European Commission, 2021; Eurostat, 2023). These processes increase societal vulnerability and raise questions about local communities' ability to adapt, maintain their quality of life, and develop successfully in conditions of constant change (Folke et al., 2002).

Similar trends are observed globally, where rural communities are exposed to structural challenges and external shocks that affect their capacity to adapt and recover (Aldrich & Meyer, 2015). In this context, social capital plays a critical role in shaping community resilience by enabling access to resources, facilitating information flows, and supporting collective action during and after crises. Communities with stronger social networks are better able to respond to disruptions and recover more effectively over time (Aldrich, 2012). Moreover, NGOs contribute to these processes by mobilising local resources, coordinating activities, and strengthening cooperation among different actors (Aldrich, 2012). Despite this growing recognition, there is still limited empirical evidence on how NGOs contribute to social infrastructure at the local level. This gap is particularly relevant in rural areas, where institutional capacity and cooperation networks may play a decisive role in shaping community resilience (Aldrich & Meyer, 2015).

Similar challenges can be observed in rural areas of Latvia, where NGOs play an important role in sustaining community life and supporting local development processes. This territorial asymmetry is consistent with broader trends observed in post-socialist Central and Eastern European contexts, where the uneven distribution of social and financial capital often hinders the developmental potential of rural non-governmental actors (Zajda, 2022; Vaznonienė & Kiaušienė, 2018). Although the NGO sector in Latvia is demonstrating steady growth, an average of 3% per year, reaching almost 27,500 registered organizations in 2024, its development is structurally and territorially uneven (Civic Alliance - Latvia, 2025). Data shows a significant gap between the number of registered and financially active organizations, indicating challenges with the sector's capacity and sustainability (The Civic Alliance - Latvia, 2025). This inequality is particularly acute at the regional level; while rural regions such as Kurzeme and Vidzeme exhibit a relatively high density of organizations, financial and human resource capacity remains heavily concentrated in the capital. Riga is home to 42% of all NGOs, yet they generate 70% of the sector's total revenue and employ more than 70% of the sector's workforce (Civic Alliance - Latvia, 2024). This centralization of resources directly affects the institutional stability of organizations working in rural areas and their ability to serve as long-term maintainers of social infrastructure.

The primary objective of this research is to construct and empirically test a conceptual framework detailing the role of NGOs in fostering community resilience within Latvia's rural regions. To achieve this, the study utilizes both a systematic literature review and quantitative survey data. By analyzing non-governmental operations across rural Latvia, this article highlights their direct influence on both socio-economic growth and the adaptive capacity of local populations. The study examines the interaction

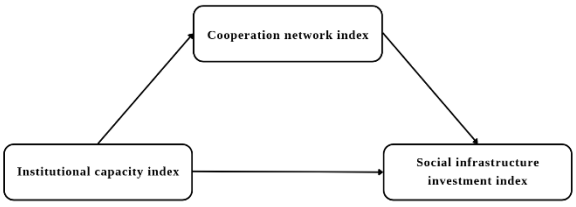
among organizational capacity, cooperation networks, and investment in social infrastructure as mechanisms through which NGOs influence community resilience in rural areas of Latvia. Socio-economic development in this study is viewed through the prism of resilience and social infrastructure.

Materials and Methods

This study employs a dual-methodological approach, comprising a comprehensive literature review and an emprical survey. Both methods were applied sequentially, and each method had a distinct objective. The objective of the literature review in the study was to structure the existing literature, identify, and summarize the main factors identified as prerequisites for community resilience. The primary outcome of the literature review is the development of an initial conceptual framework (Figure 1), which served as a hypothetical model guiding the empirical analysis. The framework presents the assumed relationships among institutional capacity, cooperation networks, and NGOs' contributions to social infrastructure, which were subsequently tested using survey data.

Figure 1

Initial conceptual framework derived from the integrative literature review



The literature review was conducted as an integrative review to synthesize various theoretical perspectives on community resilience and social infrastructure. Sources were searched in international and national databases, including Scopus, Web of Science, and ScienceDirect, among others, using keywords such as 'community resilience,' 'rural social infrastructure,' 'social capital,' and 'the role of NGOs in regional development'.

Maintaining strict academic rigor, the literature search targeted peer-reviewed journal articles and book chapters published from 1993 to 2025. Furthermore, eligible publications needed a clear theoretical or empirical emphasis on how institutional and relational factors shape resilience in rural or regional landscapes. Although the study focuses mainly on empirical findings from recent years, the theoretical basis is also based on fundamental classical works, such as M. Granovetter's (1973) study on the importance of social ties and E. Ostrom's (1990) analysis of the institutional role in community self-governance, which serve as the basis for the modern understanding of social capital and collective action (Granovetter, 1973; Ostrom, 1990; Field, 2018; Lin, 2001; Putnam, 2000).

The analysis used a thematic synthesis approach, grouping the identified factors into three main dimensions: resources (capacity), relationships (networks), and physical or service outcomes (infrastructure) (Table 1). This synthesis provided the basis for operationalising the survey indices and linking the empirical analysis to existing theory (Booth et al., 2016). Based on this synthesis, the initial conceptual framework was developed to examine the relationships among institutional capacity, cooperation networks, and NGOs' contributions to social infrastructure. The framework assumes that institutional capacity enables NGOs to build and maintain cooperation networks, which in turn strengthen their contribution to social infrastructure. In addition, institutional capacity may directly affect NGOs' ability to support social infrastructure.

The survey was used to empirically assess the role of Latvian regional NGOs in strengthening community resilience and to test the initial conceptual framework. The survey was conducted online in February 2026 by sending emails to NGOs with registered addresses in rural areas of Latvia. The survey was sent to approximately 200 NGOs registered in rural areas, resulting in a response rate of 35%. Although the sample size (N=70) is limited, it provides a sufficient basis for non-parametric statistical analysis in a specialized rural context.

In this study, rural areas are defined in accordance with the DEGURBA (Degree of Urbanisation) methodology applied by the Central Statistical Bureau of Latvia, identifying them as territories with low population density outside the capital and major urban centres. Organizations were included if their primary registered address was in a territory classified as 'rural' (Level 3) under DEGURBA and if they had been active for at least one fiscal year. Latvia's rural regions grapple with unique socio-economic vulnerabilities, most notably the restricted availability of local services and infrastructure (Central Statistical Bureau Republic of Latvia, 2024).

The institutional capacity index was created to assess an organization's internal stability and resource availability. This dimension was operationalized using statements about financial sustainability (e.g., stability of funding sources), human resource management (e.g., ability to attract and retain employees or volunteers), and technical and material resources (e.g., access to office space and necessary equipment). By measuring these internal factors, the index reflects the basic capacity an organization needs to operate effectively in rural areas.

The cooperation network index analyzed the relational dimension of NGO activities, focusing on the intensity and quality of multisectoral partnerships. The survey instrument prompted participants to evaluate the extent of their NGOs' collaboration with municipal authorities, peer organizations, and regional enterprises. In addition, the index included indicators of community engagement, such as the organization's

ability to involve residents in decision-making and joint initiatives. The chosen strategy aligns with established theoretical models, reinforcing the premise that social capital and interconnected networks act as primary engines of rural resilience.

Table 1
Survey items and index construction

Indices	Indicator	Survey Item (Likert scale 1-5)	Main Sources
Institutional capacity index	Human resources	The organisation has a stable team.	Herman & Renz (2008); Lecy et al. (2012)
	Financial and material resources	The organisation has sufficient resources to carry out its activities.	Herman & Renz (2008); Salamon (2012)
	Adaptive capacity	The organisation can adapt its activities quickly in crisis situations.	Folke (2006); Norris et al. (2008)
	Cooperation practices	The organisation regularly cooperates with local leaders.	Ansell & Gash (2008); Emerson et al. (2012)
	Public sector cooperation	Cooperation with the municipality is predictable and constructive.	Ansell & Gash (2008); Emerson et al. (2012)
Cooperation network index	Local government cooperation	The organisation regularly cooperates with the local municipality.	Ansell & Gash (2008); Emerson et al. (2012)
	Horizontal collaboration	The organisation collaborates with other NGOs and local actors.	Aldrich (2012); Provan & Kenis (2008)
	Community engagement	The organisation actively involves local residents in its activities.	Aldrich (2012); Putnam (2000)
Social infrastructure investment index	Community activities	The organisation organises activities that bring local residents together.	Vaznonienė & Kiaušienė (2018); Putnam (2000)
	Community spaces	The organisation provides spaces or opportunities for regular meetings.	Vaznonienė & Kiaušienė (2018); Low et al. (2005)
	Access to services and information	The organisation helps residents access services or information.	Vaznonienė & Kiaušienė (2018)
	Volunteer mobilisation	The organisation mobilises volunteers for mutual support.	Putnam (2000); Wilson (2000)

The social infrastructure investment index measured the practical results of NGO activities and their perceived impact on the local community. This dimension focused on providing and maintaining essential community support, including social and educational services, the management of shared spaces (e.g., community centers or meeting places), and the promotion of information flow in rural areas. In assessing these outcomes, the index examines the extent to which NGOs function as pillars of rural areas' structural social infrastructure rather than merely as temporary service providers.

A combined quantitative approach was used to analyze empirical data. First, three summary indicators were derived from several survey questions to characterize each analyzed dimension. Then, fundamental statistical indicators (such as mean values and dispersion) were calculated to characterize the overall situation. Finally, the relationship between the indices was analyzed using the correlation method. Based on the initial conceptual framework developed in the integrative literature review (Figure 1), three indices were created: the institutional capacity index, the cooperation network index, and the social infrastructure investment index. To construct the indices, the analysis averaged the corresponding five-point Likert scale items, treating each indicator equally. Subsequent evaluations used Spearman's rank correlation to assess the relationships among the newly formed indices. Because the dataset relies on ordinal responses (1 – strongly disagree to 5 – strongly agree) across 70 participants, this nonparametric test provided the best methodological fit. All findings report statistical significance at a threshold of $p < 0.05$.

The interpretation of the weighted means for the three indices was based on the equal interval methodology proposed by Pimentel (2010). By applying a uniform interval of 0.80, the scores were categorized into five distinct performance levels (Table 2).

Table 2
Interpretation levels for Likert-scale indices (derived from Pimentel, 2010)

Mean Score (M)	Interpretation Level
1.00 - 1.80	Very low
1.81 - 2.60	Low
2.61 - 3.40	Moderate
3.41 - 4.20	High
4.21 - 5.00	Very high

The data collection process prioritized ethical standards by guaranteeing voluntary, anonymous participation and fully aligning with GDPR requirements for data confidentiality and informed consent. The survey also included an open-ended question to gather qualitative insights on the specific types of support and services NGOs provide to their local communities.

Results and Discussion

This chapter presents and analyzes empirical results obtained from an online survey of 70 non-governmental organizations (NGOs) registered in rural areas of Latvia. To empirically examine the initial conceptual framework derived from the literature and measure how NGOs influence community resilience, the analytical framework centers on three core dimensions. The following subsections sequentially examine the composite indicators or indices developed for this study. Descriptive statistics, including means and standard deviations, serve to contextualize each dimension within the established theoretical literature. The analysis then examines the statistical interactions and correlations among the three indices. Together, these steps reveal how an organization's internal capabilities and external networks convert into tangible socio-economic benefits for rural communities.

Institutional capacity index

Several studies emphasize that community resilience depends on local organizations' ability to mobilize resources, coordinate activities, and ensure continuity during crises (Norris et al., 2008; Simo & Bies, 2007). Organizational capacity includes human resources, financial stability, management quality, and adaptability (Herman & Renz, 2008; Lecy et al., 2012). In rural areas, where the provision and receipt of services may be limited for various reasons, NGOs often function as organizations that stabilize situations, ensure service availability, and coordinate support (Berkes & Ross, 2013; Cheshire et al., 2015). Thus, the literature consistently shows that without sufficient institutional capacity, organizations cannot be effective resilience mechanisms. Community resilience is based on governance, leadership, and resource availability, which are considered structural prerequisites. This means that community resilience cannot be reduced to good relations within the community alone, because without institutionally organized capacity to make decisions, maintain accountability, and mobilize resources, the community's ability to act in crises and in the long term is limited. Community resilience is formulated in studies as a set of capabilities rather than a static state (Magis, 2010), and it can also be analyzed simultaneously as an outcome, a state, a characteristic, and a process (Boston et al., 2024).

NGOs, as part of the third sector, are characterized by collective action that differs significantly from that of the public and private sectors, where effectiveness depends on organizational structure and institutionalization (Uphoff, 1993; Salamon & Sokolowski, 2016). However, it is critical to recognize that NGO capacity is not uniform. Research indicates significant disparities in how these organizations are managed, the sectors they serve, and the nature of their engagement with governmental institutions. Therefore, organizations can vary significantly in terms of their actual capacity to act (Mazzei et al., 2020).

In the survey, the average value of the institutional capacity index was $M = 3.76$ (standard deviation ≈ 0.63), indicating a relatively high level of internal stability and adaptive capacity, as assessed by the organizations themselves. The majority of organizations reported stable team, a predictable financial foundation, and the adaptive capacity required to pivot operations during periods of crisis. However, the dispersion indicates significant differences between organizations, reflecting an uneven distribution of capacity in rural areas.

Institutional capacity is based on social rather than financial capital - survey data reveal a marked asymmetry in the institutional capacity of rural NGOs, although the organizations have considerable experience (70% have been operating for more than 10 years), and their financial and human resource base is fragile (almost 40% of organizations have no paid employees). Despite this, NGOs demonstrate a high capacity to respond to crises, indicating that their survival and effectiveness are primarily based on strong leadership and the mobilization of volunteers, compensating for financial shortcomings with self-sacrificing social capital (Adger, 2003; Rahman et al., 2024).

Cooperation network index

Social resilience in literature is often closely linked to various networks, with bridging logic, or a combination of various horizontal and vertical cooperation links that allow external resources to be mobilized, being particularly important (Aldrich, 2012; Aldrich & Meyer, 2015; Pelling & High, 2005). Various types of cross-sectoral cooperation and joint decision-making improve the ability to respond to uncertainty (Ansell & Gash, 2008; Emerson et al., 2012; Provan & Kenis, 2008). Empirical studies show that in crises, it is the network structure that determines the speed and efficiency of resource circulation (Forrest et al., 2018; Rockenbauch & Sakdapolrak, 2017).

If institutional capacity explains how an organization maintains its operations, the dimension of collaborative networks explains how this capacity becomes systematically effective. Systematic evaluations of community resilience consistently highlight networking as a fundamental pillar that encompasses local relationships and communication channels. This perspective shifts the focus away from resilience as an isolated characteristic and frames it instead as a dynamic byproduct of social connectivity

and information exchange (Korosteleva & Petrova, 2022). NGOs are also often involved in the management of societal crises, for example, by providing resources and knowledge and facilitating knowledge exchange between institutions and citizens (Forrest et al., 2018). The role of NGOs in cooperation networks is not only theoretical, but also very practical, as NGOs combine different types of knowledge, access, and capacity for action (Forrest et al., 2018). At the same time, it is precisely cooperation networks that can create complex situations, as the forms and management of organizations differ, which affects the quality of relations with the community (Mazzei et al., 2020).

Therefore, the collaboration network index measures an organization's integration into the local community and its collaboration with other organizations. To evaluate whether an organization functions in silos or is deeply embedded within its community, this index aggregates several key metrics. These include the extent of collaboration with municipalities and peer groups, engagement with civic leaders, and the regularity and perceived quality of these networks.

In the survey, the average value of the cooperation network index was M = 3.79 (standard deviation ≈ 0.91), which is slightly higher than the institutional capacity indicator. This shows that organizations generally perceive themselves as relatively well integrated into the local cooperation environment. Higher ratings for cooperation with local leaders and other organizations indicate the development of horizontal links. In contrast, cooperation with local governments was rated more cautiously in some cases, which may reflect institutional inequalities and differences in cooperation practices in different territories.

The data confirms that NGOs' effectiveness cannot be measured solely by their internal resources, but also by their ability to form networks. Organizations act as bridges between citizens and decision-makers, from ensuring the flow of information to directly defending interests (e.g., fighting against school closures or changing regulations). In crises, it is precisely these pre-established networks that ensure rapid and coordinated community action (Bryson et al., 2006).

Social infrastructure investment index

The framework of social infrastructure highlights the tangible locations, civic services, and institutional ties that form the backbone of any functioning community (Latham & Layton, 2019). In rural areas, social infrastructure often compensates for market and state failures (Vaznonienė & Kiaušienė, 2018; Yarkova, 2020). If capacity is potential and networks serve as a coordinative mechanism, then social infrastructure constitutes the tangible manifestation of community resilience. Social infrastructure only emerges where functioning infrastructure exists, and collective action is possible (Folke, 2006; Berkes & Ross, 2013). In this context, NGOs act as activity organizers, service providers, information providers, etc. One example of how NGOs build social infrastructure is through practical manifestations, such as NGO-initiated programs that strengthen community resilience (e.g., digital literacy programs). NGOs that help create social infrastructure make a real contribution to community life (Forrest et al., 2018). NGOs do not stop at networking or internal stability but translate this into a specific service or support that is valuable to the community on a daily basis (Forrest et al., 2018).

Finally, the social infrastructure index measures the tangible contributions an organization makes to the community's daily life. Its indicators include the organization of activities, the provision of services, the dissemination of information, the maintenance and provision of premises for residents' needs, the mobilization of volunteers, and the self-assessment of the contribution to community life.

In the survey, the average value of the social infrastructure investment index was M = 3.22 (standard deviation ≈ 0.82), which is lower than both structural indices. This indicates moderate, but not always intensive, actual investment in organizing activities, providing services, disseminating information, and mobilizing volunteers. The difference between structural preconditions and actual investment may indicate a gap between potential and practical materialization.

The NGO sector in rural areas has become a critical element in maintaining social infrastructure, as analysis shows that NGOs serve as a social safety net, regularly filling gaps in public services (Uphoff, 1993; Zajda, 2022). By providing direct practical assistance (food delivery, support during natural disasters, support for socially vulnerable groups), NGOs create and maintain local social infrastructure, a prerequisite for residents to remain in rural areas and ensure their quality of life (Latham & Layton, 2019; Vaznonienė & Kiaušienė, 2018).

Interaction between indexes

To test the initial conceptual framework's assumptions about the interaction among the three dimensions, Spearman's rank-order correlations (r_s) were calculated to assess the interrelationships among the indices.

The empirical model (Figure 2) illustrates the transition from a purely theoretical framework to a data-driven understanding of rural NGO operations. The relative strength of the observed relationships, although all correlations remain weak to moderate ($r_s < 0.5$), suggests that institutional capacity alone does not directly translate into community investment, and that cooperation networks appear to play a bridging role between internal resources and actual contributions to social infrastructure.

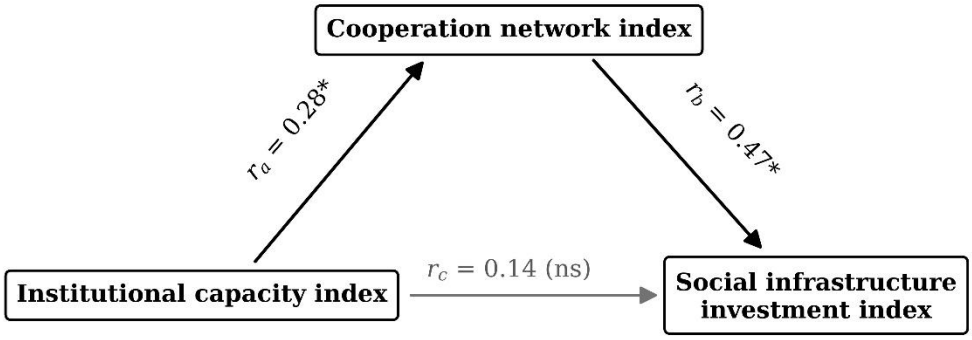
While the initial conceptual framework hypothesized a direct link between resources and community outcomes, the empirical results suggest a mediation pattern rather than a direct effect. The institutional capacity index appears to serve as a prerequisite for networking, while the cooperation network index

shows the strongest, though still moderate, association with social infrastructure investment.

These findings should be interpreted with caution given the relatively weak correlations and the limited sample size, yet they indicate a plausible pathway through which institutional capacity may be converted into community outcomes via cooperation networks.

Figure 2

The mediating role of cooperation networks: An empirical model with Spearman correlation coefficients (r_s = 0.28 between institutional capacity and cooperation networks; r_s = 0.47 between cooperation networks and social infrastructure investment; r_s = 0.14 between institutional capacity and social infrastructure investment)



** p < .05; ns = not significant*

The institutional capacity index exhibits a weak, though statistically significant, positive correlation with the cooperation network index (r_s = 0.28, p < 0.05). This indicates that organizations with greater internal stability and a larger resource base tend to be more actively involved in cooperation networks. The data indicate that stronger cooperation networks are associated with higher social infrastructure investments, as evidenced by a moderate, statistically significant positive correlation (r_s = 0.47, p < 0.05). Consequently, organizations with deeper integration into local collaborative networks demonstrate a greater propensity for resource allocation toward community initiatives and service delivery. In contrast, a weak statistical correlation was found between the institutional capacity index and the social infrastructure investment index (r_s = 0.14, p > 0.05), which formally does not exceed the threshold of statistical significance. These results illustrate that organizational stability constitutes a latent resource that does not automatically translate into practical contributions unless mobilized through formal and informal cooperation mechanisms.

Conclusions

1. NGOs in rural areas of Latvia show relatively high self-assessed institutional capacity (M=3.76) and integration into cooperation networks (M=3.79). However, their actual contribution to the development of social infrastructure is more moderate level (M=3.22), indicating a marked gap between organizations' internal potential and their practical actions for the community's benefit.

2. Statistical analysis reveals that there is no significant direct link between an NGO's institutional capacity and its investment in social infrastructure (r_s = 0.14, p > 0.05). However, the study suggests a mediation pattern operating through cooperation networks. Capacity correlates positively with networking (r_s = 0.28), which in turn demonstrates a moderate association with social investment (r_s = 0.47). These findings suggest that inter-organizational cooperation may serve as an important intermediary mechanism, linking internal institutional resources to active contributions toward rural social infrastructure, although the strength of the correlations indicates that further research with a larger sample is needed to confirm this pathway.

On a practical level, the results indicate that national and local government support instruments should not be focused solely on strengthening formal organizational capacity. It is strategically more important to invest in creating a stable, high-quality environment for cooperation among NGOs, local governments, and other local actors.

Based on the conceptual framework developed and tested in this study, it would be helpful to examine specific examples of good practice in rural areas in future studies. In-depth case studies of the most successful NGOs would help reveal the everyday strategies and actions organizations use to build meaningful cooperation, providing inspiration and practical guidance for other rural communities.

In conclusion, the study validates that the role of NGOs

in the socio-economic development of rural areas is fundamentally tied to their function as indirect components of social infrastructure. By activating local cooperation networks, NGOs facilitate resource circulation and community mobilization, which are essential for long-term community resilience and stability in rural territories.

Limitations

This study has a few limitations that should be considered. First, the sample size is relatively small (N=70). While sufficient for this exploratory study, the results cannot be fully generalized to all rural NGOs in Latvia. Second, the data are based on organizations' self-assessments, which may lead respondents to overestimate their capacity and impact. Future research should compare these results with residents' or municipalities' views. Finally, as this study relies on correlation analysis, it identifies interdependencies between variables but cannot establish definitive causality. To more accurately determine the impact of NGOs on rural development, future research should adopt a longitudinal approach.

Author contributions

All authors were equally and actively involved in all phases of the study, including study design and planning, data collection, provision of analytical tools, writing and proofreading, and overall supervision.

Authors declaration

The manuscript was initially drafted in Latvian and subsequently translated into English using DeepL. Grammarly was used for language editing and proofreading. The authors were responsible for all conceptual development, analysis, and final editorial decisions.

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SOCIAL ACCEPTANCE OF POWER GENERATION POSSIBILITIES

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Abstract
The decarbonisation of power generation systems is a critical objective for the Baltic States (Latvia, Lithuania, and Estonia) as they strive to meet European Union climate and energy goals. However, the successful deployment of renewable energy infrastructure, particularly wind and solar projects, depends not only on technical and economic viability but also on social acceptance. This study aims to compare Latvia, Lithuania, and Estonia with respect to participation requirements and practices that influence social acceptance of renewable energy infrastructure. The analysis is based on a comparative review of legal and institutional frameworks, policy documents, and documented empirical case evidence, with a focus on mandatory participation instruments, good practices, and procedural risk points, including misinformation and conflict escalation. Findings suggest that while all three countries comply with EU regulations on public participation, implementation quality varies significantly: Latvia faces challenges related to fragmented procedures and formalistic consultations; Lithuania demonstrates broader but inconsistent engagement practices; and Estonia shows more developed collaborative planning elements, especially in relation to offshore wind. The paper highlights the importance of improving consultation quality, clarifying feedback mechanisms, addressing misinformation, and strengthening energy citizenship as key strategies to enhance social acceptance and support the transition to low-carbon energy systems.
Keywords: social acceptance, renewable energy infrastructure, public participation, energy justice, Baltic States.

Introduction

Power-sector decarbonisation requires not only technically and economically viable generation options but also sustained public and stakeholder acceptance of the technologies, projects, and policies that enable their deployment. Social acceptance has repeatedly been shown to be a decisive condition for implementation, as opposition can delay, reshape, or halt projects through planning disputes, permitting appeals, and political backlash, even when system-level benefits such as emissions reduction, affordability, and energy security are widely recognised (Wüstenhagen et al., 2007; Jenkins et al., 2016; Tardin-Coelho et al., 2025). However, social acceptance is neither uniform across power generation technologies nor stable over time. It varies across technology families, including wind, solar photovoltaic (PV), bioenergy/biomass, hydropower, nuclear energy, and fossil generation with carbon capture, utilisation and storage (CCUS). It depends strongly on context, including place-based impacts, perceived fairness, trust in institutions, and the credibility of information circulating in the public sphere (Devine-Wright, 2005; Jenkins et al., 2016).

A widely used conceptual framework distinguishes three dimensions of social acceptance: socio-political acceptance, community acceptance, and market acceptance (Wüstenhagen et al., 2007). Socio-political acceptance refers to public support for a technology and policy direction, community acceptance relates to local attitudes toward specific infrastructure projects, and market acceptance concerns adoption by investors, consumers, and supply chains. This framework explains why broad societal support for low-carbon energy systems may coexist with strong local resistance to individual projects. Community acceptance is often shaped by concrete impacts on landscapes and livelihoods, as well as perceptions of fairness and legitimacy in decision-making processes (Devine-Wright, 2005).

The energy justice literature further emphasises that the perceived legitimacy of energy infrastructure depends on distributive justice (the allocation of benefits and burdens), procedural justice (fairness and transparency in decision-making), and recognition justice (respect for diverse stakeholder perspectives) (Jenkins et al., 2016). Where these dimensions are perceived as insufficiently addressed, public opposition to infrastructure projects becomes more likely. These issues are increasingly salient in Europe, where public priorities for energy policy combine affordability, energy security, and decarbonisation, and where attitudes towards energy technologies can shift in response to broader socio-economic developments and energy crises.

The literature on social acceptance identifies multiple factors influencing public attitudes toward power generation technologies. Public perception is shaped not only by environmental and climate benefits but also by concerns related to local environmental impacts, landscape change, and socio-economic outcomes, as well as by the quality of participation processes and trust in decision-makers. Evidence suggests that different technologies generate distinct acceptance challenges depending on their visibility, scale, and perceived risks. For example, public acceptance of bioenergy strongly depends on the sustainability of biomass feedstocks and their perceived contribution to climate goals (Scarlat et al., 2015).

A central problem is that participation and engagement mechanisms intended to foster social acceptance are often implemented in a formalistic manner, offering limited opportunities for meaningful stakeholder influence. Such practices can weaken procedural legitimacy and intensify local conflicts, particularly when affected communities perceive decision-making

processes as opaque, unresponsive, or unfair. In this context, public participation shapes acceptance not only through information exchange, but also through perceptions of procedural fairness and the distribution of project-related benefits and burdens among local stakeholders (Aitken, 2010; Simcock, 2016; Lienhoop et al., 2018; Susskind et al., 2022; Subotički et al., 2023). This article aims to analyse the role of public participation in shaping social acceptance of power generation options in the Baltic States, with particular emphasis on renewable energy infrastructure, such as wind and solar projects. To achieve this goal, the article examines and compares the legal, institutional, and governance frameworks of Latvia, Lithuania, and Estonia, focusing on mandatory participation instruments, participatory practices, and procedural risk points. Furthermore, the study seeks to identify the main factors that strengthen or weaken public acceptance of renewable energy development and to develop a comparative typology of participation approaches across the three countries. In doing so, the article contributes to a better understanding of how participatory governance can support more socially legitimate and effective energy transition processes in the Baltic region. The study is based on qualitative comparative analysis of legal, policy, and empirical case data to assess participation practices and social acceptance dynamics.

Materials and Methods

This study employs a comparative legal–institutional and governance analysis to assess how the Baltic States: Latvia, Lithuania, and Estonia regulate and implement mechanisms influencing the social acceptance of power generation technologies, including wind, solar, and other renewable energy infrastructure. The methodology integrates legal framework review, policy document analysis, and structured comparative assessment to identify mandatory participation instruments, good practice elements, and potential risk points within national regulatory environments.

The analytical framework is structured around three categories: mandatory participation instruments, good practice elements, and risk points. Mandatory participation instruments refer to legal procedures and statutory requirements for public consultation embedded in national and EU legislation, including environmental assessment processes, spatial planning procedures, and formal consultation obligations. Good practice elements represent institutional and procedural mechanisms that facilitate effective stakeholder engagement beyond minimum legal requirements, such as early consultation, transparency in decision-making, and mechanisms enabling meaningful stakeholder feedback. Risk points refer to institutional or procedural weaknesses that may contribute to conflict escalation, superficial consultation processes, or vulnerability to misinformation during energy infrastructure planning.

The comparative analysis draws on several types of documentary sources. National Energy and Climate Plans (NECPs), prepared under Regulation (EU) 2018/1999, provide the primary strategic policy context for renewable energy development and decarbonisation pathways in the Baltic States. The final updated National Energy and Climate Plans for Latvia, Lithuania and Estonia provide the strategic policy framework for renewable energy deployment, climate policy implementation, and governance arrangements for the energy transition in the Baltic States (European Commission, 2024a, 2024b, 2025).

Additional regulatory context is obtained from country-specific renewable energy policy analyses and legal reviews of renewable energy frameworks in the Baltic States. These sources provide insights into legislative developments, permitting procedures, and planning requirements affecting the deployment of wind and solar infrastructure (Klauberg Advokaadibüroo OÜ, 2023). The analysis is further supported by comparative implementation reports and case-based policy assessments documenting renewable energy development in the region. Such reports provide empirical evidence on project planning processes, permitting timelines, and implementation challenges, thereby enabling triangulation of regulatory differences between countries (Blumberga et al., 2021). European Union guidance documents on public participation and stakeholder engagement are also reviewed to identify minimum legal standards and recommended consultation practices under renewable energy planning frameworks, including the Renewable Energy Directive (RED III) (European Environmental Bureau, 2023).

Empirical case evidence was selected purposively from documented renewable energy planning and permitting processes where public participation, consultation quality, project delays, local opposition, or misinformation risks were explicitly discussed. The sources were included when they: (1) addressed wind, solar, or related renewable energy infrastructure; (2) covered at least one Baltic State; (3) provided verifiable information on planning, permitting, or consultation practice; and (4) were comparable with EU public participation requirements. The study, therefore, uses a documentary case-evidence approach rather than a statistically sampled case-study design.

Step 1 – Legal and policy mapping

This stage systematically identifies the national and EU regulatory instruments governing renewable energy development and public participation in energy planning. It includes legislation related to spatial planning, environmental impact assessment (Directive 2011/92/EU), renewable energy policy frameworks under the Renewable Energy Directive, and governance provisions under Regulation (EU) 2018/1999. Attention is given to provisions affecting stakeholder engagement, including mechanisms related to renewable energy communities and citizen participation introduced under the EU Clean Energy

for All Europeans package.

Step 2 – Institutional roles and governance practices

This stage analyses the institutional roles and governance practices involved in energy infrastructure planning and approval. Relevant actors, including national ministries responsible for energy and environmental policy, regulatory agencies, local governments, and transmission system operators, are identified and compared across the three countries. The analysis examines how public participation requirements are operationalised in practice, including public hearings, written consultation procedures, and digital participation mechanisms.

Step 3 – Comparative assessment

A structured comparative assessment is conducted using an analytical matrix. For each country, the matrix compares: (1) relevant legal instruments and EIA/SEA or spatial planning requirements; (2) responsible institutions and governance procedures; (3) timing and accessibility of participation; (4) mechanisms for stakeholder feedback; (5) good practice elements exceeding minimum EU requirements; and (6) procedural risk points, including formalistic consultation, limited influence on decisions, and misinformation vulnerability. The criteria are assessed qualitatively in order to identify similarities, differences, and recurring patterns across Latvia, Lithuania, and Estonia.

The assessment is supported by documented examples of onshore wind and solar projects in the Baltic region, providing empirical context for the regulatory comparison.

Step 4 – Synthesis and typology development

In the final stage, the findings are synthesised to develop a typology of participation approaches across the Baltic States. This typology categorises regulatory approaches according to their capacity to support socially legitimate energy infrastructure development, distinguishing between minimal compliance with formal consultation requirements and more advanced participatory practices that facilitate meaningful stakeholder engagement. The analysis also identifies systemic risk points common across jurisdictions as well as those specific to national contexts.

To ensure scientific rigour, the study combines qualitative document analysis with comparative policy analysis techniques commonly used in governance research. EU regulatory benchmarks, including the Renewable Energy Directive and the Governance Regulation, provide the theoretical and legal baseline for comparisons, whereas documented empirical observations are used to assess how participation mechanisms operate in practice. No statistical testing is applied because the purpose is structured cross-country interpretation rather than measuring population-level prevalence.

Results and Discussion

Step 1 – Legal and policy mapping

The legal and policy mapping indicates that renewable energy development in the Baltic States is embedded within a shared European Union regulatory framework. At the same time, national legislative arrangements introduce important institutional differences affecting the implementation of renewable energy projects and associated public participation processes.

Across Latvia, Lithuania, and Estonia, renewable energy infrastructure planning and permitting are governed through a combination of spatial planning legislation, environmental assessment procedures, and sector-specific renewable energy policies. These frameworks are strongly influenced by European Union legislation, particularly the Environmental Impact Assessment Directive (Directive 2011/92/EU, amended by Directive 2014/52/EU) and the Renewable Energy Directive (RED II and RED III), which establish minimum requirements for environmental review, public consultation, and stakeholder engagement in energy infrastructure planning.

Despite this common regulatory foundation, national legislative structures regulating renewable energy deployment differ in institutional design and implementation mechanisms.

In Latvia, renewable energy project development is primarily governed by the Law ‘On Environmental Impact Assessment’ and the Spatial Development Planning Law, which define zoning procedures, environmental assessment requirements, and consultation obligations for energy infrastructure projects.

In Lithuania, the Renewable Energy Law serves as the core legislative framework for renewable energy deployment. Project approval procedures are closely linked to Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA) requirements, which include mandatory public consultation stages during project planning and environmental review processes. These procedures are integrated into Lithuania’s national energy and climate policy framework, promoting the expansion of renewable energy and local stakeholder engagement.

In Estonia, renewable energy development is regulated through the Energy Act and the Spatial Planning Act, which govern permitting procedures, spatial planning requirements, and environmental assessment obligations. Estonia has also introduced specific regulatory provisions supporting offshore wind development and policy instruments to accelerate renewable energy deployment. These instruments are complemented by the final updated National Energy and Climate Plans, which outline national targets for renewable energy deployment, climate policy implementation, and governance arrangements in Latvia, Lithuania and Estonia (European Commission, 2024a, 2024b, 2025).

The legal mapping also highlights differences in the degree to which national regulatory frameworks support energy citizenship and community participation. European Union policy, particularly through the Clean Energy for All Europeans package,

promotes Renewable Energy Communities (RECs) and citizen participation in energy systems. While all three Baltic States have introduced legal provisions enabling community participation, practical implementation and policy emphasis vary across countries. To contextualise the policy analysis, Table 1 summarises selected official indicators on renewable energy status and targets in the Baltic States.

The legal and policy mapping demonstrates, in Table 1, that although the Baltic States operate within a harmonised European regulatory framework, national institutional arrangements and implementation practices differ in ways that may influence transparency, public participation effectiveness, and ultimately the social acceptance of renewable energy infrastructure.

Step 2 – Institutional roles and governance practices

The comparative analysis of institutional roles and governance practices shows that public participation in renewable energy planning in the Baltic States is organised through multi-level governance arrangements involving ministries, municipalities, environmental authorities, and transmission or distribution system operators.

Table 1

Selected renewable energy status and 2030 policy directions in the Baltic States

Country	Latest official renewable energy status	2030 policy target/direction	Relevance for this study
Latvia	Renewables accounted for **43.2%** of gross final energy consumption in **2023**, while renewable electricity represented **54.3%** of gross electricity consumption in **2023**	Updated NECP contribution: **61%** renewables in gross final energy consumption by **2030**	High policy ambition coexists with the need for socially accepted project deployment, particularly beyond historically strong hydro-based generation
Lithuania	Wind accounted for **43%** and solar PV for **17%** of total electricity generation in **2024**	Updated NECP contribution assessed at **55%** renewables in gross final energy consumption by **2030**	Rapid wind and solar expansion increases the importance of planning legitimacy and effective local consultation
Estonia	Renewable sources produced **more than half** of electricity in **2023**, and **63%** of total power production in **2024**	Policy targets to cover **100% of annual electricity demand with renewables by 2030**	A strong expansion trajectory underscores the importance of participation quality, especially for wind and offshore projects

The 2030 policy directions presented in Table 1 are based on the final updated National Energy and Climate Plans submitted by Latvia, Lithuania and Estonia to the European Commission (European Commission, 2024a, 2024b, 2025). In Latvia, institutional coordination appears relatively fragmented. The RTU comparative assessment shows that wind and solar projects involve multiple institutional contact points and extensive documentation requirements, particularly involving municipalities, building authorities, environmental procedures, and network operators. This suggests that participation is formally embedded in approval procedures but may be experienced as administratively complex and insufficiently integrated. Latvia also performs relatively poorly in terms of information availability for wind projects, which may contribute to perceptions of limited transparency and reduced public influence (Blumberga et al., 2021).

In Lithuania, governance arrangements are somewhat more concentrated around the energy regulator, municipalities, and network operators. Public consultation is formally present through environmental and planning procedures, yet participation effectiveness varies across projects. Although information accessibility appears somewhat stronger than in Latvia, consultation quality often depends on project-specific implementation rather than a consistently strong participatory model (Klauberg Advokaadibüroo OÜ, 2023).

In Estonia, institutional roles are shared between municipalities, environmental bodies, and energy-sector institutions. Evidence suggests that Estonia has introduced procedural measures to facilitate renewable energy development, including offshore wind planning. However, the RTU comparison still indicates relatively high institutional involvement and moderate information accessibility, suggesting continued governance complexity (Blumberga et al., 2021; Klauberg Advokaadibüroo OÜ, 2023).

Across all three Baltic States, participation tools remain formally similar: public hearings, written submissions, and consultation procedures within environmental assessment and spatial planning.

However, implementation differences are more significant than the formal instruments themselves. Latvia's main weakness is fragmented administration and limited early-stage communication, which can make consultation appear disconnected from project design. Lithuania shows a more structured but project-dependent engagement practice, while Estonia demonstrates stronger collaborative planning elements although landscape concerns and governance complexity remain relevant. Thus, the decisive difference lies in timing, feedback quality, and the perceived ability of communities to influence decisions.

Step 3 – Comparative assessment

The comparative assessment is based on a structured comparative analysis of qualitative data extracted from policy documents, legal frameworks, and documented project cases. It reveals both commonalities and notable differences in how public consultation and social acceptance of renewable energy infrastructure projects are implemented in Latvia, Lithuania, and Estonia.

All three countries comply with the EU requirements for public participation under Directives 2011/92/EU and 2014/52/EU. Nevertheless, the effectiveness of consultation processes varies. In Latvia, public participation is formally embedded in environmental assessment and policy planning procedures (Ministry of Environmental Protection and Regional Development of the Republic of Latvia, 2022). However, the effectiveness of such consultation in influencing project-level decisions remains dependent on implementation practice and information accessibility (Blumberga et al., 2021; Simcock, 2016). In Lithuania, consultation documents may be perceived as overly technical, reducing meaningful stakeholder engagement (Aitken, 2010). In Estonia, consultation processes are also sometimes viewed as formalistic, particularly where communities perceive limited influence on final decisions (Toke et al., 2008). Several good practice elements also emerge. Latvia's NECP promotes energy communities and community-led renewable energy initiatives although implementation remains uneven. Lithuania has occasionally implemented stakeholder workshops and early consultations for renewable energy projects. Estonia has introduced collaborative planning approaches in certain renewable energy initiatives, particularly in offshore wind planning.

Despite these practices, several common risk points remain. Procedural consultations, uneven stakeholder engagement, and misinformation related to environmental or health impacts of renewable technologies can influence public perceptions and contribute to project opposition (Sovacool & Ratan, 2012; Winter et al., 2021).

Step 4 – Synthesis and typology development

The synthesis of results enables the development of a typology of participation approaches across the Baltic States. The typology is derived from a systematic comparison of regulatory features and participation practices identified across the three countries. Three general models emerge: minimal compliance, enhanced engagement, and participatory innovation.

Latvia largely aligns with a minimal compliance model, where consultation procedures meet legal requirements but often offer limited opportunities for meaningful stakeholder influence. Lithuania demonstrates elements of enhanced engagement, including broader consultation practices although implementation remains inconsistent. Estonia shows certain characteristics of participatory innovation through collaborative planning and community involvement initiatives although challenges related to transparency and local acceptance persist.

Across all three countries, systemic risks affecting social acceptance include formalistic consultation procedures, uneven access to information, and the influence of misinformation. These factors highlight the importance of earlier engagement, clearer communication, and more transparent governance processes to strengthen public acceptance of renewable energy infrastructure in the Baltic States.

The key characteristics of the participation models and their associated risks are summarised in Table 2.

Table 2 summarises the main differences in participation approaches and shows that variation across the Baltic States lies primarily in implementation quality rather than in formal legal compliance.

Table 2

Summary of Typology and Key Findings

Model	Country	Key characteristics	Main risks
Minimal Compliance	Latvia	Participation fulfils EU legal requirements but has limited influence on decisions	Formalistic consultation, limited early engagement
Enhanced Engagement	Lithuania	More structured consultation practices and stakeholder meetings	Inconsistent implementation, limited influence on key decisions
Participatory Innovation	Estonia	Greater emphasis on community involvement and collaborative planning	Perceived transparency gaps, local landscape concerns

Scientific rigour and validity

Analytical validity is supported by triangulation across three source groups: EU and national legal-policy documents; comparative renewable energy permitting reports and legal reviews; and documented project-level evidence from wind and solar planning processes. Legal and policy documents establish the formal regulatory baseline, while comparative reports and empirical case evidence are used to interpret implementation quality, participation risks, and social acceptance dynamics.

Theoretical concepts of social acceptance and energy justice frame the analytical categories; empirical observations assess how participation requirements are applied in project planning and permitting practice. This distinction helps separate conceptual argumentation from implementation-based findings.

In Latvia, the NECP establishes renewable energy targets but provides limited mechanisms for early community engagement in project planning.

These patterns are consistent with NIMBY (Not in My Back Yard) dynamics, in which local opposition to renewable energy projects emerges despite general support for the energy transition, particularly when perceived local impacts outweigh broader environmental benefits (Sovacool & Ratan, 2012).

Lithuania also demonstrates a formal commitment to public consultation through EIA and planning procedures. However, transparency concerns during site selection for renewable energy projects have been identified as a factor influencing local opposition (Ministry of Environment of the Republic of Lithuania, 2024).

In Estonia, policy frameworks increasingly promote community involvement in renewable energy development. Environmental impact assessment procedures formally encourage stakeholder participation in project planning. Nevertheless, local resistance may still arise in areas where renewable infrastructure is perceived to threaten environmental or cultural heritage values (Riigi Teataja, 2017).

Empirical case evidence from renewable energy projects in the Baltic region provides additional insight into participation outcomes. In Latvia, several onshore wind projects have experienced delays due to local opposition linked to concerns about landscape impacts, noise, and perceived environmental risks. The EIA consultation process has been criticised for insufficiently addressing these concerns during project planning (Ministry of Environmental Protection and Regional Development of the Republic of Latvia, 2022).

In Lithuania, early-stage consultations in wind energy planning demonstrate that proactive engagement with local communities can reduce opposition and increase acceptance. However, rural projects still reveal inconsistencies in consultation quality, particularly where local concerns are not sufficiently reflected in final decisions.

In Estonia, offshore wind projects have used advisory groups and local consultation mechanisms that enable earlier community involvement in planning stages. While these approaches may improve transparency and dialogue, opposition can still emerge where projects are perceived to affect landscapes or marine ecosystems.

To strengthen analytical validity, national regulatory frameworks were compared against EU policy benchmarks, particularly RED II/III and the Governance Regulation (EU) 2018/1999. These policies establish minimum requirements for transparency, stakeholder engagement, and public participation in renewable energy planning.

Although Latvia, Lithuania, and Estonia formally comply with EU requirements, the practical depth of participation differs. Estonia shows stronger alignment with EU objectives related to energy citizenship and community involvement.

Lithuania occupies an intermediate position, with more structured consultation practices but uneven implementation. Latvia shows the greatest risk of minimal-compliance consultation, particularly where early engagement and feedback mechanisms remain weak. These differences should not be read as fixed national rankings, but as evidence that formal compliance alone does not ensure procedural legitimacy or social acceptance.

Conclusions

1. The comparative analysis shows that Latvia, Lithuania, and Estonia all formally comply with European Union requirements for public participation in renewable energy planning and permitting; however, the practical effectiveness of these participation processes differs across countries.
2. In all three Baltic States, public consultation is most often implemented through conventional mechanisms such as public hearings, written submissions, and consultation within environmental assessment and spatial planning procedures. The main difference lies not in their formal existence, but in how effectively they enable meaningful stakeholder influence.
3. Latvia demonstrates the strongest features of a procedural or minimal-compliance approach, where consultation is often perceived as formal rather than influential. Lithuania shows broader engagement efforts, but participation quality remains uneven and often dependent on project-specific implementation. Estonia shows more elements of collaborative, community-oriented practice, though these do not eliminate local resistance or guarantee stakeholder influence over final decisions.
4. A common challenge across the Baltic States is the persistence of formalistic consultation, fragmented governance arrangements, and uneven information accessibility. These factors weaken procedural legitimacy and may contribute to delays, conflicts, and lower public trust in renewable energy projects.
5. Misinformation and perceived risks related to environmental, health, and landscape impacts remain important barriers to social acceptance, particularly in relation to wind energy projects. These effects are reinforced where consultation processes are not sufficiently transparent, timely, or responsive to local concerns.
6. The findings indicate that stronger early-stage engagement, clearer communication, and more accessible participation mechanisms are necessary to improve the social acceptance of renewable energy infrastructure in the Baltic States. Greater attention to energy citizenship and community benefit-sharing could further strengthen the legitimacy of the energy transition.

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INCENTIVE-BASED AND EQUALIZATION-BASED APPROACHES TO MITIGATING REGIONAL INEQUALITY

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Abstract
Regional inequality is one of the most significant socio-economic factors influencing a country's overall sustainability and the well-being of its regional population. Regardless of the causes of regional inequality – be it uneven distribution of resources, historical disparities, or some consequences of state policies – it influences the ability of local governments to provide residents with equivalent services and to perform the functions assigned to them. In a globalized context characterized by heightened population mobility, shifting demographic trends, and escalating geopolitical tensions, the impact of regional inequality is intensifying. Consequently, there is an urgent need for, national and local governments, to implement targeted instruments to reduce these disparities and mitigate their consequences. The aim of this article is to analyse and classify instruments for reducing regional inequality by investigating the interaction between the subjects involved in regional equalisation – the state, local governments, entrepreneurs, and residents. Based on the analysis, the identified policy instruments are classified into two distinct categories: incentive instruments and equalising instruments. Incentive instruments are aimed at increasing regional self-sufficiency and enhancing the attractiveness of a region for both the business environment and residents. Balanced and sustainable regional policy is possible only by means of inclusion of both types of instruments in policies developed by national and local governments to reduce regional inequality, without diminishing local authorities' efforts to generate their own revenues or encouraging their dependence on external funding, while simultaneously maintaining fiscal capacity of the mentioned local authorities.
Keywords: regional inequality, fiscal equalization, incentive-based policy, local government.

Introduction

Regional inequality is a significant challenge faced by most of countries. The causes of regional inequality are varied — different access level to resources across regions, the specific historical patterns of regional development, as well as national policy decisions. Regardless of the underlying causes, the impact of inequality on regions is similar: a reduced capacity of local authorities to perform their assigned functions and to provide residents with equivalent services. In today's world, characterised by increasing population mobility, negative demographic trends in many regions, as well as rising geopolitical tension, addressing regional inequality is becoming ever more important, often focusing not on reducing regional disparities, but rather merely on preventing the widening of regional development gaps.

For a long time, the prevailing view in economic theory was that market mechanisms are self-regulating and do not require government intervention. In the 1920s and 1930s, however, an understanding emerged that differences in regional development have a systemic nature rather than being a result of isolated incidents or failures in regional governance. The academic response to this understanding was the emergence of regional development theories and the creation of regional policy as a scientific field. One of the fundamental contributions to regional policy is Gunnar Myrdal's theory of cumulative causation, which demonstrated that the free market tends to make wealthy regions wealthier and poorer regions poorer (Myrdal, 1957). Similarly, in 'The Great Transformation', Karl Polanyi emphasised that regional equalisation functions as a stabiliser of the system, emphasising that redistribution is not only an economic decision but also an instrument of societal self-preservation (Polanyi, 1944). These authors provided a theoretical justification for the necessity of regional equalisation in their works. Wallace Oates, in his work 'Fiscal Federalism', describes technical solutions for fiscal equalisation, including horizontal redistribution, as well as substantiates the efficiency of fiscal decentralisation (Oates, 1972). However, as it is noted in the research of Arthur Okun, the application of such theories to regional convergence collides with economic reality, particularly a reduction in efficiency, ultimately leading to 'the big trade-off between equality and efficiency' (Okun, 1975). In contemporary conditions, regional inequality is acquiring new dimensions as it is demonstrated in the research of Thomas Piketty, capital concentration and growing inequality have become systemic phenomena, continuing to require active state intervention and the use of redistributive mechanisms (Piketty, 2013).

Alongside the equalisation-oriented approach represented by the authors mentioned above, and as a response to the challenges identified by Arthur Okun, some theories have emerged that emphasise instruments for regional development, such as Michael Porter's cluster theory and the smart specialisation framework advanced by Dominique Foray (Porter, 1990; Foray, 2015). According to these theories, reducing regional inequality is possible through the stimulation and development of regions' strengths.

Until now, equalising and incentive-based approaches to reducing regional inequality have largely been analysed as opposing poles, with the corresponding instruments considered as separate elements. The authors present a thesis that effective reduction of regional inequality is possible only by means of combination of both approaches, by appropriately applying equalising instruments to ensure social justice and financial capacity, while simultaneously stimulating regional development and strengthening

the ability of regions to maintain fiscal capacity with the help of internal resources. As a result of municipal decisions, equalising instruments can be transformed into incentive instruments. The article presents a classification of regional policy instruments and identifies the interactions among them.

Materials and Methods

The authors conducted a qualitative study based on theoretical synthesis. A deductive approach was applied in order to derive a model for the classification of instruments based on theoretical models. The methods employed include systematic analysis and a comparative approach. The study used sources from Scopus, Web of Science, Google Scholar, and institutional databases (OECD and European Commission reports). The sources were selected according to two principles: first, fundamental scientific theories in the fields of regional development and policy; and second, the most recent academic studies and institutional reports to capture contemporary trends.

The development of the interaction framework was carried out in three stages: 1) identification of regional policy instruments based on theoretical research; 2) classification into two categories — equalising instruments aimed at ensuring social justice and basic capacity, and incentive instruments aimed at promoting regional growth; 3) identification of the subjects involved in regional equalisation (the state, local governments, residents, and businesses), as well as determination of the directions in which regional equalisation instruments operate. An institutional approach was used for the selection of subjects, ensuring representation of both the public sector (the state and local governments) and the private sector (residents and businesses). Accordingly, within the framework of this study, regional policy was analysed as a closed system rather than merely as the implementation of individual state decisions.

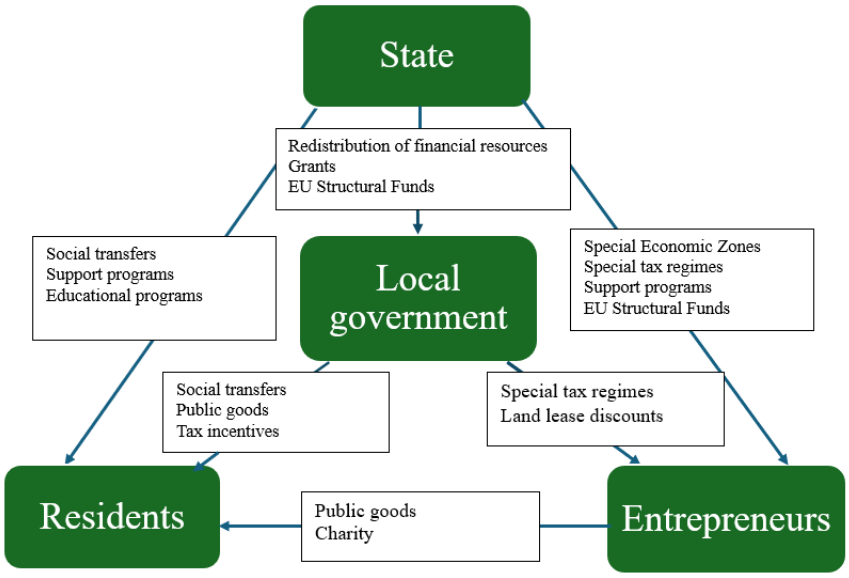
The study does not include empirical calculations, as its primary objective is the development of a theoretical model. The model developed in the course of the research is universal and applicable both at the level of Latvia and other EU countries, as the roles of the subjects remain unchanged.

Results and Discussion

Based on the theoretical synthesis and institutional approach described in the methodology section, an interaction model for reducing regional inequality was developed. The model includes four subjects involved in reducing regional inequality, and identifies the directions for the application of regional equalisation instruments, as well as determines the dimensions of interaction among the included subjects (Figure 1).

Figure 1

Directions for the Application of Instruments to Reduce Regional Inequality



Source: created by the authors.

The model illustrated in Figure 1 presents regional policy instruments as a closed system, while highlighting the pivotal role of local governments in the implementation of regional policy. Local governments should not be viewed merely as passive recipients of equalisation transfers; rather, they play an active role in shaping equalisation policy at the local level, not only by means of allocation of received funds but also by developing their own instruments to address regional disparities.

The presented model enables the identification of two principal directions in the transformation of financial resources within the process of regional equalisation. The first one is a population-oriented direction, linked

to ensuring equal opportunities for municipal residents both in terms of income levels and access to public goods and municipal services. The second direction relates to the business sector, focusing on the creation of a supportive environment for entrepreneurship applying such instruments as special tax regimes, land-lease discounts, as well as the establishment of special economic zones. The scale at which instruments are applied is also of critical importance. A distinction must be drawn between equalisation instruments that can be implemented at the local government level and those that require policy decisions at the national level (in the provided model, these instruments are reflected both in the state–business and local government–business dimensions). Accordingly, regional policy instruments can be classified based on their direction of application, their scale of implementation, as well as the underlying policy approach to regional equalisation.

The subsequent analysis focuses on the classification of regional equalisation instruments specifically according to the equalisation approach – distinguishing between equalising and incentive approaches. In the course of this classification, the authors also identify hybrid instruments that simultaneously operate within both of these approaches (Table 1).

Table 1
Classification of Instruments for Reducing Regional Inequality

Instrument Group	Instruments	Theoretical Rationale
Equalising	Redistribution of financial resources, grants, social benefits, support programmes, public goods, charitable initiatives	W. Oates (fiscal equalisation), G. Myrdal (necessity of redistribution), T. Piketty
Incentive	Education programmes, tax incentives, land-lease discounts, special economic zones, preferential tax regimes	M. Porter (clusters/competitiveness), D. Foray (smart specialisation)
Hybrid	EU structural funds, education programmes	A. Okun (efficiency–equity trade-off), F. Barca (place-based approach)

Source: created by the authors.

The diversification of regional equalisation instruments provided in Table 1 reflects the increasing complexity of local government policy-making process. Consequently, both an understanding of the applicability and effectiveness of individual instruments, as well as the synergies among them, become crucial for achieving maximum efficiency level. The role of municipalities extends beyond the redistribution of received financial resources to their transformation into incentive instruments. As a result of this transformation, not only is the provision of services to residents and businesses ensured, but the preconditions are also created for reducing local governments' long-term dependence on equalisation mechanisms. Accordingly, the role of local governments goes beyond a simple redistribution function, positioning them as active players in regional development.

The active role of the state in creating the conditions for value creation in the local economy has been analysed in the economic theory of Mariana Mazzucato, which reshapes the understanding of the role of the state and municipalities in the economy (Mazuccato, 2013). According to this perspective, public resources should not merely be spent but must generate public value. In the process of reducing regional inequality, it is not simply a matter of applying two distinct approaches; rather, the instruments used within these approaches should evolve and interact, giving rise to new and more efficient mechanisms.

By analysing the equalising instruments identified in Table 1, a particular attention must first be paid to their critical role in preventing further regional decline. According to Gunnar Myrdal's theory of cumulative causation, regions that do not receive adequate support enter a negative spiral: low levels of public services lead to the outmigration of labour, particularly highly skilled and in-demand employees. This outflow further reduces the tax base, thereby diminishing revenue of the corresponding local government and accelerating regional deterioration (Myrdal, 1957). These consequences are also reflected in Charles Tiebout's theory that 'people vote with their feet', which implies that local governments must compete with one another to attract residents – a process that becomes unfeasible under conditions of reduced fiscal capacity (Tiebout, 1956). Meanwhile, Wallace Oates emphasises the necessity of equalisation specifically at the local government level, arguing that municipalities are best positioned to identify and respond to the needs of their residents (Oates, 1972).

Although direct fiscal equalisation is considered to be one of the most effective equalisation instruments as it provides local governments with financial resources that they can allocate at their own discretion, the redistribution of funds may also generate negative side effects – a reduced motivation among local governments to pursue their own economic initiatives. Financial resources are often allocated regardless of the local governments' own tax efforts, the economic growth of wealthier municipalities may be affected,

and the efficiency of the use of redistributed funds is not always adequately monitored (Bury et al., 2024).

In the academic literature, these adverse effects are commonly referred to as 'equalisation traps', whereby local governments become dependent on state transfers and fail to make sufficient efforts to generate their own revenues or to develop their economic potential. In some cases, municipalities may even maintain an artificially low tax base in order to maximise the volume of transfers received from the state. Such equalisation traps are analysed in the work of Hans-Werner Sinn on the consequences of German reunification, which revealed a decline in the incentives for East German federal states to expand their own tax bases (Sinn, 2002).

Attention should also be paid to the psychological risks identified by János Kornai in his concept of the 'soft budget constraint'. According to Kornai's research, local governments that expect inefficiencies or underperformance to be compensated by state support or EU structural funds lose their fear of economic losses. As a result, insufficient effort is devoted to strengthening local revenue capacity, and projects may be implemented despite being identifiable from the outset as economically unviable or unsustainable in the long term (Kornai, 1986).

Beyond the economic aspects analysed above, the equalising approach also has an important social dimension. Equalisation measures directed at residents encompass not only financial support such as benefits and subsidies, but also investments in social infrastructure, including parks, libraries, and community centres. As Eric Klinenberg emphasises, such investments should not be regarded as luxury goods, but rather as fundamental components of economic security. When local governments lack the capacity to maintain this social infrastructure, regions may lose their attractiveness in the eyes of both current and potential residents and investors. According to Klinenberg's research, neighbourhoods with strong social infrastructure demonstrate greater resilience in times of crisis, meaning that equalisation instruments can also function as long-term tools of regional security and crisis management (Klinnenberg, 2018).

The equalisation approach not only produces an immediate effect in reducing existing disparities but also has a direct long-term impact on macroeconomic performance at the national level. According to Joseph Stiglitz, high levels of inequality negatively affect overall economic growth level. First, the most valuable economic resource – human capital – remains underutilised. Residents of peripheral areas, facing limited access to education and adequate healthcare, are unable to fully realise their economic potential. Second, high inequality destabilises the economy. Lower-income populations exhibit a higher 'marginal propensity to consume'; therefore, redistributing resources towards less affluent regions can stimulate aggregate demand. Third, pronounced regional poverty contributes to the intergenerational transmission of disadvantage, reducing individuals' opportunities for upward social mobility (Stiglitz, 2012).

This perspective is not merely theoretical; Stiglitz's opinion is also supported by empirical research conducted by international institutions. An OECD study from 2014 concludes that inequality constrains growth, as residents in poorer regions are less able to invest in their education. The report further indicates that high levels of inequality reduce potential GDP growth and slow overall economic development (OECD, 2014).

Research conducted by the International Monetary Fund (IMF) demonstrates that inequality is closely linked to the duration of economic growth phases within business cycles, i.e. countries and regions characterised by lower levels of inequality tend to experience longer and more stable periods of growth. One of the IMF's key findings is that moderate redistribution does not undermine economic growth; on the contrary, the benefits associated with lower inequality outweigh the potential costs of redistribution. In certain cases, redistribution may even enhance efficiency by reducing social tensions and political instability (International Monetary Fund, 2014).

A World Bank study suggests that economic concentration in rural areas is both inevitable and, to some extent, desirable. It is also impossible to force companies to operate everywhere; therefore, the level of economic development varies in different regions, so it is important to ensure convergence in living standards across regions, regardless of individuals' place of residence (World Bank, 2009).

More recent OECD researches have focused on how local governments can manage their financial resources more effectively. It is emphasized that equalisation systems must be designed in a way that preserves local governments' incentives to generate their own revenues. If local governments are deprived of the additional tax revenues they generate, they may lose the motivation to expand their tax base and risk stagnation. At the same time, one of the studies confirms that municipal performance is effective only when local governments are able to invest, rather than merely cover current expenditures (OECD, 2022).

A comparison of OECD studies from 2014 and 2020 reveals a shift in focus from simply identifying the consequences of inequality and the need for equalisation, with the state emphasised as the primary guarantor of economic stability through redistributive mechanisms, towards recognising local governments as active economic subjects capable of transforming received transfers into long-term investments. Consequently, the motivation of local governments to expand their own tax bases becomes crucial, redefining their role from that of resource consumers to main players in territorial development. This perspective aligns closely with the model proposed by the authors, in which the role of local governments extends beyond redistribution to include the

transformation of equalising instruments into incentive mechanisms.

In order to effectively select instruments for implementing an incentive approach, it is essential to understand the structural factors shaping regional development. As Paul Krugman argues, under conditions of a free market, economic activity does not tend to distribute evenly but rather concentrates, resulting in a core–periphery model (Krugman, 1991). To counteract these tendencies, Krugman's theory suggests several possible policy directions: 1) reducing effective distance to markets through investments in transport infrastructure, logistics hubs, and transport cost subsidies for residents; 2) fostering artificial agglomeration effects by developing industrial parks and offering targeted fiscal incentives in designated zones; 3) addressing regional stagnation by introducing preferential start-up conditions, such as special economic zones or temporary exemptions from land-lease payments.

While Krugman explains why regional stratification occurs, Michael Porter's theory offers practical guidance on how local governments can enhance their competitiveness. According to Porter, local governments should focus not on supporting individual companies, but on fostering groups of interconnected businesses (clusters) that both cooperate and compete. The formation of specialised clusters goes beyond simple business subsidies, creating conditions conducive to innovation and productivity growth (Porter, 1990).

Porter's cluster-based approach has subsequently evolved into the concept of smart specialisation. As Dominique Foray, one of its principal proponents, argues, that regions should not seek to replicate the strategies of already successful development centres; instead, they should identify and develop their own unique niches, grounded in their specific competencies and resource endowments. Within the framework of smart specialisation, incentive instruments are no longer generic but are strategically targeted to maximise effectiveness within the specific regional context (Foray, 2015).

By integrating the ideas of Porter and Foray, several key preconditions for an incentive-based approach within the smart specialisation framework can be identified: 1) the definition of regional priorities based on distinctive resource availability and competencies; 2) the creation of a business environment in which companies themselves are able to discover and exploit market opportunities; 3) the development of synergies between research and production, whereby incentives are more readily accessible to companies collaborating with research institutions in creation of high-value innovative products. Such an approach facilitates the emergence of new centres of development capable of competing with historically established economic hubs.

Hybrid instruments play a particularly important role in the transition from an equalisation-oriented to an incentive-based approach, as they combine financial support with targeted economic transformation. One of the most significant hybrid instruments in this regard is the EU Structural Funds. Unlike state equalisation transfers, which primarily aim to strengthen the financial capacity of local governments, EU Structural Funds are designed to address regional market failures. Through these funds, infrastructure projects are developed that local governments would be unable to implement independently, particularly in areas where private investment would not occur under free market conditions. As a result, the necessary preconditions for business development are created in regions where entrepreneurial activity would otherwise remain limited. EU Structural Funds also support the implementation of targeted training programmes, enabling residents to transition from passive recipients of social assistance to economically active and highly skilled members of the labour force, creating additional motivation for companies to enter the regions. It is precisely this combination — a favourable business environment, well-developed infrastructure, and a qualified workforce that enables regions to attract and sustain economic activity.

Despite these advantages, such instruments have a significant limitation: they are externally sourced and time-bound. While local governments can forecast tax revenues over the long term, EU Structural Funds are typically predictable only within a single planning period. This temporal constraint may render development strategies reliant on such funding unstable and fragmented. Consequently, regional development priorities may become aligned with the conditions of EU funding programmes rather than with long-term regional strategies and needs.

The European Commission has also identified a range of challenges associated with the use of Structural Funds for promoting regional convergence. One of the most critical issues is the phenomenon of 'development traps', whereby regions are no longer sufficiently underdeveloped to qualify for substantial equalisation support for infrastructure, yet have failed to invest adequately in innovation. The consequences of stagnation are a lower rate of development than the national average and regional inequality is increasing again. The report also highlights the growing gap 'urban–rural', noting that major cities and established development centres tend to absorb a disproportionate share of Structural Fund resources and related investments, leaving rural areas and smaller municipalities with comparatively limited support. The conclusion made by the EC on the quality of governance is also significant. The report finds a close correlation between the quality of governance and regional growth. The EU Structural Funds alone cannot deliver sustainable development outcomes in the absence of sufficient administrative capacity at the local level (European Commission, 2022).

These findings resonate with the arguments advanced by Daron Acemoglu and James A. Robinson in 'Why Nations Fail', which emphasise that economic

development is determined less by resource endowment or geographical location than by the nature of institutions. The authors distinguish between inclusive and extractive forms of governance at the municipal level. Inclusive municipalities are characterised by broad engagement of society and businesses, strong protection of property rights, legal certainty, and low barriers to market entry. Decision-making processes are transparent, oriented towards the broader public interest, and stable over time, with local governments fostering equal opportunities for participation in economic activity. In contrast, extractive local governments are those in which public resources serve the interests of a narrow group of businesses or institutions (Acamoglu & Robinson, 2012).

At the same time, the inclusive character of municipal governance alone is not sufficient; local governments must also possess the necessary competencies and administrative capabilities. Wallace Oates emphasised that local governments require not only formal authority but also a sound understanding of the specific characteristics of local markets. Without such knowledge, even adequate powers and financial resources may be insufficient to achieve the intended outcomes of decentralisation (Oates, 1972).

Three key competencies can be identified as essential for the effective application of incentive instruments at the municipal level: 1) strategic planning capacity. While local governments often have a strong grasp of the operational aspects of local administration, they may lack the analytical capacity to interpret market data and identify potential areas for cluster development or smart specialisation; 2) financial and risk management competencies. An entrepreneurial mindset is required, as local governments with insufficient expertise tend to avoid risk and rely primarily on equalisation-oriented strategies; 3) project management competences. Without the relevant skills, local governments may be unable to design competitive projects capable of attracting funding or to implement them effectively, thus creating the risk that projects remain incomplete, resulting either in the loss of funding opportunities or in the obligation to repay previously allocated funds.

These transformations are not significant only at the level of individual municipalities or regions. Attention must also be paid to Andrés Rodríguez-Pose's warning regarding 'places that don't matter'. His research shows that persistent regional inequality in disadvantaged peripheral municipalities leads not only to economic stagnation but also to growing social discontent and the rise of political populism (Rodríguez-Pose, 2018). Residents of lagging regions may feel neglected and marginalised. Consequently, the issue of regional equalisation evolves from a purely economic challenge into a matter of national security, particularly under conditions of heightened geopolitical tension. In this context, the challenge is not only to ensure the full utilisation of human capital as an economic resource but also to maintain citizens' loyalty to the state and its values.

Conclusions

1. The objective of the study – to analyse and classify regional equalisation instruments and to determine their interrelationships has been achieved. The analysis confirms that reducing regional inequality is not a matter of choosing between an equalisation and an incentive approach. The equalisation approach serves as a long-term safeguard for local governments and their residents, while the incentive approach fosters economic development and competitiveness. In synergy, these approaches ensure both the provision of adequate public services and living conditions for municipal residents and the long-term prospects for regional economic growth.
2. The study has revealed hybrid instruments that combine financial support with transformation into incentive-based mechanisms. These instruments are characterised by their external origin and time-limited nature. Local governments should therefore treat them as stepping stones for further development and the strengthening of self-sufficiency, rather than relying on their continued application in the long term.
3. Municipalities must shift their role from passive recipients of state transfers to active economic subjects capable of transforming received resources into incentive-based instruments that promote regional economic development and strengthen self-reliance. In the model developed by the authors, local governments occupy a central position both in the redistribution and in the transformation of resources, acting as mediators among all involved subjects – the state, residents, businesses, and the municipal administration itself.
4. Regional equalisation instruments function effectively only when local governments are inclusive and possess the necessary competencies to use available resources efficiently. Otherwise, there is a risk that public funds will be used to serve the interests of a narrow group of individuals or firms, rather than the broader interests of the region, or that inefficiencies will arise due to inadequate planning and management.
5. Regional equalisation is not solely an economic matter but also a matter of national security. In situations, where regional support is insufficient or ineffective, regions may enter prolonged stagnation, leaving residents feeling neglected and marginalised. Such regions are often characterised by declining trust in public institutions and rising political populism, which can have significant implications for national security, particularly in border areas.

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ENERGY SECURITY RESEARCH IN THE BALTIC STATES: FUNDING AND COORDINATION

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Abstract
Energy security is a critical component of economic resilience, strategic autonomy, and long-term innovation capacity, particularly in small and open economies such as the Baltic States. While previous studies have mainly examined energy security through policy frameworks, indicators, or technological pathways, less attention has been paid to the structure of knowledge production and research coordination in this field. This study maps the energy security research ecosystem in Estonia, Latvia, and Lithuania using a mixed-methods approach that combines bibliometric analysis, keyword co-occurrence mapping, and an assessment of funding and collaboration structures. The analysis is based on a validated Scopus dataset of 936 publications published between 2011 and 2025. The results show a strong increase in research activity after 2020, a clear asymmetry in country participation, and a concentration of research capacity in a limited number of institutions, particularly in Lithuania and Latvia. The thematic structure of the field is dominated by energy, engineering, sustainability, and policy-related topics, while economics-oriented research remains comparatively underrepresented. The funding analysis indicates that 38.8% of publications contain identifiable funding acknowledgements, with EU-related instruments accounting for 30.9% of funded papers. At the same time, internal Baltic coordination remains weak: only 4.8% of publications involve cross-Baltic co-authorship. These findings suggest that the Baltic research ecosystem is more externally connected than internally integrated and that its long-term innovation capacity may depend on stronger regional coordination and more balanced funding structures.
Keywords: energy security, Baltic States, bibliometric analysis, research ecosystem, research cooperation.

Introduction

Energy security is a fundamental condition for economic stability, industrial competitiveness, and long-term strategic autonomy, particularly in small and open economies such as the Baltic States (Sovacool & Mukherjee, 2011; Cherp & Jewell, 2011; Ang et al., 2015). In Estonia, Latvia, and Lithuania, secure and affordable access to energy is closely linked to price stability, investment conditions, and the resilience of critical infrastructure. In the long term, however, energy security depends not only on diversifying physical supply routes but also on the capacity to generate knowledge, technologies, and innovation domestically. When research systems are weak, fragmented, or highly dependent on external support, countries become more vulnerable to technological dependence and reduced strategic autonomy (Lundvall, 1992; Etzkowitz & Leydesdorff, 2000).

Over the past two decades, the focus on supply reliability has become a multidimensional concept encompassing accessibility, affordability, resilience, and environmental sustainability (Sovacool & Mukherjee, 2011; Cherp & Jewell, 2011; Ang et al., 2015; Azzuni & Breyer, 2018). At the same time, bibliometric and policy-oriented studies show that energy security has become an increasingly interdisciplinary field involving engineering, environmental sciences, policy analysis, and economics. However, while global energy security trends have been widely discussed, less attention has been paid to the organisation of energy security research itself, especially in smaller regional systems such as the Baltic States. Most existing studies focus on indicators, policy frameworks, or technological pathways, whereas the structure of knowledge production, institutional concentration, and research cooperation remains less systematically examined (Augutis et al., 2020; Zeng et al., 2017).

This perspective is particularly relevant in the Baltic context, where energy security has become more prominent in response to geopolitical disruption, the European energy crisis, and the policy shift triggered by the REPowerEU plan (European Commission, 2022). The Baltic States share common geopolitical risks and broad policy objectives, but their research capacities, institutional structures, and collaboration patterns differ. Earlier research on cybersecurity policy and research cooperation in the Baltic States showed that security-related research capacity develops unevenly across the region, that regional cooperation remains fragmented, and that EU-level funding plays a major structural role in sustaining research activity (Vasilevska et al., 2025). These findings raise the question of whether similar ecosystem-level patterns are also visible in energy security research.

The present study addresses this gap by examining energy security research in the Baltic States not merely as a thematic scientific field, but as a regional research ecosystem. The conceptual framework is grounded primarily in the National Innovation Systems approach and the Triple Helix model, which together enable the interpretation of scientific production as an outcome of institutional capacity, funding structures, and interorganisational coordination (Lundvall, 1992; Etzkowitz & Leydesdorff, 2000). The study aims to analyse the thematic, institutional, funding, and coordination structure of energy security research in Estonia, Latvia, and Lithuania during 2011–2025. The study seeks to assess the structure and coordination profile of the regional research ecosystem, and to identify whether its current structure supports long-term innovation capacity, resilience, and strategic autonomy. The study provides a structural and bibliometric assessment of the regional research

ecosystem and does not attempt to estimate the causal drivers of research performance.

Materials and Methods

This study employed a mixed-methods design combining bibliometric analysis, keyword co-occurrence mapping and network analysis (Donthu et al., 2021). The methodological approach was used to conceptualise energy security research in the Baltic States as a regional knowledge production system rather than only as a set of isolated scientific publications. In the present study, the Triple Helix model is used as an interpretive framework for understanding coordination patterns rather than as a full operational classification of university–industry–government actors. The National Innovation Systems approach and the Triple Helix model guided the theoretical interpretation of the results. From the perspective of National Innovation Systems, energy security research can be understood as part of a broader system of knowledge creation shaped by national institutions, research capacities, and support structures (Lundvall, 1992). The Triple Helix perspective was used to interpret collaboration and funding patterns as indicators of how effectively research activity is coordinated across institutional spheres (Etzkowitz & Leydesdorff, 2000).

Bibliometric data were obtained from the Scopus database on 16 March 2026. The search was conducted in the title, abstract, and keyword fields using the following query: ALL (‘energy security’ OR ‘energy supply security’ OR ‘energy system resilience’ OR ‘energy resilience’ OR ‘energy vulnerability’ OR ‘energy independence’ OR ‘critical energy infrastructure’) AND (LIMIT-TO (AFFILCOUNTRY, ‘Estonia’) OR LIMIT-TO (AFFILCOUNTRY, ‘Latvia’) OR LIMIT-TO (AFFILCOUNTRY, ‘Lithuania’). The search strategy was designed to capture different conceptual dimensions of energy security, including supply reliability, system resilience, infrastructure protection, and energy independence. Publications were limited to the period 2011–2025, reflecting the phase during which energy security became a more visible research topic in the Baltic region.

After export validation, the final dataset comprised 936 Scopus-indexed records with at least one author affiliation in Estonia, Latvia, or Lithuania. Articles constituted the dominant publication type. The dataset included 659 articles, 140 conference papers, 78 reviews, and 44 book chapters, while the remaining records consisted of a small number of other document types retained in the validated export. The bibliometric analysis examined publication dynamics, country involvement, institutional concentration, publication outlets, and open-access presence.

Journal articles dominate the dataset, accounting for 70.4% of all records. This indicates that peer-reviewed journals are the principal channel for disseminating energy security research in the Baltic States, while conference papers remain an important secondary outlet for emerging findings.

Table 1

Document type distribution of the validated Scopus dataset

Document type	Number of records	Share of dataset, %
Article	659	70.4
Conference paper	140	15.0
Review	78	8.3
Book chapter	44	4.7
Other document types*	15	1.6
Total	936	100.0

The thematic structure of the field was analysed using VOSviewer through keyword co-occurrence mapping (van Eck & Waltman, 2010; Waltman et al., 2010). The co-occurrence network was interpreted by analysing node size, thematic clusters, and the relative strength of conceptual linkages (van Eck & Waltman, 2010). This enabled the identification of dominant research themes and interdisciplinary patterns in the Baltic energy security literature.

To strengthen the economic dimension of the study, an additional analytical block was introduced to assess the funding and coordination structure of the research ecosystem. Because comparable participant-level grant amount data were not consistently available across all three Baltic States, the economic structure was operationalised through bibliometric funding acknowledgements and collaboration patterns derived from the Scopus export. Funding structure was assessed using two indicators: (1) the share of publications containing funding acknowledgement metadata, and (2) the share of publications acknowledging EU-related funding instruments, including the European Commission, Horizon 2020, and the European Regional Development Fund. Coordination structure was assessed through affiliation-based collaboration coding. Each publication was coded for the presence of author affiliations from Estonia, Latvia, and Lithuania, allowing identification of single-country outputs, cross-Baltic co-authorship, trilateral Baltic collaboration, and collaboration with external partner countries. To strengthen the economic interpretation of the research ecosystem, three composite indicators were introduced. The Baltic Research Coordination Index (BRCI) measures intra-regional collaboration intensity as the share of publications involving more than one Baltic State. The EU Funding Dependence Ratio (EFDR) captures the relative importance of supranational funding by measuring the share of EU-funded publications among all funded records. The Top-5 Institutional Share (T5IS) reflects the concentration of knowledge production by measuring the proportion of total publications produced by the five most active research institutions in the region.

Results and Discussion

The validated Scopus dataset comprised 936 publications published between 2011 and 2025. The results show a clear increase in energy security research activity over time, with particularly strong growth after 2020. The highest annual output was recorded in 2025. This acceleration can be interpreted in the context of the European energy crisis, the geopolitical effects of Russia's war against Ukraine, and the policy stimulus provided by the REPowerEU strategy, which intensified attention to energy independence, resilience, and infrastructure security (European Commission, 2022). Thus, the growth of scientific output appears to reflect both academic interest and broader shifts in European strategic priorities.

The country-affiliation pattern reveals uneven participation across the region. Lithuania appeared most frequently in author affiliations, with 604 records, followed by Latvia with 240 and Estonia with 144. These figures should be interpreted as affiliation-based involvement frequencies rather than mutually exclusive national shares, since one publication may include authors from more than one Baltic State. Nevertheless, the results point to clear asymmetry in regional research capacity. This pattern is consistent with earlier findings from cybersecurity research in the Baltic States, which also identified uneven national research capacity and differentiated institutional readiness across the region (Vasilevska et al., 2025).

The thematic profile of the field confirms that energy security research in the Baltic States is interdisciplinary but not evenly balanced (Azzuni & Breyer, 2018). The literature is strongly oriented toward energy systems, engineering, sustainability, and policy-related themes, while economics-oriented research remains comparatively less visible. The keyword co-occurrence network further shows that the field is structured around several interconnected thematic clusters.

Figure 1 shows that energy security is the central integrating concept in the field and is strongly connected with analytical terms such as study, model, system, and indicator. This suggests that the Baltic literature is structured around assessment-oriented and system-based approaches. At the same time, the presence of terms such as renewable energy source, energy consumption, and energy efficiency indicates the importance of energy transition, demand-side management, and technological adaptation. The emergence of Ukraine at the network's periphery reflects the increasing integration of the geopolitical variables into academic discourse. The mapping indicates. that energy security research in the Baltic States is conceptually synthesized around pillars of technology, governance, and environmental sustainability, while explicitly economic considerations occupy a less central position in the current thematic hierarchy.

'Energy security' functions as a core integrating concept, while strongly linked themes include sustainable development, energy policy, renewable energy, energy efficiency, resilience, and broader transition-related topics. This indicates that energy security research in the Baltic States is increasingly embedded within wider debates on sustainability, decarbonisation, and governance. At the same time, the weaker relative visibility of economic themes suggests that issues such as research productivity, resource allocation, and innovation efficiency remain underdeveloped in the regional literature.

Figure 1

Keyword co-occurrence network of author keywords in Baltic energy security research (VOSviewer, 2011–2025)

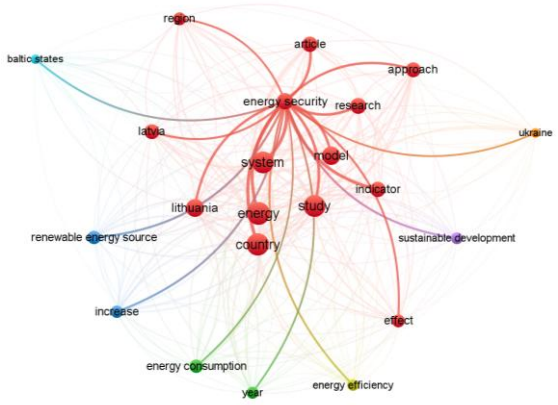


Table 2

Main subject areas of energy security research in the Baltic States

Subject area	Number of publications
Energy	453
Engineering	296
Social Sciences	294
Environmental Science	252
Economics, Econometrics and Finance	132

The field is clearly interdisciplinary, but technological and systems-oriented disciplines dominate. The comparatively smaller number of publications in Economics, Econometrics and Finance indicates that the economic dimension of energy security remains less developed than engineering, sustainability, and governance perspectives.

As illustrated in Figure 2, *energy security* serves as the primary integrative construct within the Baltic literature. It exhibits robust topological links with methodological descriptors such as *study*, *model*, *system*, and *indicator,* suggesting a research orientation heavily grounded in empirical modelling and quantitative assessment. This suggests that the field is structured around assessment-oriented and

system-based approaches. At the same time, the presence of nodes such as *renewable energy source*, *energy efficiency*, and *energy consumption* confirms the relevance of energy transition and demand-side themes, while *Ukraine* appears as a more recent geopolitical element at the periphery of the network. Overall, the map indicates conceptual integration around technological, policy, and sustainability-related themes, whereas explicitly economic concepts remain less central. The analysis of institutional affiliations reveals a concentration of research capacity in a limited number of academic and research organisations. The Lithuanian Energy Institute, Vytautas Magnus University, Riga Technical University, Vilnius Gediminas Technical University, and Vilnius University form the core of the regional research network. This concentration indicates a significant accumulation of expertise in several leading centres, but it also suggests a degree of structural centralisation in the regional knowledge production system. In smaller innovation systems, such concentration may produce efficiency in output generation, yet it may also limit wider diffusion of capabilities across institutions and countries. The network visualisation is based on co-occurrence analysis, where node size reflects keyword frequency and link thickness represents co-occurrence strength (van Eck & Waltman, 2010).

Figure 2
Keyword co-occurrence analysis of energy security research in the Baltic States based on author's keywords (VOSviewer)

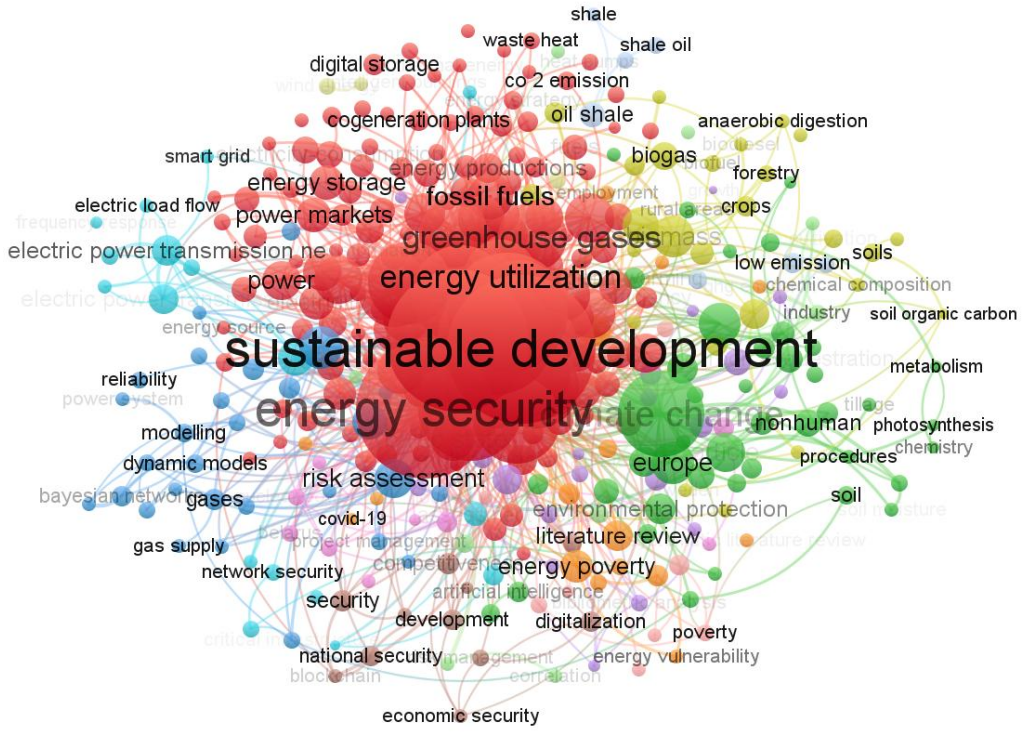


Table 3
Leading institutions in energy security research in the Baltic States

Institution	Number of publications
Lithuanian Energy Institute	134
Vytautas Magnus University	134
Riga Technical University	132
Vilnius Gediminas Technical University	119
Vilnius University	82

Research output is concentrated in a limited number of institutions, suggesting several dominant knowledge hubs within the regional ecosystem. In a small research system, such concentration may improve visibility and productivity, but it may also limit wider diffusion of expertise across the Baltic region.

The Top-5 Institutional Share (T5IS) amounts to 64.2%, indicating that more than half of all publications are produced by a small number of leading institutions. This confirms a high level of centralisation in the regional knowledge production system.

The funding structure analysis adds an important economic perspective to the study. Of the 936 analysed publications, 363 records (38.8%) contained funding acknowledgement metadata, indicating that a substantial part of the literature was linked to identifiable project-based or institutional support.

Within this funded subset, 112 publications acknowledged EU-related funding instruments, corresponding to 30.9% of the funded papers and 12.0% of the full dataset. The most frequently acknowledged sponsors were the Research Council of Lithuania, the European Regional Development Fund, Horizon 2020, the European Commission, the Latvian Council of Science, and the Estonian Research Council. This distribution shows that energy security research in the Baltic States is supported by a mixed structure, with national research council's coexisting alongside a visible, strategically important EU funding layer. For smaller research systems, this pattern suggests that supranational funding plays a significant enabling role in sustaining research capacity and cross-border knowledge production. The EU Funding Dependence Ratio (EFDR) is 30.9%, meaning that nearly one-third of all funded publications rely on European Union financial instruments. This highlights the structural importance of supranational funding mechanisms in sustaining energy security research in the Baltic region.

Table 4
Funding structure indicators of the Baltic energy security research ecosystem

Indicator	Value
Total analysed Scopus records	936
Publications with funding acknowledgement metadata	363
Share of funded publications, %	38.8
Publications with EU-related funding acknowledgement	112
EU-related share among funded publications, %	30.9
EU-related share in the full dataset, %	12.0

A substantial share of the literature contains identifiable funding support, and EU-related instruments play a visible role in the funded segment of publications. This suggests that the field of Baltic energy security research relies on a mixed support model in which national funding structures coexist with an important supranational funding layer.

The leading funding sponsors confirm the coexistence of national research councils and EU-level programmes in supporting the field. The visible role of Horizon 2020, the European Commission, and the ERDF highlights the structural importance of European funding mechanisms for smaller Baltic research systems.

The coordination structure of the field is weaker at the intra-Baltic level than at the broader international level. Out of 936 publications, 518 records (55.3%) were produced within a single Baltic country without external co-authorship, while 373 publications (39.9%) involved one Baltic country together with international partners. Only 45 publications (4.8%) involved collaboration between two or more Baltic States, and only 7 publications (0.7%) included all three Baltic States in the same record. These findings indicate that the regional energy security research ecosystem is more externally connected than internally integrated. International collaboration is relatively common, yet structured cross-Baltic research cooperation remains weak. This mirrors the broader pattern already observed in Baltic cybersecurity research, where external support and fragmented regional cooperation were also identified as structural features of the security research landscape (Vasilevska et al., 2025).

Table 5
Most frequently acknowledged funding sponsors

Funding sponsor	Number of records
Research Council of Lithuania / Lietuvos Mokslo Taryba	54
European Regional Development Fund (ERDF)	44
Horizon 2020 / H2020	44
European Commission	39
Latvian Council of Science	21
Estonian Research Council / Eesti Teadusagentuur	19

International collaboration is much more common than structured cross-Baltic cooperation. This indicates that the regional energy security research ecosystem is more externally connected than internally integrated, suggesting that the Baltic research space still functions more as three partially linked national systems than as a strongly coordinated regional innovation ecosystem. Based on the collaboration data, the Baltic Research Coordination Index (BRCI) is 4.8%, indicating a very low level of intra-regional research integration. This result suggests that structured cooperation between Baltic States remains limited despite shared policy challenges and geographic proximity.

Table 6
Coordination structure of the Baltic energy security research ecosystem

Collaboration type	Number of records	Share, %
Single Baltic country, no external co-authorship	518	55.3
Single Baltic country + external countries	373	39.9
Two or three Baltic countries only	21	2.2
Two or three Baltic countries + external countries	24	2.6
Total cross-Baltic collaboration	45	4.8
Trilateral Baltic collaboration	7	0.7

Taken together, the results suggest that energy security research in the Baltic States is characterised by four interrelated features: rapid recent growth, uneven national participation, concentration of expertise in a limited number of institutions, and partial dependence on EU-linked funding mechanisms. From the perspective of National Innovation Systems and the Triple Helix, this implies that the regional research ecosystem has developed visible scientific capacity but remains only partially integrated as a coordinated Baltic system. In this sense, the long-term innovation capacity of the field may depend not only on continued output growth but also on stronger cross-Baltic coordination, broader inclusion of economic analysis, and a more balanced relationship between national and supranational support structures.

The combined evidence from the proposed indicators reveals important structural characteristics of the Baltic energy security research ecosystem. The low Baltic Research Coordination Index (BRCI = 4.8%) indicates weak internal integration, while the EU Funding Dependence Ratio (EFDR = 30.9%) highlights a strong reliance on supranational funding sources. At the same time, the high Top-5 Institutional Share (T5IS = 64.2%) demonstrates a concentration of research capacity within a limited number of institutions. Together, these findings suggest that the system operates as a partially integrated innovation system characterised by external dependence and internal fragmentation, which may limit its long-term efficiency and resilience. This structure implies that research productivity in the Baltic States is not primarily driven by internal coordination, but rather by externally supported and institutionally concentrated knowledge production.

Conclusions

1. Energy security research in the Baltic States increased substantially during 2011–2025, particularly after 2020, indicating rising strategic and academic attention to the field.
2. The research landscape is interdisciplinary but dominated by technological, sustainability, and policy-related themes, while economics-oriented analysis remains comparatively underrepresented.
3. Research capacity is unevenly distributed across the region and concentrated in a limited number of institutions, especially in Lithuania and Latvia, which indicates asymmetry in regional knowledge production.
4. The funding structure shows that identifiable research support is present in a substantial share of publications, with EU-related instruments playing an important role in the funded segment of the literature.
5. Internal Baltic coordination remains weak, as cross-Baltic co-authorship accounts for only a small fraction of total output; therefore, stronger regional cooperation is needed to improve the long-term innovation capacity and strategic relevance of the Baltic energy security research ecosystem.

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DIGITALISATION AND TOURISM POLICY IN LATVIA: IMPLICATIONS FOR RURAL TOURISM DEVELOPMENT

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Abstract
Digital technologies play an increasingly important role in tourism development, particularly in rural areas, where they support marketing, booking processes and service delivery. However, the digital transformation of tourism enterprises is shaped not only by technological availability but also by policy frameworks that define development priorities and support mechanisms. This study examines how digitalisation is addressed in tourism-related policy frameworks in Latvia and evaluates its integration across policy domains and governance levels. The study relies on qualitative policy analysis and thematic content analysis of twelve strategic planning documents covering digitalisation, tourism, and national and regional development. The findings show that digitalisation is widely recognised as a horizontal policy priority in national strategies, particularly in relation to innovation, entrepreneurship and digital skills development. In contrast, tourism policy focuses primarily on competitiveness, export development and international visibility, with digitalisation mainly reflected through marketing and data-related activities. At the regional level, tourism is embedded within broader economic and territorial development priorities, while digitalisation is associated mainly with infrastructure and service accessibility. At the same time, the integration of digitalisation and rural tourism remains limited, and rural tourism is rarely addressed as a distinct policy priority. These results indicate a lack of policy alignment across governance levels and highlight the need for more targeted approaches linking digitalisation with rural tourism development.
Keywords: digitalization, tourism policy, policy analysis, rural tourism, Latvia.

Introduction

Tourism plays an important role in economic and social development, contributing to job creation, income diversification and improvements in infrastructure and services (Jasrotia & Gangotia, 2018; Muresan et al., 2021). Rural tourism, in particular, supports local economies and cultural heritage while offering alternative experiences linked to natural environments. At the same time, ongoing urbanisation trends are expected to increase demand for tourism in rural and nature-based destinations, reinforcing the role of rural areas in diversifying tourism supply (Sadeghi & Seidaiy, 2024).

In this context, digital technologies have become increasingly important for improving the accessibility, visibility and competitiveness of tourism destinations. Tourism is a significant component of the European economy, largely composed of micro, small and medium-sized enterprises, and has been strongly affected by the COVID-19 pandemic. At the same time, the crisis accelerated the transition towards a more digital, sustainable and resilient tourism ecosystem (Council of the European Union, 2022; Falter & Jóhannesson, 2023).

Digitalisation in tourism is associated with tools such as online booking systems, digital marketing, data-driven decision-making and platform-based services, which enhance both efficiency and customer experience (OECD, 2020). The adoption of digital technologies is increasingly essential for competitiveness and productivity, while in Latvia digitalisation in tourism remains uneven, creating additional pressure for enterprises to adapt to changing consumer behaviour (Vilcina & Bormane, 2022).

Tourism also significantly contributes to rural development across the European Union. However, rural regions face structural challenges, including population decline, limited employment opportunities and uneven economic development. In this context, tourism—particularly when supported by digital solutions—offers opportunities to strengthen local economies and improve regional competitiveness (Alonso et al., 2024).

European policy frameworks increasingly recognise tourism as a tool for economic development, cultural preservation and regional cohesion (UNWTO, 2020; European Commission, 2021). Rural tourism is associated with job creation, income diversification and reduced seasonality, while digitalisation is seen as an important enabling factor supporting innovation and connectivity (UNWTO, 2023; Alonso et al., 2024). At the same time, structural constraints—such as limited infrastructure, digital connectivity and skills—continue to affect the development of rural tourism (European Commission, 2021; UNWTO, 2023).

In Latvia, tourism contributes to regional development and employment but remains spatially concentrated, with a significant share of activity in the capital region. Rural areas continue to face demographic and economic challenges, despite the gradual recovery of the tourism sector following the COVID-19 pandemic (OECD, 2022; Van der Steina et al., 2023; CSP, 2026). While policy frameworks at European and national levels increasingly promote digitalisation and tourism development, these priorities are often developed within separate policy domains and are not always clearly integrated, particularly in relation to rural tourism.

This study examines how digitalisation is reflected in national and regional tourism-related policy documents in Latvia, with a particular focus on the extent to which digitalisation and tourism priorities are integrated in the context of rural tourism development. The study seeks to answer the following research questions:

(1) How is digitalisation integrated into tourism-related policy documents at national and regional levels in Latvia?
(2) To what extent is rural tourism addressed within these policy frameworks?
(3) How are digitalisation and tourism priorities aligned across policy levels, and what gaps can be identified in relation to rural tourism development?
To address these questions, the study applies qualitative policy analysis combined with thematic content analysis of national and regional strategic planning documents.

Materials and Methods

This study applies qualitative policy analysis to examine the interaction between digitalisation and tourism policy frameworks in Latvia across national and regional governance levels, with a particular focus on rural tourism. The research is based on thematic content analysis of strategic planning documents. As the study is based on qualitative policy document analysis, statistical analysis was not applied.
A total of twelve documents were selected, covering four policy domains: digitalisation, tourism, national development and regional development. The analysed documents include the Digital Transformation Guidelines for Latvia 2021–2027; Tourism Development Plan of Latvia 2021–2027; Tourism Export Strategy of Latvia 2021–2027; Tourism Marketing Strategy of Latvia 2021–2027; National Development Plan of Latvia 2021–2027; National Industrial Policy Guidelines 2021–2027; Sustainable Development Strategy of Latvia until 2030; and five regional development programmes (Zemgale, Vidzeme, Latgale, Kurzeme and Riga planning regions).
To ensure a systematic analysis, a thematic framework was developed, including digitalisation, innovation, entrepreneurship and SMEs, tourism, rural tourism and rural development, regional development, and data governance (Table 1).

Table 1
Coding framework for policy document content analysis

Category	Definition	Keywords used for coding
Digitalisation	Use or development of digital technologies in the economy, public services or society	digital, digitalisation, digital technologies, ICT
Innovation	References to technological innovation, innovative solutions, or research and development activities	innovation, innovative, R&D
Entrepreneurship / SMEs	Enterprise development, SMEs or business competitiveness	enterprise, business, SME, business development
Tourism	Tourism sector development, tourism policy or tourism enterprises	tourism, tourist
Rural tourism / rural development	Rural tourism activities or tourism development in rural areas	rural tourism, countryside tourism, rural development
Regional development	Territorial development, regional policy or local economic development	region, regional development, territorial development, local development
Data governance	Data management, open data systems, data platforms or data-driven decision-making	data, open data, data platform, data governance

Each document was analysed based on the presence and relative prominence of these themes, combining keyword identification with qualitative interpretation of policy objectives and priorities. To enable comparison across documents, a qualitative frequency scale was applied, distinguishing between high, medium, low and no emphasis based on the number and significance of references (Table 2).

Table 2
Frequency scale used in policy document analysis

Frequency	Interpretation
High	topic frequently discussed (>50 references)
Medium	topic moderately represented (10–50 references)
Low	topic rarely mentioned (1–10 references)
None	no references identified

The results are presented in a comparative matrix, enabling the identification of differences in thematic emphasis across policy domains and governance levels. In addition, a cross-level policy analysis was conducted examine the interactions among digitalisation, tourism, and regional development, while identifying gaps in policy alignment.

Results and Discussion

The policy analysis reveals several consistent patterns across the analysed documents. Digitalisation, innovation and entrepreneurship are strongly emphasised in national development and digital policy frameworks, while tourism-related priorities are primarily addressed in sector-specific tourism policy documents. Regional development programmes tend to integrate tourism within broader economic development objectives rather than as a standalone priority. Across all documents, rural tourism is only marginally addressed, indicating that it is largely embedded within broader tourism or regional development contexts. The structure of the analysed policy framework is presented in Figure 1.

Digital Policy Analysis

The analysis of the Digital Transformation Guidelines for Latvia 2021–2027 shows that digitalisation is positioned as a cross-sectoral and horizontal policy

priority influencing multiple domains, including innovation, entrepreneurship and regional development (Cabinet of Ministers, 2021b). Strong emphasis is placed on ICT innovation, business digitalisation and data governance, highlighting the role of digital technologies in enhancing productivity, competitiveness and data-driven decision-making.

A key priority within the framework is the development of digital skills and human capital, reflecting existing gaps in ICT competencies and the need to support digital adoption among businesses, particularly SMEs. Measures promoting training, upskilling and the integration of digital technologies into business processes are central elements of the policy.

Figure 1

Multi-level policy framework of digitalisation and tourism development in Latvia



The document also highlights the importance of digital infrastructure, particularly broadband connectivity, as a foundation for economic activity and territorial development, including reducing regional disparities.

However, tourism is not explicitly identified as a priority area within the digital policy framework, and rural tourism is not addressed. This suggests that while digitalisation is recognised as a key enabler of economic development, its direct application to tourism particularly in rural areas remains implicit rather than strategically articulated.

Tourism policy analysis

The analysis of national tourism policy documents in Latvia, including the Tourism Development Plan, Tourism Marketing Strategy and Tourism Export Strategy (Ministry of Economics, 2019; Investment and Development Agency of Latvia, 2021; Ministry of Economics, 2024), reveals several consistent patterns in policy priorities. Tourism policy documents strongly emphasise competitiveness, export development and support for SMEs, positioning tourism as a key economic sector. However, digitalisation is primarily addressed as a supporting element, mainly in relation to marketing, data use and smart solutions.

First, tourism and entrepreneurship are strongly emphasised across all documents, confirming the role of tourism as an important economic sector contributing to export growth, employment and competitiveness. This is particularly evident in the Export Strategy, where increasing tourism export and developing higher value-added products are defined as central objectives (Ministry of Economics, 2024).

Second, regional development is addressed unevenly across documents. It is more explicitly reflected in the Tourism Development Plan, particularly in relation to tourism product diversification and strengthening regional tourism offer (Ministry of Economics, 2019), while it is less prominent in the Export and Marketing strategies, which focus primarily on international competitiveness and market positioning (Investment and Development Agency of Latvia, 2021; Ministry of Economics, 2024).

Third, digitalisation is present across all documents but mainly as a supporting element rather than a core policy objective. It is most explicitly developed in the Export Strategy through data-driven approaches and decision-making (Ministry of Economics, 2024), as well as in the Marketing Strategy through digital communication and platform use (Investment and Development Agency of Latvia, 2021). In contrast, in the Tourism Development Plan digitalisation appears more indirectly, for example in relation to smart destinations and the use of data (Ministry of Economics, 2019).

Finally, rural tourism is weakly articulated across national tourism policy documents. It is typically embedded within broader tourism development priorities, such as nature-based or cultural tourism, rather than addressed as a distinct policy domain (Ministry of Economics, 2019; Investment and

Development Agency of Latvia, 2021; Ministry of Economics, 2024).

The findings suggest that while tourism policy in Latvia strongly supports economic competitiveness and export development, the integration of digitalisation and rural tourism remains limited and fragmented.

National Policy Analysis

The national policy framework in Latvia is defined by three key strategic documents: the National Development Plan 2021–2027 (NAP2027), the National Industrial Policy Guidelines 2021–2027 (NIP) and the Sustainable Development Strategy of Latvia until 2030 (Latvia 2030). These documents establish the overall direction of economic development, innovation and territorial development, while tourism is addressed only indirectly.

NAP2027 prioritises productivity growth, innovation and human capital development as key drivers of economic development. Digitalisation is integrated across several policy areas, particularly in relation to technological development and service provision, while regional development is emphasised through the objective of reducing territorial disparities and strengthening economic activity outside major urban centres (Saeima, 2020). Tourism is not explicitly defined as a policy priority; it features mainly alongside cultural development and the role of Riga as a tourism hub.

The National Industrial Policy Guidelines further reinforce the central role of innovation, export-oriented growth and participation in global value chains. The document identifies low productivity, limited innovation capacity and a relatively low level of digitalisation among enterprises as key structural challenges in the Latvian economy (Cabinet of Ministers, 2021a). Digitalisation is positioned as an essential component of industrial competitiveness, alongside investment in research and development, skills and technological capabilities. Tourism is addressed only marginally, primarily in the context of export development and higher value-added services.

Latvia 2030 provides a long-term strategic vision based on a 'capital approach', emphasising human, economic, natural and territorial capital. The strategy highlights innovation, education, infrastructure and balanced territorial development as key priorities, including the importance of accessibility, communication networks and urban–rural linkages (Saeima, 2010). Digitalisation is reflected mainly in the context of e-governance and education, while tourism is addressed indirectly through cultural and regional development objectives.

The analysis reveals a consistent prioritisation of innovation, productivity and regional development across national policy documents. Digitalisation is widely integrated as a cross-sectoral element supporting economic transformation. In contrast, tourism is weakly represented and mainly embedded within broader policy areas, while rural tourism is not explicitly addressed.

Regional Policy Analysis

Across all five planning regions, regional policy is strongly oriented towards economic development, entrepreneurship and territorial cohesion, with digitalisation, innovation and tourism integrated as supporting elements (Zemgale Planning Region, 2021; Vidzeme Planning Region, 2022; Latgale Planning Region, 2021; Kurzeme Planning Region, 2021; Riga Planning Region, 2023).

A consistent pattern across the analysed documents is the prioritisation of entrepreneurship, investment attraction and productivity growth as central drivers of regional competitiveness. This is particularly evident in Latgale, where the policy framework is structured around skills, connectivity, governance and enterprise development, emphasising the need to strengthen the private sector and reduce socio-economic disparities (Latgale Planning Region, 2021). Similar priorities are observed in Kurzeme and Zemgale, where business development, infrastructure and regional economic activity form the core of regional policy frameworks (Kurzeme Planning Region, 2021; Zemgale Planning Region, 2021).

Innovation is not equally emphasised across regions. It plays a more visible and structured role in Vidzeme and Riga, where policy priorities include knowledge-based development, smart specialisation and research cooperation (Vidzeme Planning Region, 2022; Riga Planning Region, 2023). In Zemgale, Kurzeme and Latgale, innovation appears more indirectly and is mainly linked to entrepreneurship, sectoral development and productivity.

Digitalisation is present across all regional documents but is mainly associated with ICT infrastructure, service accessibility and digital skills. Regional programmes highlight broadband development, e-services and digital competence building as key enabling factors for regional development. At the same time, explicit connections between digitalisation and tourism development remain limited.

Tourism is included in all regional programmes, most often in relation to natural and cultural resources, regional attractiveness, and economic diversification. However, it is generally not positioned as a leading development sector. Rural tourism, in particular, is rarely addressed as a distinct policy area and is typically embedded within broader tourism or regional development contexts.

Cross-document Policy Alignment Analysis

Cross-level comparison reveals a clear misalignment between digitalisation and tourism policy priorities. Digitalisation is strongly emphasised in national and digital policy frameworks, while its integration into tourism policy remains limited. At the same time, tourism policy focuses primarily on sectoral development and marketing, with weaker emphasis on digital transformation. Rural tourism is the least represented theme across all policy levels, indicating a gap between policy priorities and its potential role in regional development.

The comparative assessment (Table 3) further illustrates differences in thematic emphasis across policy levels. Digital policy documents prioritise digitalisation, innovation and entrepreneurship, whereas tourism policy documents show a more balanced structure, with tourism as the dominant focus supported by digital tools and innovation.

Table 3

Comparative analysis of thematic emphasis across national, regional, and sectoral policy documents

Policy document	Digitalisation	Innovation	Entrepreneurship / SMEs	Tourism	Rural tourism	Regional development	Data governance
Digitalisation policy							
Digital Transformation Guidelines	**High**	**High**	**High**	None	None	Medium	**High**
Tourism policy							
Tourism Export Strategy	Medium	Medium	**High**	**High**	Low	Medium	Medium
Tourism Development Plan	Medium	Medium	**High**	**High**	Medium	**High**	Medium
Tourism Marketing Strategy	Medium	Medium	Medium	**High**	Low	Medium	Low
National policy							
NAP2027	**High**	**High**	**High**	Low	None	**High**	Medium
NIP2027	**High**	**High**	**High**	Low	None	Medium	Medium
Latvia 2030	Medium	**High**	**High**	Low	Low	**High**	Low
Regional policy							
Zemgale Region	Medium	Medium	Medium	Medium	Medium	**High**	Low
Vidzeme Region	Medium	**High**	**High**	Medium	Low	**High**	Low
Latgale Region	Medium	**High**	**High**	Low	Low	**High**	Low
Kurzeme Region	Medium	Medium	**High**	Medium	Low	**High**	Low
Riga Region	Medium	**High**	**High**	Low	None	**High**	Medium

Source: Authors; document titles abbreviated for clarity.

Regional policy frameworks reinforce similar patterns. Digitalisation is mainly linked to infrastructure, service accessibility and digital skills, while direct connections to tourism development remain limited. Tourism is included across regional programmes but is generally positioned within broader economic and territorial development contexts. Rural tourism is rarely defined as a separate policy domain.

Data governance remains weakly developed across all policy levels and is not consistently treated as a distinct policy priority.

The findings indicate a fragmented policy structure, where digitalisation, innovation and entrepreneurship are systematically prioritised, while tourism, particularly rural tourism remains secondary. This suggests limited integration between digitalisation and tourism policy, especially in relation to rural development.

Conclusions

1. The analysis shows that digitalisation is strongly integrated into national policy frameworks in Latvia as a horizontal and cross-sectoral priority. However, its role in tourism policy is more limited and is mainly reflected through supporting elements such as marketing, data use and smart solutions rather than as a core strategic focus.

2. Tourism is primarily addressed within sector-specific policy documents, where the emphasis is placed on competitiveness, export development and product innovation. At national and regional levels, tourism is mostly embedded within broader economic and territorial development priorities.

3. Rural tourism is not explicitly defined as a distinct policy priority. It is generally embedded within wider concepts such as regional development, cultural heritage and nature-based tourism, indicating an indirect approach to this sector.

4. Innovation, entrepreneurship and regional development are consistently prioritised across all policy levels. While digitalisation is closely linked to these dimensions, its application to tourism and particularly in rural tourism remains limited.

5. The findings highlight a gap in policy alignment between digitalisation and tourism development. Although digital transformation is widely promoted, its integration into tourism policy and its application to rural tourism remain insufficiently developed.

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UNDERSTANDING GREEN FINANCE: DEFINITIONS AND CONCEPTUAL DEVELOPMENT

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Abstract
The increasing use of the term 'green finance' in academic, policy and financial discourse has not been accompanied by a clear and consistent understanding of its meaning. Despite its widespread application, green finance remains a concept without a universally accepted definition, as different authors and institutions use the term to describe diverse and sometimes conflicting approaches to the role of finance in addressing environmental challenges. The study aims to examine a conceptual definition of green finance in literature by identifying the underlying perspectives reflected therein. The research employs a structured conceptual literature analysis, tracing the development of green finance from earlier discussions on environmental finance, sustainable development and climate finance. The article systematically analyses and compares the dominant definitional approaches found in the literature, including instrument-based, objective-based, risk-based and normative definitions. The study demonstrates that these definitional approaches are not merely alternative descriptions of the same concept but reflect fundamentally different assumptions about how finance should contribute to environmental governance. Clarifying these conceptual differences reveals that imprecise definitions create challenges for research, measurement and policy implementation. The contribution of the article lies in conceptualising green finance as a contested term and providing a structured framework that offers a clearer conceptual basis for future theoretical and empirical studies.
Keywords: green finance, conceptual analysis, definitions, environmental governance.

Introduction

The growing scale and urgency of global environmental challenges have intensified the search for economic and financial mechanisms capable of supporting the transition toward more sustainable development pathways. Addressing these challenges requires not only technological innovation and policy intervention but also substantial financial resources to support environmentally sustainable investments. Therefore, financial systems are crucial in directing capital flows towards those activities, which contribute to environmental protection and climate mitigation. Published studies highlight that green finance has become an important policy and market mechanism for mobilising financial resources to overcome environmental challenges (Woode, 2024).

The concept that has gained popularity in recent years is 'green finance'. This term is widely used in academic research, policy documents and financial market discussions. It is used to describe financial activities that support environmentally sustainable projects and investments. In general, green finance refers to financial instruments and investments that promote environmentally sustainable activities and contribute to addressing climate-related and ecological challenges (Zheng et al., 2025). Governments, international organizations and financial institutions increasingly emphasise the role of green finance in mobilising capital for renewable energy, sustainable infrastructure and climate mitigation initiatives. The rapid growth of green finance research reflects the expanding recognition that financial markets play a critical role in enabling sustainability transitions (Woode, 2024).

Despite its growing importance, the concept of green finance remains without a universally accepted definition. Different authors and institutions employ the term in various ways, reflecting diverse interpretations of how financial systems should contribute to addressing environmental challenges. Some definitions focus primarily on financial instruments such as 'green bonds' and 'green loans'. However, others emphasise financial flows directed toward environmentally sustainable economic activities or the broader alignment of financial systems with sustainability objectives (Sárvári et al., 2025). Recent conceptual studies note that the increasing use of the term across disciplines has resulted in multiple interpretations and conceptual dimensions of green finance (Dhayal et al., 2025).

The absence of a universally accepted definition creates several challenges for both research and policy development - complicates the measurement of green financial flows, limits the comparability of empirical studies and makes it difficult to design consistent regulatory frameworks. In addition, differing interpretations of green finance may contribute to the risk of greenwashing - where financial activities are labelled as environmentally beneficial without meeting the criteria. Scholars have emphasised the need for clearer conceptual frameworks that can better explain the role of financial systems in environmental governance and sustainable development (Dhayal et al., 2025).

Although a rapidly expanding body of literature examines the development of green finance markets, financial instruments and policy frameworks, fewer studies focus specifically on analysing how the concept itself has been defined and conceptualised. A systematic examination of definitional approaches can thus provide important insights into the underlying assumptions that shape the role of finance in environmental governance and environmental sustainability transitions.

The research aim is to examine how the concept of green finance has been defined in academic and policy

literature and to identify the main conceptual approaches underlying these definitions. To reach the research aim, the following tasks are advanced: 1) to examine the conceptual origins of green finance within the broader discussions of environmental and sustainable finance; 2) to compare the main definitions of green finance found in the literature and identify their key differences.

The study contributes to the literature by clarifying the conceptual foundations of green finance and identifying the main definitional approaches used in academic and policy discussions. By demonstrating that existing definitions reflect fundamentally different perspectives on the role of finance in environmental governance, the paper conceptualises green finance as a multidimensional and contested term. The proposed framework helps structure the existing literature and provides a clearer basis for future research and policy analysis.

Materials and Methods

This study employs a structured literature review combined with conceptual analysis to examine how the concept of green finance has been defined and interpreted in academic and policy-related literature. The methodological approach is based on the premise that the development of concepts in scientific literature reflects different theoretical perspectives regarding the role of financial systems in addressing environmental challenges. Relevant publications were identified through international academic databases containing peer-reviewed research related to green finance and associated fields. The literature search was conducted using thematic keywords describing the relationship between financial systems and environmental sustainability, including *green finance*, *sustainable finance*, *climate finance* and *environmental finance*. In addition to academic studies, publications produced by international organisations and policy institutions were also considered, as these sources have played an important role in shaping the conceptual understanding and practical implementation of green finance.

The collected literature was analysed using qualitative conceptual analysis. In the first stage of the analysis, definitions and conceptual interpretations of green finance were identified within the selected sources. In the second stage, the identified definitions were systematically compared by analysing their key elements, conceptual focus and underlying assumptions regarding the relationship between financial systems and environmental sustainability.

Based on the analysis, recurring conceptual patterns were identified in the literature. The definitions were subsequently grouped according to their dominant conceptual orientation, allowing the identification of several definitional approaches to green finance. This classification enabled a structured comparison of different perspectives and provided a clearer conceptual framework for analysing the role of finance in environmental governance. The applied methodological approach allows for a systematic examination of the conceptual development of green finance and contributes to clarifying the different ways in which the concept has been interpreted in academic and policy discussions.

Results and Discussion

Conceptual origins of green finance

The concept of green finance emerged gradually within broader debates on the relationship between economic development, environmental protection and financial systems (Zhang et al., 2021). Its origins can be traced to earlier discussions in environmental economics and sustainability policy that highlighted the importance of financial mechanisms capable of supporting environmentally sustainable development (Hall et al., 2017). The growing awareness of environmental problems in the second half of the twentieth century, particularly since the environmental movement of the 1970s, created the foundation for integrating environmental considerations into economic and financial decision-making (Meadows et al., 1972).

International environmental policy initiatives further strengthened the connection between financial systems and environmental governance. In particular, the United Nations Conference on Environment and Development (Earth Summit) in 1992 played a significant role in recognising the importance of financial mechanisms in achieving sustainable development. During this period, international organisations began promoting initiatives aimed at mobilising private finance for environmental and climate-related projects (Gafoor et al., 2024).

The increasing policy focus on climate change during the 1990s and early 2000s was driven by the development of international climate agreements and growing global recognition of climate change as a major policy issue (Grubb et al., 1999). Climate finance initiatives emphasised the need for large-scale investments in low-carbon technologies and renewable energy systems to support climate mitigation efforts (Fang, 2025). These developments reinforced the understanding that financial systems play a crucial role in facilitating environmental transitions and addressing global environmental challenges.

Within this broader context, the term green finance began to appear in academic literature toward the end of the 1990s. Studies analysing the evolution of the concept indicate that the first publication referring to green finance appeared in 1997, although a clear academic definition emerged later (Dhayal et al., 2025). Since then, the concept has gradually evolved and expanded, reflecting increasing attention to the role of financial systems in promoting environmental sustainability.

The emergence of green financial instruments, particularly green bonds, played a significant role in operationalising the concept of green finance. The first green bond was issued in 2007 by the European

Investment Bank under the *Climate Awareness Bond* programme, introducing the 'use-of-proceeds' structure that links bond proceeds directly to environmentally sustainable projects (Wigley, 2023).
These instruments were created to mobilise capital for environmentally sustainable projects, particularly those related to climate change mitigation and renewable energy investments (Flammer, 2021).
More recently, the discussion surrounding green finance has become closely connected with the broader concept of sustainable finance, which integrates environmental, social and governance (ESG) considerations into financial decision-making processes. Sustainable finance frameworks aim to align financial flows with sustainability objectives and support the transition toward low-carbon and resource-efficient economies (European Commission, 2024; World Bank, 2017).
Overall, the conceptual development of green finance reflects an evolving understanding of how financial systems can contribute to addressing environmental challenges. From its early roots in environmental finance and the green economy to its current integration within sustainable finance frameworks, the concept has progressively expanded in scope and complexity. This evolution has also contributed to the emergence of multiple interpretations and definitional approaches to green finance, which are examined in the following sections.

Definitional approaches to green finance

A systematic analysis of the literature indicates that definitions of green finance can be grouped into several conceptual approaches depending on their primary focus. These definitional approaches do not simply represent alternative descriptions of the same concept but reflect distinct perspectives on how finance contributes to environmental governance. Based on the literature review, four dominant definitional approaches can be identified: instrument-based definitions, objective-based definitions, risk-based definitions and normative definitions.

Instrument-based definitions

One of the most common ways of defining green finance focuses on specific financial instruments designed to support environmentally beneficial activities. In this perspective, green finance is understood primarily through the types of financial products used to fund environmental projects.
Instrument-based definitions emphasise financial mechanisms such as green bonds, green loans and green investment funds that channel capital toward environmentally sustainable initiatives and climate-related projects (Shi & Yang, 2025; OECD, 2017). As noted by Khan & Vismara (2025), the rapid growth of the global green bond market reflects the increasing importance of financial instruments in channelling capital toward environmentally sustainable investments.
This approach is particularly common in policy discussions and financial market analyses, where financial instruments are often presented as practical mechanisms for mobilising private capital for environmental investments. For example, according to the International Energy Agency (2023) policy frameworks and financial market initiatives increasingly promote the development of new financial instruments as a means of attracting private investment to support environmental and climate-related objectives.

Objective-based definitions

Another common definitional approach focuses on the environmental objectives that financial activities aim to achieve. In objective-based definitions, green finance refers to financial flows that contribute directly to environmental protection and sustainable development goals.
Within this perspective, the defining characteristic of green finance is not the specific financial instrument used but the environmental outcomes generated by the investment. According to the United Nations Environment Programme (2018), financial resources are considered part of green finance when they support activities that contribute to environmental sustainability. Additionally, Ozili (2022) notes that green finance refers to financial activities that support environmentally beneficial outcomes, such as reducing greenhouse gas emissions, improving energy efficiency and promoting sustainable resource use.
This approach reflects the growing policy focus on directing financial resources toward activities that support environmental sustainability. For example, sustainable finance frameworks within the European Union aim to guide investment flows toward activities that contribute to environmental goals such as climate mitigation and biodiversity protection (European Commission, 2023). Compared with instrument-based definitions, objective-based definitions provide a broader understanding of green finance by focusing on the environmental impact of financial activities rather than on specific financial products.

Risk-based definitions

A third definitional approach conceptualises green finance through the lens of financial risk management associated with environmental and climate-related factors. In risk-based definitions, green finance is understood as a financial response to environmental risks that may affect the stability and performance of financial systems.
Environmental risks, particularly those associated with climate change, are increasingly recognised as important sources of financial risk. The Bank for International Settlements (2021) notes that climate change creates several types of financial risks, including physical risks caused by climate-related disasters, transition risks arising from policy and market changes related to the low-carbon transition, and liability risks associated with environmental damage. The European Central Bank (2023) highlights that financial institutions and regulators must integrate environmental and climate-related considerations into

financial risk management frameworks.

From this perspective, green finance plays an important role in strengthening the resilience of financial systems by encouraging investments that reduce environmental risks and support the transition toward low-carbon economies. Taghizadeh-Hesary & Yoshino (2023) emphasise that integrating climate-related risks into financial decision-making is becoming increasingly important for maintaining financial stability and guiding sustainable investment strategies.

In turn, the International Monetary Fund (2026) emphasises that financial regulators and supervisors are increasingly required to address climate-related risks, highlighting the growing importance of integrating these risks into financial oversight and decision-making processes.

Normative definitions

The fourth definitional approach views green finance as part of a broader transformation of financial systems toward sustainability. Normative definitions emphasise the role of finance in supporting environmentally sustainable economic development and aligning financial systems with societal and environmental values.

Xia et al. (2023) explain that green finance involves incorporating environmental assessments into financial activities, indicating a broader shift in financial markets where environmental considerations become integrated into financial decision-making.

Financial institutions, investment strategies and regulatory frameworks are increasingly expected to integrate environmental considerations into financial decision-making processes. In this context, green finance is closely connected with broader concepts such as sustainable finance and responsible investment (Dev et al., 2025).

Normative definitions often reflect a more transformative vision of financial systems where capital allocation is aligned with long-term environmental sustainability objectives. Swilling et al. (2025) emphasise that achieving sustainability transitions requires significant changes in financial governance, regulatory frameworks and investment practices to redirect financial flows toward more sustainable patterns of production and resource use. However, Hu & Gan (2025) note that the lack of a unified definition of green finance contributes to conceptual ambiguity, as it is often difficult to distinguish it from related concepts such as sustainable finance and climate finance.

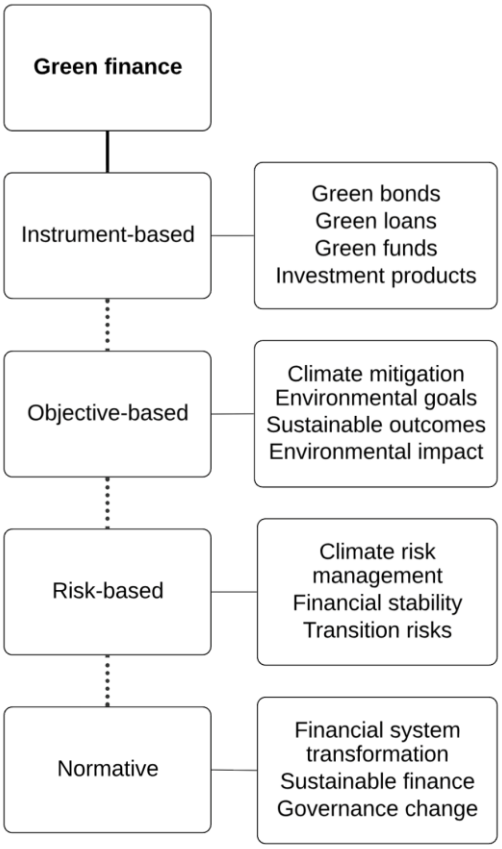
Conceptual comparison of definitional approaches

The conceptual framework illustrates the main definitional approaches to green finance identified in the literature. The framework positions green finance as a central concept that can be interpreted through several different perspectives (Figure 1).

Instrument-based definitions focus on financial mechanisms used to mobilise capital for environmentally beneficial projects. Objective-based definitions emphasise the environmental outcomes generated by financial activities. Risk-based definitions interpret green finance as a response to environmental and climate-related financial risks, while normative definitions frame green finance as part of a broader transformation of financial systems toward sustainability. These differences demonstrate that green finance is not a single clearly defined concept but rather a multidimensional term encompassing several perspectives. The diversity of interpretations reflects the evolving relationship between financial systems and environmental governance. While the coexistence of multiple definitions may create conceptual ambiguity, it also illustrates the dynamic development of the field (Fichtner et al., 2025).

Figure 1

Conceptual framework of green finance definitions



Source: *authors' construction based on literature review.*

The absence of a unified definition has important implications for both research and policy development. Conceptual ambiguity complicates the measurement of green financial flows, limits the comparability of empirical studies and creates challenges for the design of consistent regulatory frameworks. Furthermore, unclear definitions may increase the risk of greenwashing, where financial activities are labelled as environmentally beneficial without meeting substantive environmental criteria.

At the same time, the diversity of definitional

approaches highlights the evolving nature of green finance as a concept that continues to develop alongside broader discussions on sustainability and financial governance. Recognising these conceptual differences is therefore an important step toward developing clearer analytical frameworks that can support future research and policy development.

Conclusions

1. The concept of green finance has developed gradually within broader debates on environmental protection, sustainable development and climate finance, reflecting the growing recognition that financial systems play an essential role in addressing global environmental challenges.
2. The literature review demonstrates that green finance does not have a single universally accepted definition. Instead, the concept has evolved through multiple interpretations that reflect different perspectives on how financial systems should contribute to environmental sustainability.
3. The analysis identified four main definitional approaches used in the literature: instrument-based, objective-based, risk-based and normative definitions. These approaches emphasise different aspects of green finance, including financial instruments, environmental outcomes, financial risk management and systemic financial transformation.
4. The comparison of definitional approaches shows that green finance is best understood as a multidimensional concept rather than a single clearly defined term. The coexistence of different definitions reflects the evolving relationship between financial systems, environmental governance and sustainability transitions.
5. The absence of a unified definition creates challenges for research and policy development, particularly in the measurement of green financial flows, the comparability of empirical studies and the design of consistent regulatory frameworks.

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COMPETITIVENESS DETERMINANTS OF CATERING ENTERPRISES IN REGIONAL TOWNS OF LATVIA: THE CASE OF TALSI AND TUKUMS

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Abstract
The competitiveness of small and medium-sized enterprises is widely recognized as a critical factor in sustainable regional development, particularly in towns where local businesses significantly influence economic resilience and social vitality. Within this context, catering enterprises represent an important component of the urban service economy. Accordingly, the present research aims to identify and analyze the key determinants shaping the competitiveness of catering enterprises in two regional towns of Latvia – Talsi and Tukums. The research was based on a case study applying a mixed-method approach that integrates quantitative and qualitative data. Primary data were collected through surveys of enterprise managers (n=12 in Talsi; n=13 in Tukums) and consumer questionnaires (n=153 in Talsi; n=214 in Tukums), complemented by financial information from the Lursoft database. The Competitive Profile Matrix (CPM) was employed to assess competitiveness across core dimensions, including product quality, service performance, pricing policy, and location. The findings demonstrated that service quality and personnel professionalism constituted the most influential competitiveness determinants in both towns. At the same time, structural constraints such as high operating costs, limited availability of qualified labor, and financial stability challenges affected long-term sustainability. The research contributes to the understanding of competitiveness in regional service enterprises and provides practical recommendations for strengthening local business ecosystems in Latvia. The research is among the few that integrate consumer perception, managerial insights, and financial performance to analyze the competitiveness of regional catering enterprises in Latvia.
Keywords: competitive profile matrix, financial resilience, food services, regional competitiveness, service quality.

Introduction

Catering is one of the most prominent sectors of the Latvian economy in towns and medium-sized cities, serving as an important driver of the local economy and an element of tourism. The ability of regional enterprises to remain competitive has a direct impact on employment and the attractiveness of the urban environment. According to the National Development Plan of Latvia for 2021-2027 (Saeima of the Republic of Latvia, 2020), the productivity and efficiency of small and medium-sized enterprises have been identified as a national priority to reduce regional disparities and foster smart growth. In the context of NACE 2.1 classification, this economic activity is officially designated as 'Food and beverage service activities'; however, for clarity and conciseness, this text uses the term 'catering sector' throughout.

The economic shocks of recent years, including the energy crisis and soaring inflation, have created new challenges for food service providers. As emphasized in the Regional Policy Guidelines for 2021-2027 (Cabinet of Ministers, 2019), businesses in the regions face a limited local market and a shortage of skilled labor. In such circumstances, a traditional approach to the provision of services is no longer effective; therefore, businesses need to identify and harness specific competitive factors to ensure long-term operational stability. The research problem corresponds to the main pathways of regional development and economic diversification. In areas outside Riga and in the most remote areas of Latvia, the catering and hospitality sector significantly contributes to local economic activity, employment, and the maintenance of social infrastructure. By analyzing the competitiveness and financial resilience of small and medium-sized catering enterprises (SMEs) in regional centers, the research provides an empirical basis for the socio-economic processes that ensure the sustainability of the business environment outside metropolitan areas, thereby highlighting issues related to the sustainability of regional growth.

Despite the important role of the catering sector in Latvia's regional economy, few research studies analyze its competitiveness holistically by combining consumer ratings, business opinions, and financial indicators. Previous research studies have focused on individual aspects, not sufficiently revealing the interaction of factors in the context of regional cities and towns. Although many research studies focus on the competitiveness and financial recovery of the hospitality sector in cities, there is still a lack of research on small and medium-sized catering enterprises in rural areas and towns. The significance of the present research study lies in its multidimensional approach that combines post-crisis consumer perception data with the financial indicators of regional enterprises, including profitability, liquidity, and liabilities ratios. Thus, the present research contributes to the knowledge of regional entrepreneurship by applying an empirical approach to assessing the strategic capabilities and financial resilience of SMEs in the hospitality sector under constrained and saturated market conditions.

The present research aims to analyze factors in the competitiveness of catering enterprises in the regional towns of Latvia, based on a case study of Talsi and Tukums.

The research combined two independent case studies, thus allowing for the identification of both common sectoral trends and specific challenges faced by food service enterprises outside the capital city of Latvia. The research results revealed the current situation in the catering sector and can serve as a basis for improving the business environment in regional centers.

Materials and Methods

The research was based on a case study applying a mixed-method approach, integrating quantitative and qualitative data. The analysis was designed as a synthesis of the results of two independent case studies conducted at the regional level, which allowed for the identification of trends in the competitiveness of the catering sector in two towns in Latvia: Talsi and Tukums.

To perform an objective comparison within the catering sector, two towns in Latvia were selected for the research: Tukums and Talsi. Both towns are administrative centers in municipalities located in the historical Kurzeme region and have similar socio-economic characteristics, which makes them representative examples of the regional business environment.

Tukums: the town is located about 65 km from the capital, Riga. By population (approximately 16,529 inhabitants as at 01/01/2024) (Official Statistics Portal, 2025), it is one of the largest towns in Latvia. Economic activity in Tukums is significantly affected by its proximity to the capital and the developed transport infrastructure, which contributes to tourism and the local catering sector.

Talsi: the town known as the 'town of nine hills' is located about 110 km from Riga. With approximately 8,816 inhabitants (as at 01/01/2024) (Official Statistics Portal, 2025), Talsi is smaller than Tukums; however, the town serves as an important cultural and tourism center of Northern Kurzeme.

Despite the different population sizes, the two towns are comparable within the present research due to several important factors. Firstly, both towns perform an important function as the municipality center, thereby providing services to the surrounding area. Secondly, both Tukums and Talsi are recognized tourist destinations, which directly affects the seasonal demand for catering establishments and the need for a diverse supply of tourism services. Crucially, in both towns, the catering market represents local capital and small or medium-sized enterprises, not international enterprises, which makes it possible to examine the mechanisms of local competitiveness under identical business conditions.

The choice of the towns allows us to analyze how the population size and the geographical location affect the financial stability of businesses and their competitiveness strategies in a similar cultural environment.

The primary data were collected at two consecutive stages, which allows us to analyze changes in the sector over time:

- the first stage (2023): a case study of Talsi, focusing on the adaptation of enterprises to post-crisis economic conditions;
- the second stage (2024): a case study of Tukums, thereby complementing the analysis with an in-depth assessment of financial stability.

To make the research results comparable and valid, the two case studies were combined into a single analysis using the following sources:

- primary data: the results of structured surveys of 25 enterprise managers (n=12 in Talsi; n=13 in Tukums) and consumers (n=153 in Talsi; n=214 in Tukums).
- secondary data: financial information from the Lursoft database for the period from 2021 to 2023 was used to refine the economic profile of enterprises.

To ensure the reliability of the research data and methodological consistency, enterprise executives were purposively selected to represent key local stakeholders. Consumer surveys were conducted using convenience sampling, while efforts were made to obtain responses from different age groups and both genders to improve the representativeness of the sample. Furthermore, selecting two socio-economically similar regional towns provided a comparative framework that facilitated the identification of common and differing regional trends and strengthened the reliability of the comparative analysis.

The primary data were used in three ways:

1) to determine the most important factors: based on the results of population surveys, customer priorities were identified (for example, the quality of products versus price), which made it possible to calculate accurate weights (coefficients) for the competitiveness matrix.

2) to assign points: the ratings of the service culture and the premises given by residents served as the basis for an objective assessment of each enterprise in the comparative matrix.

3) to identify market opportunities: unfilled business niches and development potential in both towns were identified by comparing the wishes of the population with the planned investments by enterprise managers.

The main tool for combining and interpreting the data from both case studies was the Competitiveness Profile Matrix (CPM). It allows an objective assessment of the relative strengths and weaknesses of enterprises based on four critical success factors (CSFs):

- product quality: a combination of taste, freshness, and visual presentation of dishes.
- service: service culture and the impact of personnel professionalism on customer loyalty.
- price policy: the price-quality ratio, given regional purchasing power and inflation.
- location: infrastructure availability and physical reach in an urban environment.

According to the methodology, each factor was assigned a specific significance weight (totaling 1.00), and individual enterprises were rated on a scale from 1 (significant weakness) to 5 (significant strength).

To assess market positions in depth, the research determined the relative competitive advantage of each enterprise (Equation 1).

$$\text{Relative Competitive Advantage} = \left(\frac{\text{Rating of the enterprise under analysis,in point}}{\text{Rating oh the strongest competitor,in point}} - 1\right) \text{x } 100\% \quad (1)$$

This approach, based on the methodology developed by Muška (Muška et al., 2018), makes it possible to determine the position of an enterprise in the market by comparing its competitiveness with that of its strongest competitors. At the same time, this approach is consistent with recent research studies on the competitiveness of small and medium-sized enterprises, which highlight the importance of assessing the various factors of an enterprise's capabilities and operational factors (Saunila et al., 2014).

The consumer survey data obtained were processed using descriptive statistical methods by calculating average ratings and percentage distributions. The results were used to determine the weights of critical success factors in the Competitiveness Profile Matrix (CPM). The comparative analysis of the data made it possible to identify both similar and different competitive trends in the enterprises of the two towns.

Results and Discussion

Theoretical aspects of competitiveness in the catering sector

In today's dynamic business environment, competitiveness is no longer just a goal for an enterprise, but a basic prerequisite for survival. Competition (from the Latin *concurrere* – 'to run together', 'to compete') is defined in the scientific literature as the process by which market actors strive to achieve similar goals, thereby limiting the opportunities of others to achieve them (Barney & Hesterly, 2019).

According to M. Porter's theory (Porter, 2008; Barney & Hesterly, 2019), the competitiveness of a sector is not determined only by direct competitors, but by the interaction of five forces: the struggle of existing competitors, the threat of new entrants, the availability of substitute products, as well as the bargaining power of buyers and suppliers. Depending on the results achieved, three levels of competitiveness are distinguished:

- normal: the results meet the expectations of stakeholders;
- below normal: the true results are below expectations, contributing to the outflow of customers to competitors;
- higher than normal: the enterprise exceeds market averages, strengthening stakeholder loyalty (Barney & Hesterly, 2019).

The present research emphasizes that the position of a catering establishment at any of the above levels is not static, and its increase directly depends on the targeted use of specific resources and the creation of unique advantages.

To outperform its competitors, an enterprise must possess a clear competitive advantage. It could be achieved in two ways: by offering lower prices (cost-effectiveness) or by creating something unique and of higher quality (product differentiation). This approach is based on the Resource-Based View Theory, which states: long-term success is ensured by resources that are valuable, rare, and difficult to imitate (Barney & Hesterly, 2019). In catering enterprises in Tukums and Talsi, the resources include human resources (qualified personnel), physical resources (equipment and settings), intangible resources (brand and location), as well as financial resources that represent investment capacity. Recent research studies have revealed that the long-term competitiveness and financial stability of enterprises are largely linked to the ability to develop sustainable organizational capabilities and make effective use of available resources (Saunila et al., 2014).

However, the resources do not function in isolation, as their effectiveness is significantly affected by both the internal structure of the enterprise and changes in the external business environment.

The performance of catering establishments is affected by the internal environment, which involves controllable factors, e.g., corporate culture and financial management, and the external environment, whose uncontrollable factors (inflation, tax policy, seasonality) in regions can affect stability more significantly than internal errors. The analysis of the impact of the factors reveals that management needs accurate tools for assessing positions. In the hospitality sector, increased attention is being paid not only to cost reduction but also to the quality of services and operational efficiency (Çelikel, 2025). Therefore, enterprises need to use clear analytical methods to assess their competitiveness. Systematic competitor analysis is referred to in the literature as one of the main tools for risk mitigation and strategic planning. The Competitiveness Profile Matrix (CPM) is considered one of the most effective methods (David F. R. & David F. R., 2023). Furthermore, identifying specific structural tools and operational factors is crucial for measuring and sustaining market positions in the broader hotel, restaurant and tourism sectors (Mashika et al., 2021). It allows an enterprise to be quantitatively compared with its main competitors based on Critical Success Factors (CSF). In parallel with the CPM matrix, the SWOT method enables a comprehensive analysis by pairing internal strengths and weaknesses with external opportunities and threats, thus facilitating a more accurate definition of the enterprise's market position.

The specific features and trajectory of the Latvian catering sector are inextricably linked to the country's economic cycles and general level of prosperity. Data from the World Economic Forum show that Latvia demonstrates relatively high performance in macroeconomic stability and technological skills (Ministry of Economics, 2018); however, at the regional level, the catering sector is hampered by a lack of skilled labor and low productivity. These challenges are similar in other European countries.

Some research studies have found that shortages of skilled labor and low labor productivity remain significant challenges for SMEs in the food and catering sector in Europe (Tidjani et al., 2025). The latest research studies highlight that various analytical and modelling approaches are increasingly being used to assess business competitiveness and development (Volosova et al., 2025).

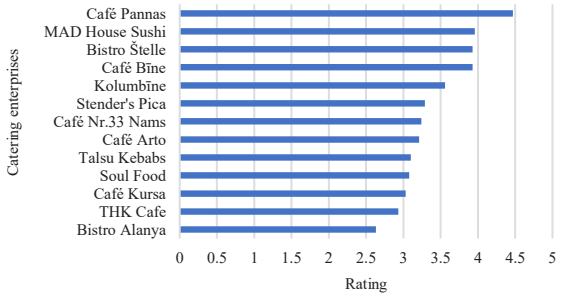
It should be noted that international competitiveness and the ability to innovate begin with a stable and strong internal market. The more intense competition is observed in regional centers such as Tukums and Talsi, the better prepared local enterprises are for the challenges of globalization. Local market rivalry compels enterprises to pursue innovative solutions and deploy limited resources more efficiently, forming the basis for the sector's long-term sustainable growth.

Analysis of the competitiveness of catering enterprises in Talsi

The competitiveness assessment of the catering sector in Talsi reflects a pronounced segmentation among market actors. Using the Competitiveness Profile Matrix (CPM), overall ratings were calculated for 12 enterprises in the town based on several critical success factors (Figure 1).

Figure 1

Overall ratings for the catering enterprises in Talsi



As shown in Figure 1, Café Pannas (rating above 4.00) was recognized as a convincing market leader, followed by MAD House Sushi, Bistro Štelle and Café Bīne. A detailed analysis of the factors allowed us to identify specific trends on a regional scale.

The quality and range of products: the highest ratings for the quality of dishes were given to Café Pannas, MAD House Sushi and Café Bīne. The enterprises provided high visual standards and fresh, locally prepared products. In terms of the variety of dishes, the leaders were Café Pannas and Stender's Pizza, whose extensive menus satisfied various groups of customers. In contrast, smaller enterprises such as Soul Food and Café No.33 focused on a narrower and specific niche due to limited space and personnel resources.

Pricing policy: this factor was critical in the region. The highest ratings (as the most affordable enterprises providing high quality) were given to Café Bīne, Kolumbīne, and Bistro Štelle, where consumers could receive large portions at a relatively low price. Café Pannas and MAD House Sushi were positioned in the higher price segment, which created a noticeable difference with their competitors, but still maintained a quality advantage.

Service culture: most of the enterprises received high ratings (3.00-4.00), thereby indicating qualified and friendly personnel. However, the case study also highlights problems; for example, unfriendly service was found in Café Kursa, which might relate to an unsatisfactory working environment or remuneration system, thus indicating the risks of human resource management.

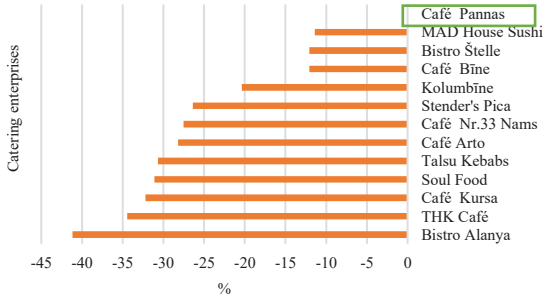
Aesthetics and cleanliness: Café Pannas was also a leader in the design of premises after the reconstruction. In contrast, long-term market players (Stender's Pica, Café Arto, Café Kursa) received lower ratings in terms of cleanliness and modernization, which might indicate over-self-reliance and a lack of investment in refreshing the visual image. An interesting example was Talsi Kebabs, where improper planning of premises (an excessively large children's area at the expense of the guest hall) lowered the overall competitiveness rating.

Availability: most of the Talsi enterprises worked on weekends, thereby receiving the maximum rating. An exception was Soul Food, whose specific opening hours (from 17:00 to midnight) limited its overall competitiveness, but at the same time filled a unique niche of night-time dining in the town.

To assess the market positions in depth, the research determined relative competitive advantage for each enterprise (equation 1), which shows the enterprise's competitive advantage over the strongest competitor. The percentages of relative competitive advantage for Talsi catering enterprises are presented in Figure 2.

Figure 2

Relative competitive advantage for the catering enterprises in Talsi



The results of the analysis revealed that there is no dominant leader controlling the Talsi catering market. This situation indicated a fragmented market, typical of regional towns, where enterprises have limited growth opportunities. Although Café Pannas achieved the highest relative competitive advantage, the margin was not large enough (below 30%) to be classified as significant according to the methodology. This indicated very active competition within the town. The lowest relative competitive advantage was found for THK Café, Café Kursa, and Soul Food, which

indicated the need for strategic changes in their operations.

An in-depth analysis of the financial performance of the enterprises and the impact of state support in 2022 revealed an alarming trend – most of the Talsi catering enterprises ended the year with losses, which could be explained by post-crisis inertia and a sharp increase in costs. The analysis of changes in profit and turnover revealed that the largest turnover was reported by Stender's Pica (EUR 1.860,908); however, the enterprise also suffered the largest losses, amounting to EUR 145,345. A similar situation was observed for Kolumbīne (including Café Bīne, Kolumbīne, and Bistro Štelle), whose losses amounted to EUR 48,613. MAD House Sushi (EUR 12,487) and Bistro Alanya (EUR 15,609) were the only profitable enterprises in 2022.

Regarding profitability and liquidity ratios, it should be concluded that the highest net profit margins were shown by Bistro Alanya (134.43%) and MAD House Sushi (40.93%). Conversely, the remaining enterprises reported negative profitability indicators, ranging from -8.17% to -49.27%, reflecting the severe operational challenges within the regional market. However, the liquidity ratios that indicate the ability of enterprises to cover their short-term liabilities in a timely manner, were relatively low for all the enterprises included in the case study (below 1.0). The highest results were shown by Bistro Alanya (0.78) and MAD House Sushi (0.70), which indicates the general financial fragility of the catering sector in the area around Talsi.

The analysis of the impact of state support on the viability of the catering sector revealed that, in order to overcome the consequences of the COVID-19 crisis, seven enterprises have received state support. The most notable funding was received by Stender's Pica (over EUR 550,000) and Café Arto (EUR 62,259). This support has been mainly used in the form of grants to ensure the flow of working capital and downtime allowances for employees, which proved to be critical elements for business continuity and job retention in the area.

Analysis of the competitiveness of catering enterprises in Tukums

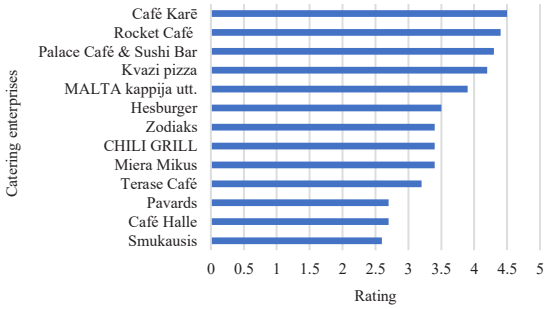
The competitiveness assessment of the catering sector in Tukums was performed employing an expert method and the Competitiveness Profile Matrix (CPM). A total of 13 enterprises in the town were rated based on factors identified as priorities by residents themselves in the survey (Figure 3).

As shown in Figure 3, Café Karē (4.55) was recognized as the market leader, closely followed by Rocket Café (4.49) and Palace Café & Sushi Bar (4.32). The analysis of factors across Tukums revealed several key trends.

Product quality and range emerged as the most critical factor, weighted at 0.24. Within this category, the highest ratings were awarded to Café Karē, Rocket Café, Palace Café & Sushi Bar, and MALTA kappija utt. In contrast, Café Halle received the lowest rating due to a lack of texture and taste. In terms of dish variety, the Tukums market proved abundant, with all enterprises receiving high ratings for satisfying various customer preferences.

Figure 3

Ratings of the catering enterprises in Tukums



Pricing policy: in most of the enterprises (7 out of 13), the price corresponded to quality. However, in Pavards and Café Halle, the prices were rated as inadequately high relative to the service provided, compared with the competitors.

Service culture: the most professional service was observed in Café Karē, Palace Café & Sushi Bar, Rocket Café, and Kvazi pizza. In the case of Café Halle, low employee interest was identified as a significant risk to the long-term competitiveness of the enterprise.

Aesthetics and location: in Tukums, the location was rated ambiguously. Although the centre (Smukausis, Zodiac) was attractive, the poor accessibility (lack of parking spaces) reduced customer convenience. Visually, the highest level was shown by the new enterprises Rocket Café and MALTA kappija utt., as well as Café Karē after a major renovation. In contrast, the interiors of Smukausis and Pavards were outdated and did not correspond to the modern concept.

Availability and opening hours: the most stable opening hours (availability all week) were provided by Café Karē, Palace Café & Sushi Bar, and Hesburger. The changing opening hours of Café Terase and Smukausis caused distrust among consumers.

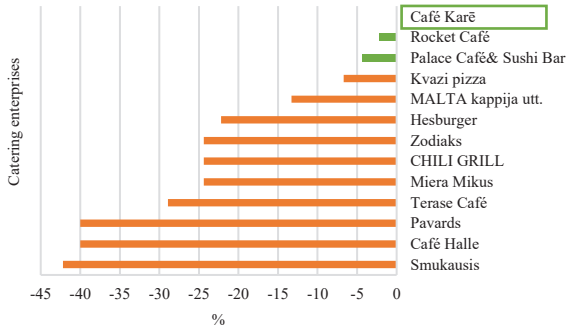
To assess the market positions in depth, the research determined the relative competitive advantage for each enterprise (equation 1), which shows the enterprise's competitive advantage over the strongest competitor. The percentages of relative competitive advantage for the Tukums catering enterprises are summarized in Figure 4.

The analysis results showed that in the catering market of Tukums, there was extremely tough and dynamic competition between the leading enterprises. This was evidenced by the fact that the market leader Café Karē had a lead of only 2.2% over the closest competitors, which in practice meant that none of the enterprises had a pronounced and stable predominance. Such a situation indicated the saturation of the market, with even minor changes in the quality of services drastically changing the flow of customers. In contrast

to the leading players, the relative competitive advantage of the enterprise Pavards (-40.0%) indicated critically low competitiveness, thus signaling the need for immediate strategic adjustments.

Figure 4

Relative competitive advantage for the catering enterprises in Tukums



The analysis of the financial performance of the enterprises in Tukums in the period from 2020 to 2022 allowed us to objectively assess their real sustainability and financial resilience. An analysis of changes in profit and profitability revealed that the fastest growth was observed for Café Karē, whose profit in 2022 increased by EUR 25,904. This increase directly correlated with improvements in asset profitability and efficient resource management. In contrast, the largest losses during the analyzed period were incurred by the enterprise Pavards (EUR 19,454 in 2020), which were mainly caused by a sharp decrease in customer volume and inability to adjust fixed costs to changing market conditions.

Regarding liquidity ratios, it can be concluded that all market-leading enterprises, including Café Karē and Palace Café & Sushi Bar, remained stably within the range of rational liquidity (1.0 to 3.0 points). This confirms the ability of enterprises to cover their short-term obligations on time, serving as an important indicator of financial stability. However, an analysis of the debt ratio revealed that the most financially unstable situation was observed at Miera Mikus, whose debt ratio exceeded 1.0, thus indicating high risk. In contrast, Café Karē and Palace Café & Sushi Bar showed a low debt ratio, which not only made them more attractive in the eyes of creditors and investors, but also provided significantly better positions for further development and investment.

After summarizing the analysis results on the competitiveness of catering enterprises in Talsi and Tukums, it was possible to identify several common regularities and specific differences that were specific to the catering sector in the regional centers of Latvia. The analysis of common determinants of competitiveness demonstrated that, in both towns, the quality of products and services was recognized as the paramount factor. The consumer survey data clearly confirmed that the local customer tend to be increasingly demanding, and lower prices can no longer compensate for unfriendly service or outdated interiors. The market leaders of both Talsi (Café Pannas) and Tukums (Café Karē) strengthened their positions purposefully, directly through investments in aesthetics and personnel motivation. The research results showed that not only the quality of dishes, but the whole experience, including service and the visual image of the enterprise, which was fully in line with modern trends in the service economy, played a decisive role in consumer choices. These trends are consistent with the latest findings on the challenges faced by traditional catering businesses. The research studies emphasize that long-established enterprises often find it more difficult to adapt to the demands of today's customers. Outdated interiors, insufficient use of digital technologies, and slow adaptation to new trends can reduce the competitiveness of enterprises compared with that of newer and more flexible market players (Zhang, 2025).

The analysis of structural challenges revealed a clear discrepancy between the marketing image of the enterprises and their actual financial performance. Although most of the enterprises could attract and retain customers and ensure stable competitiveness in the market, their financial performance showed the opposite – low liquidity (below 1.0) and losses in 2022 signalled increased operational risks in the long term. Similar trends were found by other research studies on SMEs in the catering and hospitality sector. Although enterprises are often able to attract customers and gain popularity, their financial stability is negatively affected by rising resource prices, external economic risks, and limited financial resources (Hlatshwayo, 2020). The findings are consistent with previous international research, indicating that the financial challenges observed in Talsi and Tukums are not unique to these towns but reflect broader trends reported in the hospitality sector. The managers of the enterprises in both regional towns also mentioned the lack of qualified labour as one of the most significant problems, which affected service quality and opportunities for business growth. The literature emphasizes that professional and motivated personnel is an important factor in competitiveness (Barney & Hesterly, 2019; Wujarso et al., 2021). This indicates that the competitiveness of regional enterprises is affected not only by their internal decisions, but also by the overall economic and demographic situation in the country.

The analysis of market density and shifts in relative competitive advantage showed that neither town had a dominant market leader player. In Tukums, competition was characterized as more intense, which was determined by a larger population and the location of the town near the capital. In contrast, there was a marked segmentation in the Talsi catering market, where new entrants, such as specialized sushi and kebab bars, could gain a significant market share in a

relatively short period, thus successfully competing with traditional enterprises.

The analysis of the ratio of supply to demand led to the conclusion that there was an insufficient supply of ethnic cuisine and higher-level restaurant services in both towns. While consumers point to the need for this kind of service, the priority of enterprise management was mostly the optimization of current processes and the restoration of technical resources, rather than the introduction of innovative concepts. This problem indicated untapped potential for both the entry of new market participants and a change in the operational strategy of current enterprises to adapt more effectively to consumer expectations.

The research results revealed that there was a causal association between consumer ratings and enterprise competitiveness. The high ratings of service quality and personnel professionalism in Talsi and Tukums confirmed that quality service was one of the most important factors in the competitiveness of regional enterprises (Saunila et al., 2014). At the same time, the financial performance indicators and high operating costs indicated the limited financial stability of regional catering enterprises and the need to carefully plan resource use (Çelikel, 2025). This means that maintaining competitiveness requires a balance between high service quality and effective cost management.

The data analysis revealed that high customer satisfaction with personnel performance was a significant factor in business growth. In regional markets, where populations and buying power are reduced, quality customer service strengthens customer loyalty and helps compensate for limited advertising opportunities. The performance of the examined enterprises in Talsi and Tukums confirmed that service quality was one of the main prerequisites for competitiveness under economically unstable conditions.

At the same time, the analysis of financial performance indicators revealed that high-quality maintenance required significant expenses, especially for wages and quality local raw materials. This means that a good reputation and a steady flow of customers do not always guarantee high financial stability. Therefore, it is important for regional enterprises to carefully plan their costs and manage their resources efficiently.

Conclusions

1. The research confirmed that the predominant competitive factors in the regional catering markets of Talsi and Tukums were service quality and product excellence. Consumer loyalty was no longer determined only by the lowest price, but by the overall experience, which was formed by the professionalism of the personnel, the aesthetics of the setting, and the visual appearance of dishes.
2. Both towns had a high market fragmentation without a clear leader controlling the catering sector. In Tukums, competition was more intense (the lead was only 1.33%), which could be explained by the larger population and proximity to the capital, while in Talsi, new niche players (sushi and kebab bars) successfully competed with long-standing traditional enterprises.
3. Despite the ability of the enterprises to attract new customers, the financial stability of small and medium-sized catering enterprises remained fragile. Low liquidity ratios (below 1.0) alongside reported 2022 losses demonstrated that external economic factors, such as inflation and rising energy costs, had a significant impact on the sustainability of these enterprises, regardless of how efficiently their internal operations were run.
4. A shortage of qualified personnel emerged as a systemic barrier to the development of the catering sector in both areas. This showed that the long-term stability of the catering sector and the maintenance of service quality directly depended on regional demographic trends and access to professional training.
5. A significant difference was found between consumer demand for diverse culinary experiences (ethnic cuisine, higher-end restaurants) and the current market supply. This gap creates significant strategic opportunities for new entrants or for the conceptual transformation of current enterprises.
6. Based on the research results, it is recommended that regional catering enterprises prioritize investments in service quality improvements and digital adaptation. At the municipal level, it is necessary to strategically improve urban infrastructure, specifically the availability of parking spaces, to enhance accessibility to local enterprises and support overall competitiveness.

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GENERATIONAL SUCCESSION IN SMALL FARMS AND FARMING RESILIENCE IN LATVIA

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Abstract
The aging of farm owners, youth outmigration, and rural depopulation have made generational succession a major challenge to agricultural sustainability in Latvia, particularly for small family farms that sustain regional identity and rural socio-economic vitality. This study aimed to identify the factors that facilitate or hinder farm succession, focusing on young people's motivation, family attitudes, and broader economic and social conditions. Conducted between February and May 2025, survey of students enrolled in agricultural programs at the Latvia University of Life Sciences and Technologies (LBTU) was complemented by semi-structured interviews with farm owners and potential successors. Findings indicate that succession is more likely when children are involved in farm work from an early age and develop a strong emotional attachment to rural life. Such individuals often pursue agricultural education and consider continuing the family farm. However, early engagement does not guarantee commitment to farm management. Many young people report burnout, low income prospects, and limited quality of life, leading to uncertainty about their future in agriculture. Succession planning is frequently unclear or postponed, as older farmers emphasize their children's freedom of choice. Although many students acknowledge the influence of family farming on their educational decisions, only a minority intend to become farm managers. Structural and emotional barriers—urban lifestyle preferences, heavy workload, and insufficient state support—further discourage long-term engagement. Farm succession thus emerges as a complex, multi-dimensional process shaped by identity, family dynamics, and socio-economic context.
Keywords: farm succession, family farm, farming resilience, rural development.

Introduction

According to the results of the Integrated Statistical Survey of Agricultural Holdings conducted by the Central Statistical Bureau of Latvia, in 2023 there were 46.2 thousand small farms with a standard output of up to EUR 15 thousand annually managed 313.1 thousand hectares of agricultural land. The Integrated Farm Statistics Survey is conducted every three years in the European Union and European Economic Area, bridging the agricultural censuses that occur once a decade. This survey collects data on various aspects of farming, including the number and structure of farms. Compared to 2020, the number of farms in this category declined by 12.6 thousand, or 21.5%, while the area of agricultural land under their management decreased by 134.6 thousand hectares, representing a reduction of 30.1%. These figures indicate a significant structural shift in the agricultural sector, characterized by the consolidation of land and a decline in the number and land share of small-scale farms. In turn, 3,000 large farms, whose standard production exceeds 100 thousand euros per year, managed approximately 1.2 million hectares, which accounts for 61% of the country's total agricultural land (CSP, 2024).

Small farms are an important support for the employment of the rural population, maintenance of the natural environment and traditional cultural landscapes, ensuring biodiversity. These farms create an aesthetic rural environment, offer new recreational and health services, produce regional cuisine, establish short food chains, operate in an environmentally friendly manner and more often use organic farming methods. These farms mark new trends in rural development, such as part-time farming, lifestyle farms, pension management, educational, social care, rehabilitation, therapeutic functions, agricultural diversification, artisan food processing (Zasada, 2011; De Krom & Dessein, 2013). Small family farms make a positive contribution to rural development, particularly through the closer relationship that farmers maintain with their land compared to large-scale agricultural enterprises. Many authors (Mazancová et al., 2025; Redlichová et al., 2023; Thiemann & Rolle, 2022) note that small farms are often better positioned to foster strong social ties within rural communities. Furthermore, they emphasize that these farms hold significant potential to strengthen connections with consumers, especially by engaging in shorter supply chains that promote more direct and trust-based relationships between producers and customers.

Generational renewal in agriculture is widely acknowledged as a fundamental precondition for the sustainability and long-term viability of the European agricultural sector (Hayden, 2024). This process extends beyond merely attracting and retaining young people in rural areas; it is intrinsically linked to farm inheritance and succession, which substantially shape the future continuity, management, and development of agricultural holdings.

Across most European Union member states, the age structure of the farming population remains unfavourable, with the proportion of older farmers significantly exceeding that of farmers under the age of 35, only 5.6% of all European farms are run by farmers younger than 35 while more than 31% of all farmers are older than 65 (EU, 2017). These demographic patterns suggest the existence of structural barriers and underlying factors contributing to delayed or postponed succession. One of the most critical determinants of a successful generational transition in agriculture is the implementation of timely and carefully considered succession planning.

Early and strategic preparation for the transfer of farm ownership and management can facilitate a smoother intergenerational transition, thereby supporting the long-term sustainability and operational continuity of farm enterprises (Hayden, 2024). Nevertheless, younger generations frequently encounter limited economic incentives and insufficient motivation to continue family farming activities. This challenge poses risks not only to the viability of individual farms but also to the broader rural economy and the preservation of traditional rural lifestyles. In this context, examining the viability of small farms in rural regions of Latvia is particularly significant. Statistical data indicates a marked structural shift in recent years, characterised by a substantial increase in the proportion of large-scale farms and a sharp decline in the number of small farms (CSP, 2024).

Although farm succession is predominantly not a matter of 'rational' decisions taken at a specific turning point in the farm family life cycle, it is better understood as a long-term, gradual process. This process involves the parallel development of both the successor and the farm in such a way that the successor's expectations, skills, and identity as a future farmer become aligned with the evolving characteristics and needs of the farm (Fischer & Burton, 2014).

Nevertheless, the identification of a successor plays a significant role in shaping farmers' behaviour and influencing strategic farm management decisions. Once a potential successor is recognised, farm owners may adjust investment patterns, production choices, and long-term planning in anticipation of the forthcoming generational transfer (Bertolozzi-Caredio, 2024).

The limited motivation of the younger generation to engage in agriculture is further intensified by the discrepancy between the idealised representation of rural life as simple, harmonious, and inherently fulfilling, and the complex economic and social realities faced by contemporary farms. The notion of a rural idyll may foster unrealistic expectations, which are subsequently challenged by the necessity to adapt to structural changes, market volatility, regulatory pressures, and increasing demands for economic competitiveness. This tension between a romanticised vision of the rural past and the lived reality of modern agricultural practice significantly shapes young people's perceptions of farming as a viable career path and influences their decisions regarding continued involvement in agriculture (Shucksmith, 2018).

The aim of this study is to develop a more comprehensive understanding of the factors that facilitate or hinder generational succession on regional farms in Latvia, as well as to examine the principal challenges these farms encounter. The findings are intended to inform policymakers, farmers, and regional development planners in designing strategies that support sustainable rural development and strengthen the long-term viability of agricultural enterprises.

Materials and Methods

In this study, the following research assumptions are proposed: 1) Early involvement assumption: Farm succession in rural regions of Latvia is more likely to occur in families where potential heirs have been involved in farm activities from an early age; 2) Inherited asset motivation assumption: Students whose families already own or have inherited agricultural property are more likely to express an intention to continue the family farming tradition; 3) Owner expectation assumption: farm owners in rural Latvia generally expect intergenerational succession and express a preference for the transfer of farm ownership and management to younger family members.

Conducted between February and May 2025, survey of students enrolled in agricultural programs at the Latvia University of Life Sciences and Technologies (LBTU) were complemented by semi-structured interviews with farm owners and potential successors. The study adopts a convergent research design, whereby qualitative and quantitative data collection methods are implemented concurrently (Creswell, 2023). This approach enables the integration and comparison of findings derived from different methodological perspectives to develop a more comprehensive understanding of generational succession within farms.

Quantitative methods are employed to identify broader patterns and trends, whereas qualitative methods facilitate an in-depth exploration of respondents' individual perceptions, experiences, and contextual interpretations. The combination of these approaches enhances the validity of the findings and allows for a more nuanced analysis of the research problem.

The quantitative component of the study consisted of an online survey administered to current and potential farm successors—students enrolled in the study programme in Agriculture at the Latvia University of Life Sciences and Technologies (LBTU) (n = 33). The aim of the survey was to identify trends in students' attitudes toward farm succession and to examine their future career intentions in relation to agriculture.

The selection of a quantitative approach was justified by its capacity to generate generalisable findings and to numerically identify patterns within a defined target group. Given that the respondents represented a specific study programme, the survey enabled the systematic analysis of trends in their responses. However, it is acknowledged that quantitative methods primarily provide structured and surface-level insights and are less suited to exploring the deeper contextual meanings and lived experiences of respondents.

An online survey format was chosen due to its accessibility, flexibility, and efficiency in reaching the target population. The instrument was tailored to the specific respondent group and distributed electronically, facilitating broader outreach with minimal administrative burden. Elements of snowball sampling were also employed, as respondents were encouraged to share the survey within their networks.

Participation was voluntary and anonymous. Data were used exclusively for research purposes and analysed in aggregated form, ensuring that no identifying information was disclosed. The survey sought to examine students' motivation for studying agriculture, the role of potential farm inheritance in their educational and career choices, and their perspectives on the future of the agricultural sector in Latvia.

The questionnaire included items on demographic characteristics (gender, age, study level, and year of study), followed by questions addressing motivations for studying agriculture, employment opportunities in farming, knowledge of agricultural practices in Latvia, and influencing factors. The final section assessed respondents' familiarity with different farming approaches and methods.

The survey remained active for one month and was redistributed three times to maximise response rates. Initial distribution through student communication groups coincided with fieldwork activities, resulting in low participation. Subsequently, the student council assisted in disseminating the survey via social media, and it was later reposted in communication groups. Although the intended sample size was 60 respondents, only 33 responses were obtained due to non-response. Nevertheless, all collected data were included in the analysis.

Qualitative data were collected through semi-structured interviews conducted to obtain in-depth insights into respondents' perspectives and lived experiences, thereby facilitating a more comprehensive interpretation of the survey findings and the broader context of generational succession. A semi-structured format was employed, allowing flexibility to adapt the interview process to the specific circumstances of each case and to pose follow-up questions where clarification or elaboration was required. This approach is particularly appropriate when open-ended questions need to be supplemented with probing inquiries to achieve a deeper understanding of respondents' views.

In total, five semi-structured group interviews were conducted (1–2 participants per interview; n = 9 informants) with farm owners and young potential successors regarding future operational and development plans. The sample comprised six farm owners (each with at least ten years of experience in agriculture) and three potential successors. The interviews aimed to explore participants' perceptions of their farms, the challenges faced by both the current and next generation, their views on agricultural sustainability, and their attitudes toward maintaining the farm as a family legacy. Interview duration ranged from 24 to 40 minutes. In three of the five interviews, both generations were represented, allowing all prepared questions to be addressed; in the remaining two interviews, questions focused primarily on farm owners' perspectives regarding succession prospects.

Ethical considerations were ensured throughout the research process in accordance with established qualitative research principles (Creswell & Poth, 2018). Participation was voluntary and anonymous, and informed consent was obtained prior to each interview. Respondents were informed about the purpose of the study, the intended use of the data, and their right to withdraw at any stage. No information that participants wished to withhold was disclosed. One respondent requested anonymity; accordingly, a pseudonym was used in the transcript and subsequent analysis. All data are accessible only to the researchers and the commissioning body.

The interviews followed a structured progression to ensure respondent comfort and thematic coherence. Initially, neutral questions addressed the history and characteristics of the farm, fostering engagement and providing contextual background. The discussion then shifted to external factors influencing farm operations, followed by more personal reflections on the farm's future, family involvement, succession opportunities, and related influencing factors. The interviews concluded with questions concerning traditions maintained within the farm, encouraging reflective responses on the role of continuity and heritage in farm development.

At the conclusion of each interview, a brief summary of key points was presented to confirm the accuracy of interpretation. Respondents were thanked for their participation and offered the opportunity to provide additional comments or clarifications.

For analytical purposes, the interviews were coded as P1–P5, with distinctions made between representatives of the older generation (informant 'A') and the younger generation (informant 'B').

Results and Discussion

The survey of potential farm successors—students enrolled in the study programme in Agriculture at the Latvia University of Life Sciences and Technologies (LBTU) (n = 33) revealed a strong positive correlation between students' intention to inherit a farm and their family's aspiration for farm succession. Twenty-six students who indicated that 'My family wants me to be the next farm owner' also affirmed that 'I intend to take over the family farm in the future'.

The interviews reveal the issue of farm succession, in its various manifestations, as a significant component of rural vitality. Some authors (Bertolozzi-Caredio, 2024; Hāzners et al., 2024) note that the current policy framework does not fully harness the potential of generational renewal, as the available instruments are primarily targeted at young farmers after they have taken over the farm, rather than at incumbent farm owners who are preparing for the transfer process. The author agrees with the cited argument that such an approach does not effectively encourage timely and well-considered decision-making regarding farm succession, as it lacks targeted support mechanisms that would motivate and assist both the transferor and the successor already at the preparation stage. the

current policy framework does not fully harness the potential of generational renewal, as the available instruments are primarily targeted at young farmers after they have taken over the farm, rather than at incumbent farm owners who are preparing for the transfer process. Such an approach does not effectively encourage timely and well-considered decision-making regarding farm succession, as it lacks targeted support mechanisms that would motivate and assist both the transferor and the successor already at the preparation stage. Therefore, it is important to undertake a more in-depth analysis of the factors that can both facilitate and hinder the decision to take over the farm within farming families.

Group interviews with farmers from different generations in family farms show that succession is a multi-layered issue – intertwining farming conditions, family dynamics, and the younger generation's attitudes toward rural life.

The issue of succession can also manifest from the opposite perspective – there are farms that would not have engaged in agriculture at all if they had not inherited the farm from parents, grandparents, or relatives. *'I like the idea that these are my father's and grandfather's homes. That land and property – they worked there, tended livestock and cut the forest, and I continue that'* (Farms P1–P5). *'My grandfather started it'; 'And when he (the owner's father) passed away, then I took over, yes'. 'The land has been inherited through generations and I do not want to risk it'* (Farms P1–P5). Inheritance refers both to material assets (land, machinery) and to lifestyle and identity. Receiving an inheritance is a crucial precondition for establishing a farm, especially in families where agriculture is not the primary occupation but part of diversified livelihoods.

Although the data obtained from the survey of agricultural students are not statistically significant, they indicate trends that confirm the views expressed in the interviews.

The survey reveals a strong positive correlation between a student's willingness to inherit the farm and their family's desire for it to be taken over. This means that the more a young person feels that their family wants the farm to continue into the next generation, the more they recognize their own willingness to take it over. A moderately strong positive correlation can also be observed between the statements *'I would like to take over the family farm in the future'* and *'It is important for me to continue the family legacy'*. This may suggest that young people often perceive inheritance as a responsibility, particularly in cases where they themselves also have a desire to continue the family business.

Other interviews reveal both the potential for continuing farming and doubts about it. For example, in farm, where the son has studied agronomy and is involved in the farm, this is seen as an advantage: *'It's really great that our son is interested in it; he trained as an agronomist'* (Farms P1–P5).

The issue of gender in intergenerational succession emerges when the youngest generation in the family consists only of women. The older generation feels that it would be more difficult for daughters to take over the farm. *'We would rather rent our land out to others, because with succession, it's harder for girls'. 'I only have daughters. One has her own career, the other – a family. I doubt that either of them would want to continue farming'* (Farms P1–P5). This may indicate the presence of gender role stereotypes in agriculture, where women are not automatically seen as potential successors, even if they would otherwise be capable.

Family support is highlighted as both an emotional and practical resource. *'Family is the biggest support in all this, they are the ones who encourage us…'. 'Financially, we asked both mothers to help us at the beginning'* (Farms P1-P5). These examples show that family and kin support is important, especially in the early stages of farming, when the farm's financial independence has not yet been established.

This group includes quotations that demonstrate close family involvement in daily farm life, division of labour, and decision-making – essential aspects of viability. *'We really do everything together. Both the paperwork and the practical side. 'The rest of us help with the work whenever needed'. 'I handle all the accounting and sales. My husband takes care of the whole farm – the 'men's work, 'feeding the animals, collecting hay, planting potatoes'* (Farms P1–P5). *'L. and her mother deal with the livestock. The two of us, and I have one employee, handle the land and all the other work. We don't divide things in detail; whoever is needed does it. In practice, one person does all the jobs. It's not set that one only does this and another only that. Whoever is needed does the job. That's roughly the division'* (Farm P3, informant A).

Farmers sometimes see succession as hope for the farm's renewal, but also as a major uncertainty. At the same time, concerns are expressed about whether the next generation will even want to engage in agriculture. *'There is a generational change happening; many are stopping, our son continues'.'It depends on the next generation – whether they themselves will want it'* (Farms P1-P5).

The interviews emphasize that succession is not automatic. The quotations show that many farmers see succession as gradual participation rather than merely the transfer of ownership.

Motivation and interest from the younger generation are essential preconditions for succession. Parents understand and recognize that at this age young people have other interests – the desire to study something that personally interests them; to *'see the world, see everything that life offers'*; to develop their potential career opportunities; to *'broaden their horizons and shape themselves as individuals'* (Farm P2, informant A).

The older generation often deliberately avoids putting pressure on young people – this is both an expression of respect and a rational attitude, so that succession

would come from free will. *'I don't really have expectations, because realistically looking at life and also considering what perhaps I had in mind earlier, compared to my daughter now at her age – 25 – time will show! In youth you need to see the world, see everything that life offers, and also use career opportunities to broaden your horizons and shape yourself as a person'* (Farms P1–P5).

Some parents noted that because it was clear from the start that their children would not continue the farming business, they did not encourage succession, wishing not to impose it upon them. *'There is no forcing or persuading from my side either, because at this age you want to try many new and interesting things, especially if something attracts you. So I'm not trying to convince him at this moment'* (Farms P1–P5). For example, the owner of Farm P2 has never planned to pass the farm on to her children; importantly, she currently does not see a long-term future for agriculture at all, which undoubtedly influences her opinion and possibilities regarding succession. However, some responses show that parents emphasize that succession is not possible if a young person does not have a particular liking or interest in this field. They admit that they themselves truly enjoy and love what they do, and seeing that their children do not have this emotional attachment, it becomes clear that there is no need to push for something that is not there. One must engage in what one likes, rather than trying to convince someone that family inheritance is more important than individual interests. Nevertheless, all owners acknowledge that they are very grateful for and appreciate their children's involvement in any kind of farming activity.

'It is clear to me that no one here will take over the agricultural activity. It will last only as long as we are able to do something' (Farms P1–P5).

The continuation of farm activity is also linked to children's life priorities. *'One of the aspects of taking over, inheriting, or starting – however you call it – is that you tie yourself down. To the place, to the machinery, to the work, to the fields. If you need it and you want it – you do it! If not, then it's not worth it'* (Farms P1–P5). The contrast between rural life and urban opportunities is a significant issue. In the interview with the younger generation representative Farm P2, informant B, it becomes clear that the young person is aware that he would definitely not want to make agricultural activity his main occupation or source of income. It is important to note that Farm P2, informant B has been involved in farm work since childhood and still helps his parents in his free time. He admits that although he likes life and the peace of the countryside, he feels that *'having grown up in the countryside, I miss the city environment more'*. Longing for the urban environment is just one of the reasons why Farm P2, informant B indicated that he does not wish to continue agriculture as his main occupation; he revealed that, in his opinion, he would eventually grow tired of it and simply burn out. In the interview, he also said that *'in my case, I had to help the farm compulsorily, because there was simply no other choice'* (Farm P2, informant B).

Farmers often entrust farm work and responsibility to family members. However, this may also pose a risk to the continuation of farming. *'Everything happens within the family. We haven't really thought about employees. But if the children at some point go their own way, we will have problems'* (Farms P1–P5). Moreover, this responsibility in a sense ties a person to a particular place and to farming as a form of service for various reasons. *'One of the aspects of taking over, inheriting, or starting – however you call it – is that you tie yourself down. To the place, to the machinery, to the work, to the fields. If you need it and you want it – you do it! If not, then it's not worth it'* (Farms P1–P5).

Some representatives of the older generation acknowledge that children decide not to take over the farm, and this is perceived not as disappointment but as reality. *'The children work elsewhere. It's not bad. I suppose that's how it is – everyone has their own life. As long as we can, we work'*. There are farms that state that if there is no successor, a pragmatic decision is made to partially scale down the farm or transfer it to other persons.

Policies can be more effective if they address not only economic viability but also the social and demographic dimensions of farm succession. Ireland's farm partnership model, particularly Registered Farm Partnerships (RFPs), demonstrates a successful approach by reducing older farmers' workload while gradually integrating younger farmers into management. By supporting joint management and providing targeted financial incentives, RFPs facilitate intergenerational transfer, address labour challenges, and encourage early involvement of potential successors (Loughrey et al., 2024). While alternative structures can support generational renewal, their effectiveness depends on the economic viability of the farm. Therefore, policies should adopt a dual approach: promoting alternative business models both in economically strong systems and in lower-income farms where cooperation may enhance sustainability. At the same time, further research is needed to assess these structures from both economic and social sustainability perspectives, particularly in the context of generational renewal (Shin et al., 2023).

Continued research and systematic data collection are needed to further refine and target succession policies.

Conclusions

Farm succession is a significant component of farming resilience in Latvia.

1. Succession in rural farms is not only the transfer of material assets, but also the inheritance of knowledge, identity, and way of life. In Latvia, this process faces several challenges and limitations, but there are also clearly identifiable facilitating factors.

2. Main barriers to generational succession in small farms are: demographic pressure – an ageing farming

population and an insufficient new generation of farmers, as indicated, in rural areas the number of farm owners aged over 65 is increasing, while the proportion of young farmers (under 35) remains low; lack of youth motivation – many young people, even if involved in farm work, choose careers in cities or in other sectors such as culture, digital industries, or services, many of them perceive agriculture as an emotionally, physically, and economically demanding profession; insufficient economic incentives – low income levels, high risks, and limited access to financing make farming less attractive as a career choice; lack of family pressure or a clear succession offer – interviews reveal that many farm owners do not wish to impose the continuation of the farm on their children; however, at the same time, a concrete succession plan is often absent – the transition process is postponed or does not take place at all.

3. Factors, facilitating generational succession in small farms are: early involvement of children in farm work – experience shows that children who are engaged in daily farm activities from an early age are more likely to develop an emotional attachment to the farm and later choose to inherit it; alignment of field of study and targeted education – education related to agriculture or farm management strengthens the likelihood of successful succession

4. A 'partnership' approach to succession (example from Ireland) – intergenerational cooperation, where young people gradually assume leadership while the older generation retains some influence and ensures a smooth transition, could be considered an effective model also in the Latvian context.

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SOCIAL ENTERPRISES IN LATVIA: AN UNTAPPED RESOURCE FOR COMMUNITY SOCIAL WORK IN RURAL AREAS

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Abstract
This article examines the contribution of social enterprises to community social work in rural Latvia. It analyses how social enterprises mobilise local resources and support community-oriented practice in rural municipalities. The study seeks to: (1) identify the principal domains of community resources activated by social enterprises; (2) compare the forms of social impact generated in two rural municipalities and (3) assess their potential to strengthen community social work through cooperation with local welfare systems. The research is situated within recent pressures on Latvian social work, including the humanitarian consequences of the war in Ukraine, which have intensified the need for preventive, community-oriented, and resource-mobilising approaches. A comparative case study was conducted of two social enterprises: Ltd. *Majas TUVU* in Jelgava Municipality and Ltd. *Visi Var* in Sigulda Municipality. Data were generated through contextual desk research and in-depth qualitative interviews with key organisational actors. The analysis examined seven community resource domains: income and employment; housing; health care and psychosocial rehabilitation; transport access; family support; leisure and personal development; and civic participation and leadership. The findings reveal two complementary pathways of impact: a micro-level model centred on family support, youth participation, and accessible community spaces, and a system-oriented model based on advocacy, demonstrable impact, and intersectoral coordination. The article concludes that social enterprises can strengthen community social work in rural Latvia when effectively integrated into local governance and welfare support systems.
Keywords: social work, community social work, social entrepreneurship, rural Latvia, comparative case study.

Introduction

Social entrepreneurship is increasingly recognised as a means of addressing social inequality, mobilising local resources, and creating innovative responses to unmet needs. Yet its relevance to social work remains insufficiently explored, particularly in rural and community-based contexts. In Latvia, this question has gained urgency. Social work practice has been shaped in recent years by the long-term shortage of human resources in municipal social service agencies (Baltic Institute of Social Sciences, 2023) and by the humanitarian implications of the war in Ukraine. These pressures have exposed the limits of predominantly micro-level and reactive service responses and have strengthened the case for more preventive, community-oriented, and locally embedded approaches.

In this article, community social work is understood as a form of social work practice in which communities constitute both the setting and the focus of intervention. It seeks to strengthen participation, mobilise local resources, develop responsive support systems, and address the structural and relational conditions that shape collective well-being at the local level (Weil, 1996). This understanding is consistent with community practice scholarship in social work and with the profession's broader commitment to social change, social development, social cohesion, and empowerment (International Federation of Social Workers (IFSW), 2014; Weil, 1996).

In this context, social enterprises deserve closer attention. They can complement public and nonprofit provision by combining social mission with organisational flexibility, resource diversification, and local embeddedness. As previous scholarship suggests, collaboration between social work and social entrepreneurship can widen the range of available interventions, strengthen labour-market inclusion, and support community cohesion while maintaining a focus on rights, participation, and empowerment (Berzin, 2012; European Commission, 2011; Germak & Singh, 2010; Godwin et al., 2022; Gray et al., 2003; OECD & European Union, 2017). Social enterprises may therefore function not only as service providers but also as community actors capable of sustaining social infrastructure, building partnerships, and translating social policy goals into situated practice.

This article examines how social enterprises contribute to community social work in rural Latvia. It focuses on two study organisations (units of analysis) that already operate in collaborative environments involving local municipalities and social service systems. Following Hepworth et al. (2017), the analysis is structured around seven community resource domains: income and employment, housing, health care and psychosocial rehabilitation, transport, family support, leisure and personal development, and civic participation and leadership. The article addresses the question of *how social enterprises mobilise local resources for the benefit of the local population, and what this reveals about their role in community social work?*

Materials and Methods

This study employs a comparative case study design. A case study approach is appropriate for examining a bounded social phenomenon within its real-life context, especially when the phenomenon cannot be meaningfully separated from the institutional, social, and territorial conditions in which it occurs (Creswell et al., 2007; Stake, 1995; Yin, 2018). In community social work, this design enables close attention to the interplay between local actors, service systems, relationships, and resources.

The two units of analysis were selected purposively. Both organisations have more than ten years of local embeddedness or sustained situated experience, and both have established patterns of interaction with local municipalities, especially social service agencies. The study draws on two interconnected sources of evidence: desk-based contextual mapping and qualitative in-depth interviews with key actors in the selected social enterprises. Contextual mapping covered the main features of the local setting, including population profile, service ecosystem, institutional environment, and relevant risks and assets. The interviews explored how the organisations create, strengthen, and connect community resources.

The analysis was structured through seven resource (7R) domains: (1) income security and employment, (2) housing, (3) health care and psychosocial rehabilitation, (4) transportation access, (5) family support, (6) leisure and personal development opportunities, and (7) civic participation and leadership.

A phenomenologically informed approach guided the interpretation of the qualitative interview material, with particular attention to participants' lived experience, everyday meaning-making, and their own understandings of practice (Raza, 2024). In methodological terms, this meant that the analysis began not with predefined explanatory categories, but with close reading of how interviewees described their work, relationships, decisions, and challenges in their own terms. The researcher sought to remain attentive to the meanings participants attributed to their experiences, especially where these illuminated how social enterprises were enacted in everyday community settings. Phenomenological principles shaped the analytic process in three ways. First, during data interpretation, priority was given to first-person accounts and experience-near descriptions rather than to externally imposed classifications. Second, the researcher engaged in a process of analytic reduction by identifying the most significant meanings and recurrent experiential elements within each interview, while bracketing, as far as possible, premature normative or theoretical judgements. Third, these condensed meaning units were clustered into broader interpretive categories that captured shared patterns across cases. Only after this phenomenologically informed stage was completed was the material coded thematically, enabling the identification of recurring patterns in organisational orientation, forms of support, collaboration, and sustainability. In this way, phenomenology informed the interpretive logic of the analysis, while thematic coding provided the cross-case analytical structure. Comparative analysis was used not simply to list similarities and differences, but to interpret how distinct local contexts shape different forms of community-oriented practice (George & Bennett, 2005).

Results and Discussion

Case 1: Ltd. Majas TUVU in Jelgava Municipality

Jelgava Municipality represents a large and predominantly rural service territory characterised by spatial dispersion and agricultural settlement patterns. The municipality describes itself as a typical agricultural area, with 67.6% of land used for agriculture, while forests cover about 26% (Municipality of Jelgava County, n.d.). Jelgava Municipality has a population of 32,751 (as of 1 January 2026), and the municipality notes a longer-term population decline since 2008, reflecting wider demographic trends in Latvia (Municipality of Jelgava County, n.d.). This suggests a context where ageing, outmigration, and uneven service accessibility may be important community-level considerations, especially across dispersed rural settlements. Institutionally, the municipality has a broad local governance structure with dedicated sectors for social affairs, health, education, culture, civil protection, and public participation. Its Social service agency is explicitly tasked with providing and administering social assistance and social services for residents.

In such a context, mobility, access to services, and the availability of community-based infrastructure are central to everyday wellbeing and service delivery. Within this rural and spatially dispersed service context, Ltd. *Majas TUVU* can be interpreted as a hybrid form of community social infrastructure rather than merely a charitable initiative. Its significance lies not only in the range of activities it provides—material assistance, youth work, educational and cultural events, and locally embedded community spaces—but in the way these activities are combined to address several community resource domains simultaneously. Analytically, the case is important because it shows how a social enterprise can bridge immediate crisis support with longer-term developmental aims. The organisation does not only respond to need; it also creates conditions for participation, belonging, and gradual movement away from dependency from social assisstance. In this sense, its contribution is best understood as community-oriented social work enacted through a hybrid organisational model that links charitable support, social participation, and income-generating activity within one locally grounded ecosystem.

The organization fits the concept of community social work through social enterprise, because it combines direct social support, community participation, and resource mobilisation across sectors. First, it addresses immediate needs through material assistance and crisis support, which aligns with community social work's practical and relational orientation. Second, it builds participatory community spaces through youth evenings, camps, and cultural activities, suggesting an emphasis on prevention, belonging, and social inclusion

rather than crisis response alone. Third, its use of charity shop and cultural venue as income-generating and community-building mechanisms: it reflects a hybrid model in which commercial and event-based activity helps sustain charitable and developmental work. The organisation's own description of volunteer engagement, donation logistics, youth programming, and partnerships with supporters indicates a model rooted in collective action, local embeddedness, and social solidarity. In this sense, Ltd. *Majas TUVU* can be interpreted not only as a charity, but as a community-based social infrastructure that links material aid, youth development, civic participation, and social-enterprise mechanisms within one locally grounded ecosystem.

The thematic analysis of interviews with two board members (BM1, BM2) of this social enterprise identified several interrelated themes that illuminate the organisation's practice orientation, support model, collaborative dynamics, community contribution, and sustainability challenges.

The first major theme in this case is **mission-driven work**. The interview material suggests that the organisation's activities are grounded in a strong ethical and value-based orientation. Work is described not merely as an occupation but as a meaningful commitment to improving lives and sustaining community solidarity: *'...the work itself is already the meaning of it all — indeed, the meaning of life…'* (BM2). This mission orientation appears to support organisational persistence in the typical rural settings with ageing, outmigration, and uneven service accessibility, where outcomes are often long-term, indirect, and not immediately visible.

A second theme is the **evolution of family support towards greater sustainability**. The organisation appears to have moved from highly intensive outreach-based practices towards a more structured model in which families access support on site and exercise greater choice over the resources they use. This shift suggests organisational learning: support becomes less emotionally exhausting for staff, more sustainable institutionally, and more enabling for service users. In terms of the 7R framework, this case shows especially strong contribution in **family support,** where the organisation supplements the work of municipal social service agency in providing diversified social assistance and social services for residents **(7R5)**.

A third theme concerns **boundaries and the management of dependency risks**. Support is not framed as unconditional provision, but as balanced assistance shaped by clear expectations and shared responsibility. Particularly in work with children and young people, the organisation emphasises participation, responsibility, and active engagement rather than passive receipt: *'…profit is directed towards the child's rehabilitation…'* (BM1).

This reflects a developmental rather than purely compensatory logic.

A fourth theme is **person-centred collaboration**. Effective cooperation with institutions often depends on the initiative of particular professionals rather than on stable systemic arrangements. This relational strength can support rapid response and mutual trust, but it also introduces fragility when collaboration remains insufficiently institutionalised.

The fifth major theme concerns **organisational sustainability**. Future development is connected with infrastructure improvements and the exploration of new operational formats, indicating an orientation towards growth and adaptation. However, this future-oriented perspective is constrained by several structural challenges, including staff shortages, dependence on project-based funding, taxation pressures, and limited financial-administrative capacity. Sustainability is not solely a matter of programme design but is also deeply shaped by organisational resources and the wider administrative environment. Stronger strategic, financial, and administrative support is necessary to ensure long-term organisational resilience. Informants emphasized *'Communication skills and the ability to resolve crisis situations'. (..) 'to hire professionals who are more knowledgeable than oneself....'* (BM2).

Taken together, the case suggests that *Majas TUVU* contributes to community social work less through formal service specialisation than through relational embeddedness and the capacity to combine practical help with developmental participation. Its strongest contribution lies in **7R5 (family support)** and **7R6–7R7 (leisure, personal development, and civic participation)**, while its creation of a safe and supportive environment also has indirect relevance for **7R3 (health and psychosocial rehabilitation)**. The analytical significance of the case therefore lies in showing that social enterprises may extend community social work not only by filling service gaps, but by sustaining locally meaningful spaces in which support, participation, and socialisation are interwoven.

Case 2: Ltd. Visi Var in Sigulda Municipality

Sigulda Municipality presents a different context: a mixed urban-rural and comparatively polycentric territory with a stronger development profile, a more stable demographic situation, and a relatively networked institutional environment. It was shaped by the 2021 territorial reform, and currently includes Sigulda town together with Allazi, Incukalns, Krimulda, Ledurga, Malpils, More, and Sigulda parish (Siguldas novada pasvaldiba, n.d.). This creates a municipality with both a strong central town and several surrounding parish communities, making it territorially more polycentric than a single-town municipality. Sigulda community profile combines residential life, tourism, recreation, and heritage-based local identity. Sigulda Municipality had 31,480 declared residents in 2025 (according to Official Statistics Portal, n.d.), with a slight decrease over the previous year. That suggests a comparatively stable

demographic profile by Latvian municipal standards. Institutionally, Sigulda Municipality presents a relatively developed and modern local governance profile. Its Social service agency provides social assistance, social work, services for families with children, services for adults, individual consultations, and explicitly includes community social work in cooperation with state institutions, municipal bodies, NGOs, and other actors. In addition, the municipality maintains open data sets in areas such as residents and society, education and sports, tourism, and council work, which suggests a comparatively transparent and data-aware institutional culture (Municipality of Sigulda County, n.d.).

Ltd. *Visi Var* functions as a work-integration social enterprise closely linked to the NGO *Ceribu sparni*. Established in Sigulda on 30 January 2018, the enterprise defines its primary aim as promoting the employment of people with disabilities, their relatives, and other socially vulnerable groups. Within the comparatively networked setting of Sigulda Municipality, Ltd. *Visi Var* illustrates a different configuration of social-enterprise practice. Rather than primarily building community space through relational proximity, the organisation operates through work integration, cross-sector partnership, and the redistribution of earned income into social support activities. Its analytical importance lies in the way it links labour-market participation, inclusion, and organisational coordination. The enterprise should therefore be understood not simply as a business with a social purpose, but as a community-based mechanism for translating economic activity into employment access, practical support, and institutionally recognisable forms of social value. This makes the case particularly relevant for examining how social entrepreneurship can function as a system-facing component of community social work.

The thematic analysis of interview with a chair of the board (CB) of this social enterprise identified several interrelated themes that illuminate the organisation's community contribution, social impact logic, and sustainability challenges.

The first key theme in this case is **social impact as a continuous cycle of evidencing**. The interviewee does not describe impact in abstract terms, but as a set of concrete effects distributed across community resource domains. These include support for parental employment, continuity of services for families, and indirect contributions to psychosocial stability and rehabilitation: *'...more than 90% of parents ... are employed. And this is thanks to the fact that these services exist…'* (CB). At the same time, these outcomes do not automatically translate into recognised public value. They must be repeatedly demonstrated through data, feedback, and outcome narratives. The case thus highlights how impact becomes both a substantive achievement and an institutional requirement.

The second theme is **the human factor in the sustainability of collaboration**. Civic participation, leadership, and networked cooperation depend heavily on specific individuals with commitment, initiative, and relational credibility. The interviewee's account of the disappearance of regular NGO meetings after a leadership change illustrates the fragility of collaborative structures that are not institutionally anchored. *'The human factor is very important ... whether a person will truly carry out this work wholeheartedly…'* (CB). This suggests that community resources may be undermined not only by material scarcity but by discontinuities in governance and partnership routines.

A third theme is **hybrid competence and crisis responsiveness**. The case demonstrates the capacity of the social enterprise to operate as a flexible community actor under conditions of uncertainty. In the context of support for refugees from Ukraine, the organisation mobilised practical assistance, logistics, transport coordination, documentation support, and volunteer action. *'... from the very first week ... we collected and delivered loads to Ukraine…'* (CB). This indicates that its contribution extends beyond employment inclusion alone. It functions as a local resilience actor able to connect formal and informal support mechanisms in crisis conditions.

Overall, the case demonstrates that *Visi Var* operates not only as a work-integration social enterprise but also as a locally embedded coordination actor. Its strongest contribution lies in **7R1 (income and employment)**, **7R3 (health and psychosocial rehabilitation)**, and **7R7 (civic participation, leadership, and advocacy)**, while its crisis-related actions also show relevance for housing, transport, and family support. The broader analytical implication is that social enterprises may contribute to community social work through institutionally legible forms of impact—employment, advocacy, and crisis coordination—while remaining anchored in community-based support relations.

Discussion: Two complementary pathways of community-oriented social impact

The comparison points to two distinct yet complementary pathways of community-oriented social impact.

The first pathway, exemplified by *Majas TUVU*, is a **micro-level community support model**. Here, social impact is generated through direct engagement with families, youth work, community events, and practical everyday support. The organisation's contribution lies in the cultivation of accessible spaces, psychosocial safety, and development-oriented participation. Its strength is proximity: it is embedded in the rhythms of local life and responds through relational, preventive, and participatory practices.

The second pathway, exemplified by *Visi Var*, is a **system-oriented impact and advocacy model**. In this case, social value is articulated through demonstrable

outcomes, strategic partnerships, employment inclusion, and policy-facing legitimacy. The organisation's strength lies in its capacity to translate local social needs into recognisable institutional claims while also acting flexibly in crises.

Across both cases, several broader analytical points emerge.

First, **mission-driven practice remains central**, but it operates under conditions in which outcomes are often difficult to measure or render visible. This creates a tension between relational work and the demand for evidence. Social enterprises must therefore sustain both ethical commitment and organisational legibility.

Second, **collaboration remains overly person dependent**. Informal trust and proactive individuals can enable strong cooperation, yet they do not guarantee continuity. For community social work, this suggests the need to move from relational dependence to more formalised and durable partnership structures.

Third, **adaptive service design matters**. The movement from intensive outreach to more choice-oriented and sustainable support models in the first case illustrates how organisations refine practice to balance care, empowerment, and staff sustainability. In the second case, hybrid competences make it possible to combine inclusion, advocacy, and crisis responsiveness within one organisational form.

Fourth, the **7R framework helps clarify differentiated resource profiles**. The first case is especially strong in family support and participation-oriented resource development; the second is stronger in employment-related, advocacy-oriented, and institutionally legible forms of impact. Taken together, the cases suggest that social enterprises can broaden the repertoire of community social work by linking practical support, participation, employment, advocacy, and resilience.

At the same time, the findings also indicate that social entrepreneurship should not be treated uncritically as an inherently positive solution for community social work. The empirical material points to several vulnerabilities already visible in both cases: dependence on project-based or unstable income streams, limited financial-administrative capacity, staff shortages, person-dependent collaboration, and the continuing burden of evidencing social value. These issues suggest that hybridity creates opportunities, but also structural tensions. The literature on social enterprise has repeatedly shown that organisations combining social and commercial logics are exposed to risks of mission drift, accountability imbalance, and internal trade-offs between financial survival and social purpose (Cornforth, 2014; Doherty et al., 2014; Ebrahim et al., 2014). In the present study, these risks do not appear as fully developed mission drift, but rather as pressures that may narrow organisational autonomy, redirect attention toward measurable outputs, or make community-oriented work overly dependent on exceptional individuals.

From a community social work perspective, this is important because market-oriented instruments do not automatically strengthen local welfare ecologies. Where funding is unstable, reporting burdens are high, or cooperation remains informal, social enterprises may be pushed toward short-term deliverables and administratively legible outcomes at the expense of slower relational work, prevention, and community trust-building. Thus, the cases support a more balanced interpretation: social enterprises can extend the repertoire of community social work, but their contribution is contingent on institutional conditions that protect the social mission, recognise relational outcomes, and distribute risk more fairly across local welfare partnerships.

Conclusions

1. This article has argued that social enterprises constitute an underused resource for community social work in rural Latvia. The comparative analysis demonstrates that they can do more than supplement existing services. They can act as locally embedded, hybrid actors that mobilise resources, create meaningful participation, support inclusion, and respond flexibly to emerging needs.

2. The two study organisations illuminate different but compatible forms of contribution. One operates primarily through community presence, family support, youth development, and participatory space-making. The other operates through work integration, advocacy, evidence-based legitimation, and crisis responsiveness. Together, the two cases suggest that social enterprises may strengthen rural welfare ecosystems not only by filling service gaps, but by extending the practice repertoire of community social work through resource mobilisation, participation, and coordination; however, this contribution remains conditional on stable partnerships, adequate administrative capacity, and protection of the social mission from excessive market and reporting pressures. At the same time, their potential is constrained by weak institutionalisation of collaboration, administrative burdens, and uneven recognition in local governance.

3. This suggests several practical implications.

(1) The findings suggest that social work development benefits from integrating micro-level community practice (relational support, empowerment, participation) with system-level governance capacities (institutional coordination, advocacy, and impact reporting). When these dimensions are disconnected, micro-level initiatives risk remaining fragile and under-recognised, while system-level frameworks risk becoming procedural and detached from lived realities. A combined model supports both responsiveness (to immediate needs) and scalability (through stable cooperation and policy alignment). Municipalities and social service agencies should develop more formal cooperation infrastructures with social enterprises, including clearer referral pathways, regular

partnership forums, and shared feedback mechanisms. (2) In policy terms, a shared 'minimum package' for impact measurement can strengthen sustainability without imposing excessive administrative burden. A small set of jointly agreed indicators (e.g., employment-related outcomes, continuity of support, participation frequency, wellbeing self-assessments, and reduced crisis recurrence) can improve decision-making transparency and stabilise funding relationships, particularly in contexts where political priorities shift. Importantly, quantitative indicators should be complemented with short qualitative accounts to preserve the meaning of relational and developmental outcomes. A light but common impact framework could also help stabilise recognition and funding without reducing relational outcomes to narrow metrics. (3) Comparative evidence supports an expanded role for the community social worker as coordinator, mediator, and advocate. At the local level, this role centres on mapping resources, guiding referrals, and building trust across stakeholders. At the municipal level, it includes translating community realities into policy-relevant narratives and supporting institutional learning through evidence and partnership development. This dual positioning can help bridge the gap between everyday practice and system-level governance. (4) Finally, the sustainability of community-oriented social initiatives depends on strengthening hybrid competencies: communication and de-escalation skills, project and financial management, data-informed reporting, and crisis management.

4. For community social work theory, the findings suggest that social enterprises should be understood not only as market-based innovations, but as community actors embedded in local welfare ecologies. Their significance lies in their capacity to link social mission, practical action, and relational infrastructure in ways that are especially valuable in rural and changing environments.

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POLITICAL DIMENSION FOR PUBLIC ENGAGEMENT IN REGIONAL DEVELOPMENT AND RESILIENCE

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Abstract
Public engagement plays a pivotal role in promoting sustainable development at international, European Union, and national levels, including the pursuit of innovative growth models for territorial, regional, and community resilience. It is crucial for implementing nature-based solutions that address social, economic, and environmental challenges, while building resilient communities in line with EU policies and global sustainability goals. Academic interest in regional economic resilience has surged since the 2008 financial crisis, though debates persist over its definition and measurement. Early studies focused on economic output indicators, but recent work incorporates sociodemographic factors. Future research must dynamically assess resilience drivers to deepen understanding. Resilience on the regional scale is inherently relational, intertwining individual, social, governance, and economic dimensions. Community resilience, in turn, depends on connections to broader regional and systemic factors particularly through local engagement with governance structures, economic systems, and social networks. This study examines the concepts of regional development and resilience through multi-dimensional, participatory, and systemic lenses, embedding community dynamics within regional governance. Its objective is to analyze the theoretical, political, and regulatory dimensions of public involvement in territorial development and resilience. By integrating monographic (descriptive), synthesis, and analysis methods, the study advances a nuanced understanding of participation dynamics in these domains.
Keywords: sustainable development, resilience, public engagement, community, regional development.

Introduction

Public engagement's role is an integral part of sustainable development concept emphasized at the international, European Union, and national levels promoting inclusive policies and decision-making process and development of specific approaches related to regional, urban and rural development. One of the main principles of the United Nations Sustainable Development Goals is public engagement at all levels. The European Union underscores the importance of public participation in territorial and local development strategies to foster ownership, collective commitment, and stakeholder dialogue (Publications Office of the European Union, 2022).

Latvia's National Development Plan for 2021–2027 emphasizes advances in technology, public administration, and civic engagement, highlighting citizen involvement as pivotal to economic growth (State Chancellery, 2024).

Regional development must address globalization's challenges, economic inequality, and territorial competition by prioritizing sustainable, holistic, and forward-looking strategies (Pike et al., 2016).

Evolution of the concept of regional resilience has obtained growing academic interest, especially due to the economic crisis in 2008. The debates still exist on the definition of regional resilience and its measurements, but the current studies have put the focus not only on the economic indicators but have been expanded to the sociodemographic factors dynamically accessing resilience and its drivers (Crawley et al., 2025). Participation, social networks, mental health, and well-being are indicated as elements building resilience (Weitzel et al., 2022).

The objective of this study is to analyze the theoretical, political, and regulatory dimensions of public involvement in territorial development and resilience for nuanced understanding of participation dynamics in these domains.

Materials and Methods

The study employed descriptive methods by analytical mapping of theoretical, political, and regulatory dimensions of public engagement in territorial development and resilience. The study design includes a literature review, a conceptual-analytical approach, and the formulation of conclusions. The literature reviewed includes scientific publications, monographs, studies and articles from international organizations, EU and Latvian policy planning documents, reports, commissioned studies from Latvian institutions, and relevant Latvian regulatory enactments. This research paper was supported using artificial intelligence (AI) tools. ChatGPT (Mar 14 version) [large language model], developed by OpenAI, 2024, was used exclusively for language editing, translation, and improvement of linguistic quality. The scientific content, research design, conceptual development, and critical analyses were entirely created, structured, and validated by the authors. No generative AI tools were used for the creation of scientific content, formulation of research ideas, or development of research approaches presented in this paper.

Results and Discussion

Researchers' interest in civil society and its interactions with the state has grown, increasingly highlighting the interconnectedness of public and private spheres. Public participation plays a key role in supporting public administration and territorial development, as highlighted in both academic research and policy documents. Ravazzoli et al. (2021) define community as a group bound by shared territory or

interests, contrasting it with society as a larger, heterogeneous, organized collective. This distinction is relevant in rural contexts, where their work on commons explores how socioeconomic changes challenge traditional community-based resource management (Ravazolli et al, 2021).

Theoretical dimensions

Macroeconomics theories exploring the growth factors start with the aggregated production function relating two factors of production: capital and labour. Increases in output per worker are related with capital accumulation and technological progress (Blanchard, 2006).

The analysis of the drivers of economic growth across European Union (hereinafter - EU) highlights multi-scalar factors like labour productivity, foreign direct investments, and innovation as key to sustainable development. Growth varies spatially: core regions leverage infrastructure and innovation proximity, while peripheries depend on migration and public investment. Boldeanu stresses related variety and social filters (e.g., human capital) for adaptive territorial paths. The necessity to develop targeted cohesion policies enhancing productivity and connectivity, noting no single model fits all scales, is identified. The role of the state is examined as a key public sector determinant influencing economic growth across EU country, regional, and metropolitan levels (Boldeanu, 2018).

The concept of resilience has transformed from an ecological term into an idiom of global governance, influencing different fields, for example, international finance, economic policy, national security, urban planning, etc. Rooted in 1970s systems ecology, resilience now serves as an operational strategy for management in circumstances defined by unpredictable, endogenous crises. Scientific genealogy of resilience begins with the ecologist Holling. He was seeking for management approach capable of sustaining productivity even under conditions of extreme instability. Later he introduced the adaptive cycle consisting of four stages: growth, conservation, collapse, and reorganization, suggesting that it is not an end but a necessary stage for renewal. Like Holling, Hayek rejected the idea that external actors could predict or control complex systems arguing that any attempt by the state to engineer stability would only lead to more profound crises. The evolution of resilience theory represents a shift from the focus on control toward a world where disequilibrium is the organizing principle. By naturalizing crisis, resilience functions presenting adaptation to catastrophe as an inescapable necessity (Walker & Cooper, 2011). The 2008 economic crisis sparked research interest in adaptive models for sustainable development while elevating resilience as a core element of regional development. This shift moved beyond recovery-focused approaches to emphasize long-term adaptive capacities in territories. The global financial crisis exposed regional vulnerabilities, stimulating researchers to advocate evolutionary perspectives on resilience, integrating path dependence and branching for territorial renewal. Studies across Europe and beyond analysed resistance, recovery, and renewal phases, revealing spatial disparities and marking new vector from static models to dynamic ones incorporating social capital and public engagement as resilience drivers. Resilience became integral by addressing uneven crisis impacts. In territorial contexts, it supports sustainable development through opportunities for restructuring, countering lock-ins through flexible networks and institutions indicating social capital's role in collective mobilization. (Boschma, 2015). Social capital and public participation emerged as enablers, fostering community-driven adaptation in fragile areas. Engaged publics channel trust into governance, enhancing institutional agility for green transitions and equitable growth.

While debates still exist on the definition of regional resilience and its place in the context of territorial development, researchers put efforts to explore the factors influencing and shaping the metrics measuring the resilience of territorial development. Crawley et al. 2025) provide a systematic review of regional resilience metrics through bibliographic and cluster analysis, emphasizing measurement frameworks relevant to territorial development. It highlights challenges in quantifying adaptive capacities while underscoring public engagement's indirect role in resilience-building. The authors apply cluster algorithms to identify dominant metric themes like gross domestic product (GDP) recovery rates, employment volatility, and diversification indices. In territorial contexts, they cluster metrics around economic resistance (shock absorption) and adaptability (post-shock renewal), noting gaps in spatially explicit indicators for rural or peripheral regions. Public engagement appears peripherally in social dimension clusters through proxies like civic participation rates or trust (Crawley et al., 2025).

The scope of researchers explores how public participation strengthens community resilience as a dynamic social process during polycrises, directly applicable to territorial development by framing communities as adaptive units in spatial planning. Kirby develops an indicator-based assessment breaking resilience into interdependent dimensions: individual, social, governance, and economic, positioned as proactive resource mobilization for uncertainty. Participation emerges as a key enabler, fostering collective action that integrates local knowledge into territorial strategies. Participation promotes resilience by empowering communities to navigate change. In public engagement contexts, it builds self-organization, enhancing territorial adaptability through bottom-up input that balances immediate needs with sustainable future (Kirby, 2025).

Political dimensions

Public engagement plays a central role in sustainable

development frameworks across different scales: from international agendas to EU policies and national strategies by implementing inclusive approaches to policymaking, decision-making processes, and tailored solutions for regional, urban, and rural areas. Inclusive principle promotes ownership and collective commitment, aligning with principles like 'leaving no one behind' in the United Nations Sustainable Development Goals (hereinafter - SDGs), particularly SDG 16 (peace, justice, and strong institutions) and SDG 17 (partnerships for the goals) (United Nations, 2015, 2024).

International level

The need for adaptive, place-based strategies focusing local natural, cultural etc. to foster resilience in the uncertain environment, as well as coordination across national and subnational levels, engaging civil society and non-governmental organizations (hereinafter – NGO) for inclusive roadmaps is indicated for post shock recovery by Organisation for Economic Co-operation and Development (hereinafter - OECD). The regions face challenges in a global environment affected by post-COVID recovery, geopolitical disruptions like Russia's invasion of Ukraine, energy crises, digital transformation, climate change, and demographic shifts. These external shocks have an impact on territorial disparities. The peripheral and rural areas suffer talent outflows, reduced foreign direct investments, and strained infrastructure. Traditional attractiveness models, overly reliant on globalization benefits, prove insufficient, that is why regions have to build resilience against poly-crises at the same time balancing economic development, sustainability and inclusivity. Proposed attractiveness compass reveals that strengths of regions vary across six domains: economic, connectedness, visitors, environment, wellbeing, housing. Attractiveness should be recognized as the multidimensional and dynamic concept integrating investor, talent, and visitor needs with resident quality of life (OECD, 2023).

In the context of Latvia, the OECD with support of European Commission has evaluated the Latgale region in the context of attractiveness compass six dimensions: natural environment, connectedness, resident well-being, land resilience and housing, cultural and visitor appeal, and economic attractiveness. This study identifies challenges and strengths, develops policy recommendations, and places Latgale as a model for EU border regions highlighting inclusive strategies for post-shock recovery. The areas of best performance in the context of Latgale region and comparing with EU level are digitalization and housing (OECD, 2025a).

Tailored policies to each region's specific needs, challenges, and opportunities are the cornerstone to develop territorial resilience focusing at depopulation and demographic shifts in rural areas. OECD outlines main trends, impacts, and policy recommendations, emphasising adaptation strategies that build territorial resilience in rural areas facing labour shortages, service overcapacity, and fiscal strain. Demographic shifts demand moving beyond growth paradigms to integrated adaptation and mitigation that build territorial resilience. Without action, shrinkage undermines resilience; with it, depopulating places can prioritise liveability, reducing congestion, enhancing shock absorption, and fostering inclusive, low-carbon environments (OECD, 2025b).

The five areas including facilitation of stakeholders' engagement are proposed by OECD for multi-level governance frameworks to support policy makers on the way to developing place-based strategies that foster resilience, inclusiveness and long-term sustainability. The key areas to incorporate principles of good governance and to develop coherent policies are strategically planning, harnessing coordination, innovating governance and fiscal tools, facilitating stakeholder's engagement, and training and retaining skilled public staff (OECD, 2025b).

The Open Government Partnership, in which Latvia has participated since 2011, is based on the following values: openness, accountability and public participation. They are implemented through national plans (Open Government partnership, s.a.).

EU level

A participative and innovative integrated territorial development approach is identified as an essential principle, emphasizing civil society and local community engagement to advance well-being, social trust, good governance, and strategic investments. In the context of external shocks like the COVID-19 pandemic, the resilience of municipalities, regions, and countries plays a crucial role not only in overcoming crises but also in strengthening recovery processes. The Territorial Agenda 2030 of the European Union (hereinafter – Agenda 2020) provides guidelines for spatial planning, pilot projects, and SDG alignment. It emphasizes the necessity for cross-sectoral cooperation and engagement of different stakeholders and actors moving toward sustainable territorial development and reducing disparities and inequalities between people and places (European Commission, 2020).

The diversity of rural areas is a basis which forms the need for locally designed solutions corresponding to specific needs and possibilities of the territory and engagement of rural communities. Empowered communities are the one of the drivers making rural areas stronger in combination with social innovations and social resilience. A long-term Vision for the EU's Rural Areas - Towards stronger, connected, resilient and prosperous rural areas by 2040 (hereinafter – Vision 2040) defines EU's rural areas as a core part of the European way of life. Vision 2040 addresses a broad scope of challenges such as globalisation, population decline and aging, shrinking employment possibilities, and service accessibility., By considering the lessons learnt from the COVID 19 pandemic, the vision aims to build on the opportunities presented by the EU's green and digital transitions (European Commission, 2021).

Vision 2024 sets up ten shared goals grouped into four pillars: stronger, connected, prosperous, and resilient rural area (see Table 1).

To address rural residents' needs and aspirations and to unlock opportunities to draw innovative businesses, secure quality jobs, enhance skills development, improve infrastructure and services, and harness sustainable agriculture alongside diversified economic activities EU has developed two tools: The Rural Pact and EU Rural Action Plan promoting mobilisation of public authorities and stakeholders (European Commission, 2021).

Table 1

Main drivers shaping the future of rural areas for 2040 and the four complementary areas for action

Pillars for the future	Goals for the future of rural areas
Strength	Empowered communities
	Access to services
	Social innovation
Prosperity	Diversification of economic activities
	Sustainable food production
Connection	Digital connectivity
	Transport links and new mobility
Resilience	Resilience to climate changes
	Environmental resilience
	Social resilience

Source: compiled by authors (European Commision, 2021).

EU integrates territorial development and resilience within cohesion policy to promote balanced regional growth in uncertain space facing challenges of globalization, inequality, and external shocks. EU cohesion policy targets economic, social, and territorial cohesion for balanced development. For 2021–2027, it allocates €392 billion (European Commission, 2018).

The concept of resilience is embedded in the regional development model emphasizing the role of the public engagement and empowerment of communities to achieve the goals of sustainable development and environmental and social resilience.

Latvia's situation

Sustainable Development Strategy of Latvia until 2030 (hereinafter - Latvia 2030), approved by the Saeima of the Republic of Latvia in 2010, serves as the principal national long-term development planning document. It identifies key spatial development areas of national interest, including rural development zones, the Baltic Sea coast, the Riga metropolitan area, the eastern border region, and territories of exceptional natural, landscape, and cultural-historical value (Ministry of Smart Administration and Regional Development, formerly Ministry of Regional Development and Local Government Affairs, 2010). Analysis of Latvia 2030's implementation framework reveals limited public participation foreseeing primarily to the roles of social partners and NGOs during the implementation and monitoring phases. In contrast, the planning phase remains the responsibility of local municipalities, regions' administrations, line ministries, and the Cabinet of Ministers (Ministry of Smart Administration and Regional Development (formerly Ministry of Regional Development and Local Government), 2010).

Strengthening community development emerges as a key measure to retain residents, enhance well-being, and foster civic participation in societally critical processes according to the National Development Plan of Latvia for 2021–2027 (hereinafter - NDP 2027), approved by the Saeima on 2 July, 2020. ND P2027 defines a vision of public governance as a two-way process. In this model, citizens and organisations actively propose and drive improvements, while state and local government institutions proactively engage the public, earning trust through effective solutions, openness, and strong reputational integrity (Cross-sectoral Coordination Centre, 2020). NDP 2027's strategic objectives highlights equal opportunities as a cornerstone for advancing social justice across all Latvian regions, while simultaneously boosting productivity, economic stability, and civic engagement. Building mutual and political trust through public involvement is important encompassing not only dialogue with policy makers but also active roles in civil society NGOs. The plan outlines actionable priorities through 2027, including efforts to stabilise urban and rural populations while elevating living standards (Cross-sectoral Coordination Centre, 2020).

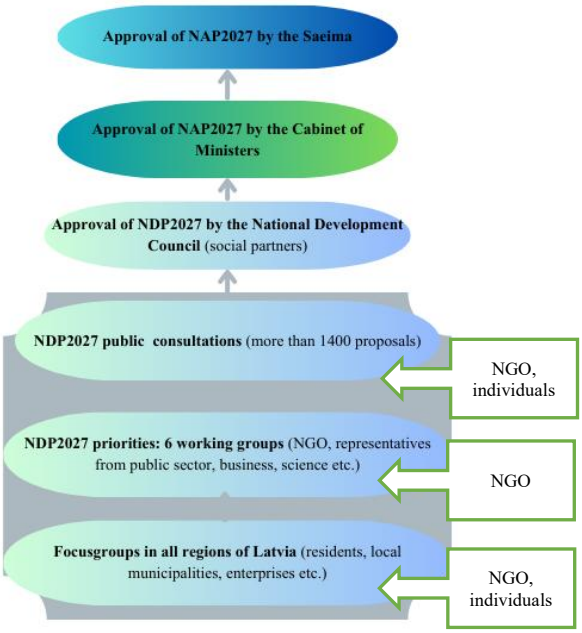
The authors view it as an important point that this national planning document integrates productivity and income growth with regional development and public trust. These outcomes can be advanced directly through substantive public participation across levels, including local municipalities.

Equality of opportunities further strengthens this approach, ensuring engagement not only from proactive citizens and NGOs but also from marginalised groups facing objective barriers (e.g. limited technology access) or subjective ones (e.g. institutional distrust). Over 150 stakeholders including NGO representatives, state and local government officials, academics, and business representatives contributed to NDP 2027's development. Focus group discussions covered all Latvian regions. Examination of preparation progress and planned actions indicates active public involvement: at the planning stage through NGO inputs, and at implementation with allocated resources, including funding (Figure 1).

The broader public involvement to achieve the goals of balanced regional development prioritising engagement from entrepreneurs, civil society groups, and residents is emphasized by the Regional Policy Guidelines for 2021–2027 (hereinafter - Regional Policy), approved by the Cabinet of Ministers on 26 November, 2019. Participation is the one of key

elements to strengthen mutual trust between municipalities and communities, and to mobilise essential territorial development resources. Regional Policy seeks to foster economic potential across all regions reducing socio-economic disparities. Municipalities' openness to collaboration is essential not only in drafting and implementing territorial plans, including support for community - led initiatives, but also in daily routine operations and broader development efforts. The measures include backing community initiatives, advancing a multi-fund approach in Latvia (blending funding streams for local projects), and strengthening ties between municipalities and civil society, notably local action groups and communities. Participatory budgeting empowers residents to shape municipal funding priorities, fostering public trust and indirectly encouraging tax compliance (Ministry of Smart Administration and Regional Development (formerly Ministry of Environmental Protection and Regional Development, 2019)).

Figure 1
Model of public engagement in the preparation of the NDP 2027



Source: compiled by the authors using Canva.com.

Five regional seminars, attended by over 400 participants including civil society and NGOs, has been held during the preparation of the policy (Ministry of Smart Administration and Regional Development (formerly Ministry of Environmental Protection and Regional Development, 2019)). The authors conclude that public involvement was integral at the planning stage and remains embedded in implementation through regional NGO centres and synergies with European Agricultural Fund for Rural Development and European Maritime, Fisheries and Aquaculture Fund (EMFF)-supported activities under community-led local development approaches.

The public participation in decision-making is a priority set up by the Open Government National Action Plan 2026–2027 (hereinafter – Plan), adopted by the Cabinet of Ministers on March 10, 2026. Plan emphasizes clearer communication between public sector institutions and citizens on key issues such as state budget, security, welfare, and health. Implementation focuses on expanding participation among youth, seniors, rural residents, and other underrepresented groups, meanwhile developing civic education in schools and public self-organization skills for addressing shared challenges. A resident survey conducted during the plan development revealed a strong demand for direct communication with governmental institutions, transparent decision explanations, and concise messaging. The plan also incorporates insights from 'Dialogue Circles' discussions on Latvia's development to 2050, which underscored the vital role of communities and rural areas, alongside calls for mutual respect, humane treatment, and opportunities to be heard (State Chancellery, 2026).

Latvia's regulatory framework supports public participation at national, regional, and local levels, including the recent Law on Local Governments. Ministry of Culture commissioned study by SIA 'Civitta Latvia' reveals that current mechanisms primarily engage educated, majority residents, excluding lower-income groups and those with specific needs or characteristics (SIA 'Civitta Latvia', 2023). NGOs and organized civil society play a pivotal role, as regulations and past practices have cantered on direct dialogue with them. To broaden involvement, additional strategies are needed for neighbourhoods and inactive residents. Informal participation is rapidly evolving while local municipalities offer new tools. A key challenge lies in integrating informal engagement into the policy system through identification, support, and monitoring, positioning community initiatives as a foundation for social cohesion (SIA 'Civitta Latvia', 2025).

Although targeted studies exist, for example, the State Chancellery's 2024 public opinion survey on societal resilience (State Chancellery, 2024a), systemic, regularly measurable set of resilience indicators remains essential.

To foster civic dialogue beyond NGOs and to reach unaffiliated citizens, Latvian institutions implement participatory and deliberative methods at the national level:

- The State Chancellery in partnership with NGOs organizes nationwide Dialogue Circles (adapted from Finland) to discuss Latvia's future. This method creates safe, informal spaces that build trust and mutual understanding (State Chancellery, 2025).
- The Ministry of Culture regularly applies deliberative democracy (2022–2024) to issues like cohesive, civically active societies and media policy (Ministry of Culture, s.a.).

These participatory and deliberative approaches have strong potential for spatial planning at national, regional, and local levels, engaging not just civil society but also informal groups and activists. Municipal guidelines and training for officials on these methods would facilitate knowledge transfer and activate informal communities. Municipalities should develop tailored communication plans using diverse channels suited to varied groups: youth, remote rural residents, seniors, and ethnic minorities, to effectively involve the public and NGOs.

Conclusions

1. Academic perspectives on regional resilience have shifted from static economic indicators to dynamic models that incorporate sociodemographic factors, social capital, and public engagement.
2. Public participation is a core principle of the United Nations Sustainable Development Goals promoting inclusive policies and decision-making at international and national levels. It fosters ownership, collective commitment, and stakeholder dialogue, which are essential for long-term territorial development.
3. The need for place-based strategies that engage civil society and NGOs to foster resilience in uncertain environments is emphasized by the OECD. In the context of Latgale region, the OECD highlights inclusive strategies as a model for EU border regions to balance economic development with resident well-being.
4. At the EU level, empowered communities are identified as primary drivers for making rural areas stronger, combined with social innovation and resilience. Long-term Vision for the EU's Rural Areas 2040 establishes development pillars, where community engagement is vital to unlocking local opportunities and addressing demographic shifts.
5. Latvia's National Development Plan 2021–2027 and related policies integrates productivity and income growth with regional development, ensuring that public involvement is integral to achieving social justice and open governance.
6. To move beyond traditional NGO dialogue and reach unaffiliated citizens, Latvia is implementing deliberative methods. A key future challenge is integrating informal participation and community initiatives into the policy system to build stronger social cohesion.

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EMPIRICAL RESULTS OF MENTORSHIP IMPACT ON ACADEMIC PROGRESS AND ATTITUDES OF VETERINARY MEDICINE PRECLINICAL STUDIES

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Abstract
This study investigates the impact of peer-led mentorship on the academic progress and attitudes of first-year veterinary medicine students during their preclinical studies, with a focus on the subject of veterinary biochemistry. Engaging students in practically oriented curricula at an early stage is challenging due to limited opportunities for direct animal interaction, making it essential to foster both interest and a positive learning environment. The research involved voluntary second-year students mentoring first-year cohorts through seminars and consultations, with the effects assessed via examination results, course feedback, and targeted surveys. The analysis revealed that, although the mentorship program did not yield a statistically significant improvement in academic achievement as measured by examination grades, it positively influenced students' attitudes and self-esteem. Participants reported high satisfaction with the mentorship experience and expressed a desire for more extensive and earlier implementation of such programs. The findings align with existing literature indicating that mentorship primarily enhances student confidence, engagement, and integration into university life rather than directly boosting grade performance. Furthermore, the study notes a weak but consistent trend of increased passing rates over recent years, coinciding with improved student perceptions of their ability to achieve learning outcomes. The results suggest that peer-led mentorship is a valuable educational strategy that supports students' positive attitudes toward learning in demanding preclinical settings, even if its direct effect on academic performance is limited. Further development of mentorship structures may optimize their benefits for veterinary medical education.
Keywords: mentorship, peer-led learning, student attitudes.

Introduction

From the perspective of rural development, it is important that employees, including veterinarians, are motivated and well-educated. Engaging students in a curriculum with a practical focus, such as veterinary medicine, at the beginning of their studies is difficult, as preclinical subjects do not provide the opportunity to directly work with animals, and therefore, generating and maintaining interest in students and creating a positive attitude is crucial. There are several methods to promote academic progress and awareness for studies. Our earlier experiences include student activation by using debate (Karl Popper Debate) as groupwork in seminars (Claxton, 2006) and organising study experiments in a specialty from the very beginning of studies (Karus A. & Karus V., 2025); however, such experiments are difficult to organise due to limitations caused by biosafety rules, especially for starting-level students (Järveots et al., 2025). One most common method is to apply mentorship, especially to introduce students to the university and vice versa (Ocupa-Gabrera et al., 2025). In natural sciences, the most commonly used approaches are student-to-student (one-to-one) mentorship and one-to-group (peer-led team learning) (Frey et al., 2018; Wilson & Nelson, 2016) mentorships. Our goal was to enhance the academic progress and raise awareness for biochemistry, and we achieved these goals through peer-led team learning. The aim of this study was to investigate how the peer-led mentorship will help to achieve these goals and to describe the changes in students learning outcomes and their subjective self-esteem and attitude toward the studies overall and to veterinary biochemistry as a preclinical subject.

Materials and Methods

All educational activities were performed according to Regulation of Studies (hereinafter the Regulation), which provides the basis for organising formal study in the Estonian University of Life Sciences (hereinafter the University). The subject of veterinary biochemistry is part of the preclinical studies in the first study year of the veterinary medicine curriculum. It includes lectures, practical laboratory works, seminars and independent work and ends with differentiated assessment (exam) as follows: A grade of 'excellent' reflects a student's ability to use their knowledge and skills creatively and at an advanced level, demonstrating thorough understanding of the subject matter (Regulations…, 2024), B as 'very good' indicates a strong grasp of the learning outcomes, shown through effective and innovative application of knowledge and skills. While the student generally performs at a high level, minor or less significant mistakes may be present in more advanced aspects. C– 'good' – demonstrates a solid attainment of learning outcomes, with appropriate and effective use of knowledge and skills. Some uncertainty or inaccuracy may appear in more detailed or advanced areas; D – 'satisfactory' – meets the basic expectations for learning outcomes, showing the ability to apply knowledge and skills to routine tasks. However, when dealing with unusual situations, noticeable deficiencies and doubts may be evident. The last passing rate E 'sufficient' reflects just meeting the minimum requirements for learning outcomes, with knowledge and skills applied adequately only in standard contexts; when faced with unfamiliar scenarios, significant shortcomings and lack of confidence become apparent, whereas F grade of 'fail' means that the student's understanding and abilities do not meet the basic criteria necessary for passing the course (Regulations…, 2024). Written examination works are assessed independently by two lecturers. In

the event of a difference in results, the final grade will be the grade that is more favourable to the student. Passing rate (PR) is calculated as a percentage of examination grades A-E from all students in the first examination attempts.
Passing rate final (PRf) is calculated as a percentage of passed students (grades A-E) from all registered students after the retake exam (only one regular exam and one retake are allowed per semester)
The success rate is calculated as the proportion of students with 'excellent' and 'very good' grades (A and B) among all students taking the first (regular) exam.
Mentors were selected by teaching staff from volunteers with the final grade in subject C or better. Mentoring was done by voluntary second-year students in the form of peer-led team learning in the form of seminars/consultations in the fall semester 2024, and was followed by an anonymous online survey by Google Forms. Mentoring ended shortly before the first exam.

The student feedback on the study course was anonymously recorded in the university electronic study system (ÕIS) (Study Information System, 2024). Participation in that survey is obligatory for students, and it is done during the following semester.
Total number of students in analysed years was 139 and 38 of them were in mentoring year. The effect of the program on mentors was not assessed, as only two individuals served as mentors, making meaningful analysis unfeasible.

Results and Discussion

The first exam attempt is taken to estimate the direct response on peer-led learning effect. The overall performance did not show a direct and significant effect on examination results. According to literature data, the effect of mentorship can be positive (Frey et al., 2018; Le et al., 2024) or may not cause any or can cause indirect changes (Koziol & Wagner, 2024; Le et al., 2024).

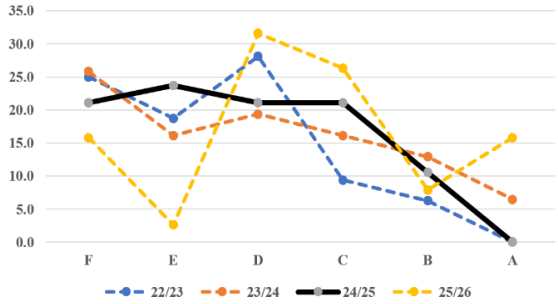
Table 1

The absolute numbers of exam results, passing and success rates (%); (mentoring year is highlighted)

Exam results	22/23	23/24	24/25	25/26
n (Total)	32	31	38	38
F	8	8	8	6
E	6	5	9	1
D	9	6	8	12
C	3	5	8	10
B	2	4	4	3
A	0	2	0	6
NA (not attended)	4	1	1	0
Success rate (%)	6.3	19.4	10.5	23.7
1st attempt passing rate (%)	62.5	71.0	76.3	84.2
Passing rate final (%)	93.8	84.4	94.7	97.4

Figure 1

First exam attempt grades in years 2022-2025 (mentoring in 24/25), %



The feedback from first-year students on mentors was excellent, which shows the strong influence of active volunteers and close relationships among students of the same age with similar interests. The survey done immediately after mentoring, but before the exams, shows that students were fully satisfied with the mentorship, and would prefer even more peer-led mentorship hours starting earlier. This finding is fully in agreement with data from other publications (Lahiri et al., 2025) and does not need further evidence. However, if the relationship between mentors and mentees has problems, it may lead to disappointment in students (Zaniewski & Reinholz, 2016) and may necessitate changing the mentor to achieve the best effect.
The university-organised students' perception feedback questionnaire shows the tendency to increase the awareness of the study subject, and thus, students tend to evaluate the subject better. This corresponds to earlier published results by Koziol & Wagner (2024).
However, most of the earlier publications describe other mentorship schemes and mostly focus on student awareness and settling into university life (Ocupa-Cabrera et al., 2025; Tinoco-Giraldo et al., 2020).
The last study year – 2025/2026 evaluation of students' feedback recording via the Electronic Study System is ongoing and the final evaluation results will be available in late spring 2026. However, the passing rate has shown a downward trend over the last few years. This tendency has not changed in the current study year, even though no mentorship was provided.

Figure 2
Student feedback on mentorship, %

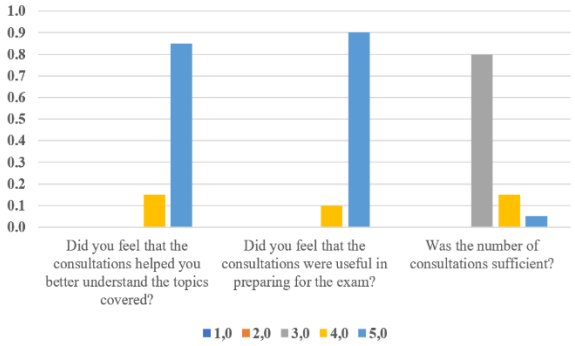
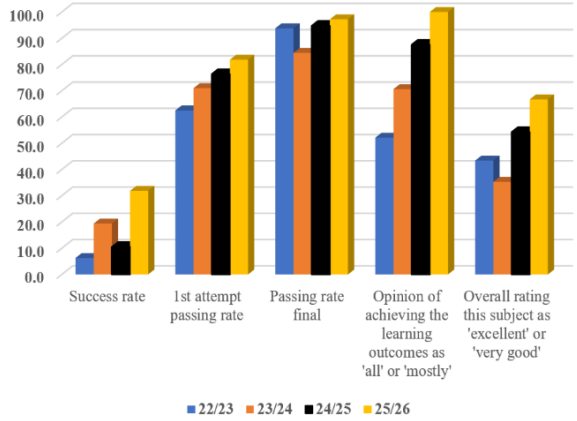


Figure 3
Academic progress and students' feedback in years 2022-2025, %



These results are fully consistent with many of the earlier studies showing no statistically significant grade point average (GPA) improvements, despite clear gains in student confidence, engagement, and attitudes toward coursework. This suggests that mentoring may influence *how students approach learning* even when grade outcomes remain unchanged or the positive effect was gained by one-to-one mentoring (Le et al., 2024). Still, the analysis shows a strong correlation between passing rates and student self-esteem (defined as the perceived feeling of achieving all goals) over recent years.

Conclusions

1. Student mentorship in the form of peer-led team learning tends to increase students' self-esteem, as evidenced by a higher proportion of students who rated their attainment of learning outcomes (knowledge and skills) as highly successful. This interpretation is based on monitoring results from targeted surveys and subject ratings, which showed improved perceptions among first-year students - a critical finding given the complexity of preclinical subjects like biochemistry (especially basic knowledge in it) and their perceived disconnect from the profession.
2. The analysis of examination data and GPA monitoring indicated no significant improvement in students' academic progress; however, there was a consistent upward trend in passing rates throughout the monitoring period. This suggests that while mentorship may not directly raise grades, it could contribute to greater persistence or successful course completion.
3. Taken together, the monitoring results confirm that mentorship is a multifaceted educational strategy with a positive influence on academic attitudes, professional identity, and student engagement, even if the magnitude of impact on academic performance is limited. The study's interpretation of both quantitative (exam results, passing rates) and qualitative (survey feedback) monitoring data highlights the need for further refinement of mentorship program structure, duration, and type to better realize its potential benefits.

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Zaniewski, A. M. & Reinholz, D. (2016). Increasing STEM success: A near-peer mentoring program in the physical sciences. *International Journal of STEM Education, 3*(14). https://doi.org/10.1186/s40594-016-0043-2

ARTIFICIAL INTELLIGENCE IN HIGHER EDUCATION: A CROSS-DISCIPLINARY SURVEY STUDY

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Abstract
The incorporation of AI into education is not only improving how instruction is delivered but also reshaping underlying pedagogical approaches. Rather than relying on traditional teacher-centred models, AI-supported learning increasingly promotes student-focused, interdisciplinary, and individualized educational practices. The study aimed to determine engineering students' views on the use of AI, the importance of AI in their future professions, the risks to their professional identity associated with AI use, and their competitiveness in the labour market without AI skills. The data were analyzed using inferential statistics and visualized through graphs. Respondents generally considered their knowledge of artificial intelligence to be average (58%, p-value = 0.000). A significant, portion felt that AI tools is are necessary for text generation (46%, p-value = 0.000) and that, their primary purpose in studies is information searching (42%, p-value = 0.000). However, respondents were unsure about the importance of AI in their future careers (37%, p-value = 0.000) and partially disagreed that using AI a poses risk to their professional identity (34%, p-value = 0.000). 64% (p-value = 0.00) believed they would remain competitive in the labour market without AI skills). Respondents were unsure whether work automation through AI represents an opportunity or a threat to their profession (p-value = 0.099).
Keywords: artificial intelligence, higher education, engineering students.

Introduction

Artificial intelligence (AI) refers to technologies that allow computers and machines to imitate human cognitive abilities, including learning, understanding, problem-solving, decision-making, creativity, and autonomous functioning (Stryker & Kavlakoglu, 2026).

AI and digital tools can make work more productive and creative, and they must serve people (Survey results show…, 2025).

The higher education sector is confronted with a range of challenges arising from the dynamic advancement of AI, which is reshaping traditional models of teaching, learning, and research (Mohamed et al., 2025).

Artificial intelligence in education extends beyond improving teaching methods; it is fundamentally reshaping instructional approaches, curriculum design, and educators' roles. This transformation supports a move away from traditional teacher-centred systems toward models that prioritise student engagement, interdisciplinary learning, and personalised educational experiences (Kong & Yang, 2024; Siddiqui et al., 2025).

When AI is used effectively, it can enhance student autonomy, critical thinking, and learning. To maximize their usefulness in the classroom, AI systems should be able to adapt to the culture and subject matter (Mohamed et al., 2025).

AI algorithms significantly enrich brainstorming processes by providing insights derived from current trends, historical data, and cross-disciplinary studies (Alshater, 2022).

Awareness of different types of AI and their practical uses remains quite limited, and many employees who are expected or allowed to engage with AI tools at work may naturally show resistance toward them. Despite the growing presence and adoption of generative AI in recent years, hesitation and opposition to its use continue to pose significant challenges in the workplace (Golgeci et al., 2025).

As continuous skill and knowledge development becomes essential, individuals' initiative in improving their abilities and directing their career progression is likely to play a more significant role (Hirschi, 2018; Lent et al., 2022).

Figure 1 presents the domains where artificial intelligence contributes to the improvement of academic activities.

The first domain, *Idea Development and Research Design*, highlights AI's ability to support the generation of research ideas through brainstorming processes. Its effectiveness in research planning, particularly in assisting with study design, reflects its potential to contribute to well-structured and rigorous research methodologies (Alshater, 2022; Dergaa et al., 2023).

The second domain, *Content Development and Structuring*, emphasises AI's role in supporting the creation and organisation of academic material.

The fourth domain, *Data Management and Analysis*, demonstrates AI's strength in handling and interpreting data. By applying advanced analytical and visualisation methods, AI is able to transform complex datasets into clear and meaningful insights (Christou, 2023; Currie et al., 2023).

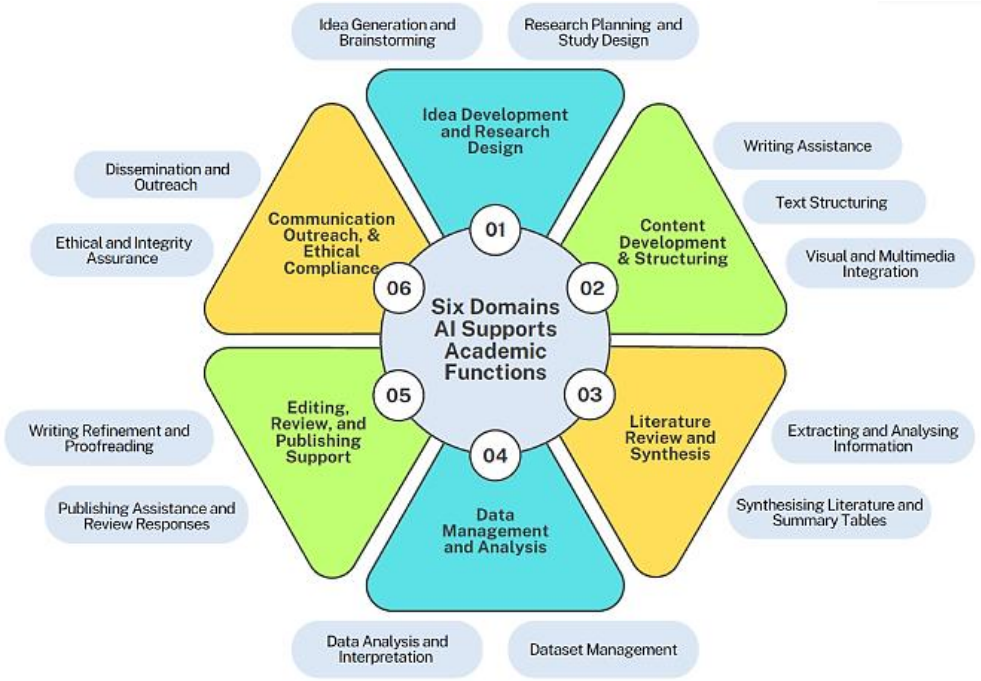
In the fifth domain, *Editing, Review, and Publishing Support*, AI is increasingly recognised as a valuable tool for enhancing academic writing by supporting proofreading, editing, and abstract preparation (Huang & Tan, 2023; Giglio & Costa, 2023).

The sixth domain, *Communication, Outreach, and Ethical Compliance*, highlights AI's role in facilitating the dissemination of research outcomes and ensuring adherence to ethical standards (Tang et al., 2024; Meyer, 2023).

AI functions as a significant productivity tool, influencing academic writing and research in

numerous disciplines. It supports idea development and research design by delivering insights and refining methodologies, while also enhancing writing quality through drafting assistance and sentiment analysis (Khalifa & Albadawy, 2024).

Figure 1
The six domains where AI can improve academic functions (Khalifa & Albadawy, 2024)



Artificial intelligence has a substantial influence on individuals' career trajectories (Bankins et al., 2024a; Bankins et al., 2024b; Donald et al., 2024). Although it is likely to create new occupations and even entire industries, it is also expected to transform or replace existing roles, thereby requiring the development of new skills and diminishing the importance of some current competencies (Behrend et al., 2024; Selenko et al., 2022).

The study aimed to determine engineering students' views on the use of AI, the importance of AI in their future professions, the risks to their professional identity associated with AI use, and their competitiveness in the labour market without AI skills.

Materials and Methods

The study was conducted from October 2025 to January 2026. 160 engineering students (1st to 4th year) from the Latvia University of Life Sciences and Technologies (LBTU) answered the electronic questionnaires; some students answered that they don't use AI at all. For the most part, 143 engineering students' surveys were analyzed in the following analysis. Students are currently pursuing programs in landscape architecture and planning, forest engineering, information technologies for sustainable development, forestry science, food technology, civil engineering and constructions, environment and water management, environmental engineering, agricultural engineering, biosystems machinery and technologies.

Results from 17 questions of the survey were used in the study. Participants in the study were selected through random sampling, and the online survey was conducted under consistent conditions.

During the survey, participants were asked to rate the use of AI, the importance of AI use in respondents' future professions, the risks to professional identity posed by AI use, and competitiveness in the labour market without AI skills.

The survey data are qualitative; therefore, nonparametric statistics were used for the analysis: the distributions of respondents' answers to the survey questions were statistically analysed using the chi-square test (the null hypothesis assumed that the frequency of respondents' answers was uniform). Statistical data were analysed using the SPSS software package.

Results and Discussion

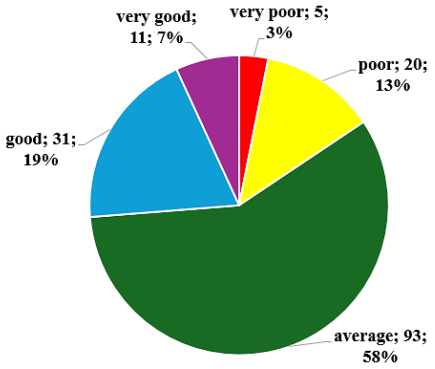
In response to the question regarding AI knowledge, the majority of respondents rated their understanding as average (58%), followed by good (19%), poor (13%), very good (7%), and very poor (3%) (Figure 2).

The majority of respondents (84%) use artificial intelligence, which indicates that AI has become an integral part of the educational process, helping them with homework and expanding their knowledge.

58% of respondents indicated that they have an average understanding of AI, which may suggest that

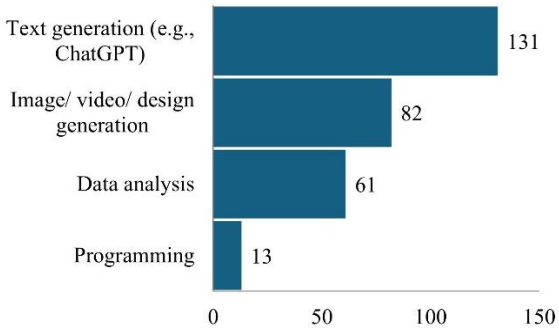
AI is used sporadically depending on educational needs.
Only 3% of students reported having very poor knowledge of AI, confirming that AI has become an almost indispensable necessity in education.
Similar findings are shown by the results (Vieriu & Petrea, 2025), where the majority of students (57.6%) use AI once a week, while 18.8% use AI every day, and only 1.2% of students indicated that they do not use AI at all.

Figure 2
Respondents' knowledge of AI (n=160)



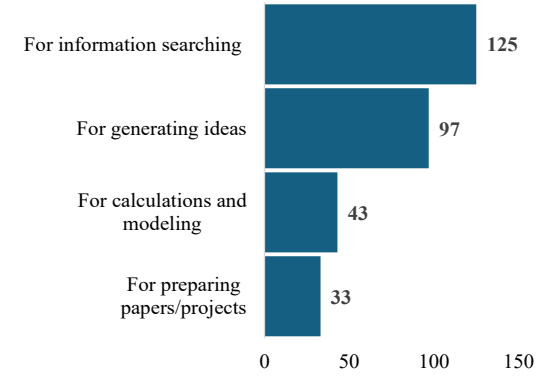
The chi-square test statistics for respondents' knowledge of artificial intelligence are as follows: the p-value of 0.000 is less than the significance level of 0.05, so the null hypothesis is rejected. This indicates that response frequencies are not equal, with a statistically significant dominance of the answer 'average' (61.0).
AI tools are most frequently applied to text-based tasks such as writing and translation, helping employees save time and improve productivity (Survey results show…, 2025).
The main types of AI used in academic activities, 88.2% of respondents use virtual assistants (e.g., ChatGPT, Google Assistant, etc.), 42.4% of respondents use AI-based educational platforms (e.g., Coursera, Duolingo, etc.), 17.6% of respondents use automatic content generation tools, 8.2% of respondents use data processing tools, while 3.5% of respondents use other types of AI (Vieriu & Petrea, 2025).
Responsible AI is not keeping pace with AI capabilities; safety benchmarks are lagging and reported incidents are rising sharply. Documented AI incidents rose to 362, up from 233 in 2024. Adding to the challenge, recent research found that improving one responsible AI dimension, such as safety, can degrade other, such as accuracy (AI index report, 2026).
Our respondents responded similarly to the question about the use of AI tools, and results were as follows: 46% text generation (e.g., ChatGPT), 29% image/video/design generation, 21% data analysis, and 5% programming (Figure 3).

Figure 3
Use of AI tools (response frequency = 287)



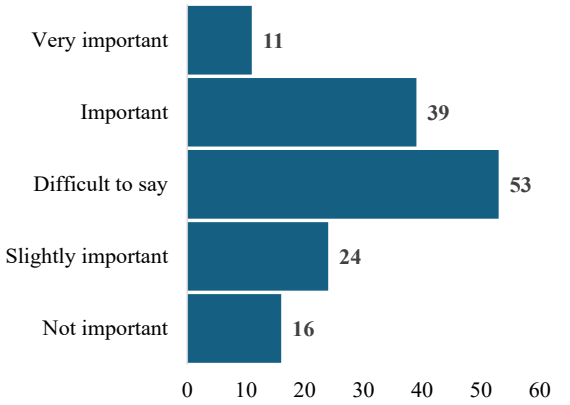
The chi-square test statistics for use of AI tools are as follows: the p-value of 0.000 is less than the significance level of 0.05, so the null hypothesis is rejected. This indicates that response frequencies are not equal, with a statistically significant dominance of the answer 'text generation (e.g., ChatGPT)' (59.3).
Over 80% of U.S. high school and college students now use AI for school-related tasks, but only half of middle and high schools have AI policies in place, and just 6% of teachers say those policies are clear (AI index report, 2026).
In response to a question about the purposes of using artificial intelligence in studies, the following results were obtained: 42% use AI for information searching, 33% - for generating ideas, 14% - for calculations and modelling, and 11% - for preparing papers/projects (Figure 4).

Figure 4
The purposes of using artificial intelligence in studies (response frequency = 298)



The chi-square test statistics for the purposes of using artificial intelligence in studies are as follows: the p-value of 0.000 is less than the significance level of 0.05, so the null hypothesis is rejected. This indicates that response frequencies are not equal, with a statistically significant dominance of the answer 'for information searching' (50.5).
When asked about the importance of AI in their future careers, respondents reported the following: 8% - very important, 27% - important, 37% - difficult to say, 17% - slightly important, and 11% - not important (Figure 5).

Figure 5
The importance of using AI in your future career (n =143)



The chi-square test statistics for the importance of using AI in your future career are as follows: the p-value of 0.000 is less than the significance level of 0.05, so the null hypothesis is rejected. This indicates that response frequencies are not equal, with a statistically significant dominance of the answer 'difficult to say' (24.4).

A higher degree of knowledge and frequent use of AI tools among graduates is associated with employment in their field of study, as well as with higher perceived productivity and better career alignment (Ramos et al., 2025).

A growing body of academic research has begun to measure AI's impact both at the micro level, examining how individual workers perform their jobs using AI tools, and at the macro level, examining how AI adoption impacts aggregate productivity and employment figures (AI index report, 2026).

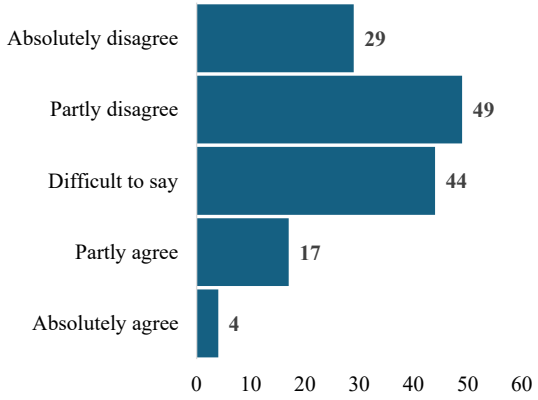
A further significant concern is the expansion of digital monitoring, where AI technologies are employed to observe employees' activities, performance, and even emotional conditions, potentially diminishing autonomy and eroding trust (Monod et al., 2024). Meanwhile, the digital divide remains a persistent structural barrier, as individuals who lack access to training, infrastructure, or reliable connectivity may be excluded from ongoing digital transformation processes (Golgeci et al., 2025; Liu et al., 2024).

Software engineers who relied heavily on AI for learning showed no measurable speed improvement. Overall, AI's productivity effects are highly context-dependent. The gains are strongest when work can be divided into well-defined, repeatable tasks with clear quality monitoring (Shen & Tamkin, 2026).

In response to a question about risks to professional identity when using AI, the following results were obtained: 3% - absolutely agree, 12% - partly agree, 31% - difficult to say, 34% - partly disagree, and 20% - absolutely disagree (Figure 6).

The chi-square test statistics for risks to professional identity when using AI are as follows: the p-value of 0.000 is less than the significance level of 0.05, so the null hypothesis is rejected. This indicates that response frequencies are not equal, with a statistically significant dominance of the answer 'partly disagree' (20.4).

Figure 6
Risks to professional identity when using AI (n =143)

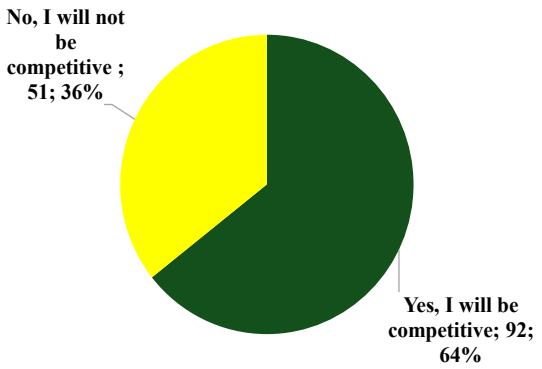


New technologies primarily displace routine work, most commonly associated with middle-skilled workers, while boosting the need for low-skilled service positions and high-skilled roles that involve non-routine tasks (Autor et al., 2024).

Most CEOs say their companies have-not yet seen a financial return on AI investments. While nearly a third (30%) report increased revenue over the past 12 months and a quarter (26%) achieved cost reductions, more than half (56%) reported neither revenue gains nor cost savings (PwC's 29th Global CEO Survey…, 2026).

Regarding the competitiveness in the labour market without AI skills, the following results were obtained: 64% admit- yes, I will be competitive, and 36% - no, I will not be competitive (Figure 7).

Figure 7
The competitiveness in the labour market without AI skills (n =143)



The chi-square test statistics for the competitiveness in the labour market without AI skills are as follows: the p-value of 0.000 is less than the significance level of 0.05, so the null hypothesis is rejected. This indicates that response frequencies are not equal, with a

statistically significant dominance of the answer 'yes, I will be competitive' (20.5).

Graduates who regularly engage with these technologies tend to experience increased efficiency, creativity, and responsiveness, which is consistent with Jia et al. (2024), who show that human–AI collaboration can significantly improve employee performance, especially in complex tasks. In a similar vein, Kong et al. (2023) and Shao et al. (2024) report that continuous use of AI is associated with greater well-being, enhanced day-to-day creativity, and stronger perceived self-efficacy in the workplace.

It is essential for students to develop greater awareness and understanding of AI-related risks, including bias and surveillance, as these issues increasingly appear across all areas of life (U.S. Department of Education, 2023).

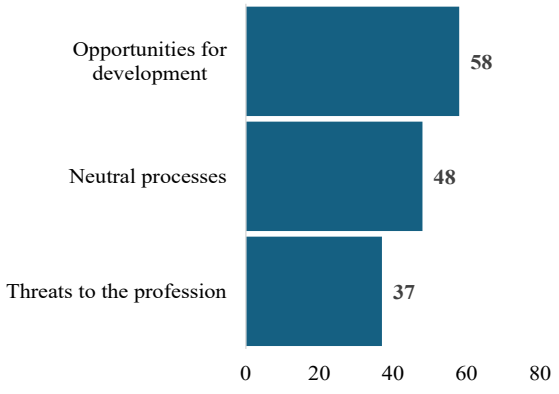
AI dangers and risks and how to manage them:

- data privacy issues;
- environmental harms;
- existential risks;
- intellectual property infringement;
- job losses;
- lack of accountability;
- lack of explain ability and transparency;
- misinformation and manipulation (Saravanan & Kumar, 2025).

When asked about AI-driven work automation, respondents reported the following: 41% consider it as an opportunity for development, 34% are neutral, and 26% see it as a threat to their profession (Figure 8).

Figure 8

The work automation using AI (n =143)



The chi-square test statistics about the work automation using AI are as follows: the p-value of 0.000 is less than the significance level of 0.05, so the null hypothesis is rejected. It can therefore be concluded that the frequencies of respondents' answers are equal. Respondents are unsure whether the automation of work using AI represents an opportunity or a threat to their profession.

As AI technologies continue to advance, more jobs will likely be automated, especially those that involve tasks that require technical skills. The impact of AI on job automation will depend on various factors such as the feasibility of the technology, labor market conditions, cost-effectiveness, social acceptance, and potential economic benefits. As advancements in AI.

Technologies continue to revolutionize various industries, individuals, and organizations need to stay informed and adapt to the changing landscape of job automation (Saravanan & Kumar, 2025).

The gap between AI-related opportunities, practical skills, and ethical or regulatory considerations reflects current challenges at both national and institutional levels. It suggests that developing AI literacy and competencies is a complex process that depends on the willingness to keep pace with the evolving knowledge society (Sergejeva et al., 2024).

From one perspective, AI will automate various tasks, leaving a large number of people without a job, and leading to a widening skills gap. Less than 5% of occupations can be fully automated with current AI technology (McKinsey) that being said, 60% of occupations could be impacted by AI, which in this case means fully automatable tasks comprising at least 30% of the total tasks used in a job (Saravanan & Kumar, 2025).

The study's authors align with Ramos et al. (2025) in emphasizing that AI is already part of contemporary life, and that readiness to collaborate with it is a collective responsibility of graduates, universities, and society. Preparing an education system for 21st-century challenges demands a comprehensive, ethical, and inclusive framework.

Conclusions

1. The majority of respondents (84%) use artificial intelligence, which indicates that AI has become an integral part of the educational process, helping them complete homework and improve their knowledge; however, based on the respondents' answers, it can be concluded that AI is used irregularly, depending on their educational needs.
2. The use of AI also creates challenges, such as overreliance on technology and a decline in critical thinking skills; although 64% of respondents believe they will be competitive in the labor market without AI skills.
3. To ensure the effective integration of artificial intelligence into education, it would be desirable to:
   - foster a deeper understanding of artificial intelligence tools and their proper use;
   - develop and implement clear institutional guidelines or standards for AI use in student work, particularly in final theses;
   - mitigate excessive reliance on technology by promoting critical evaluation and verification of AI outputs.
4. Future research with a larger, more diverse sample is needed to provide more robust insights.

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VOCATIONAL AGRICULTURAL EDUCATION AND LABOUR MARKET DYNAMICS: IMPLICATIONS FOR SUSTAINABLE REGIONAL DEVELOPMENT AND ECONOMIC GROWTH

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Abstract
Agricultural vocational education is essential for Latvia's sustainable development and regional economic growth. As the agricultural sector adapts to technological and environmental changes, the need for qualified specialists and employer-oriented training becomes increasingly important. However, the system faces challenges such as slow legislative adaptation, uneven regional development, insufficient economic justification in school planning, and a mismatch between employer expectations and graduate skills. This research assesses the alignment between agricultural vocational education provision and labour-market demand in Latvia using measurable indicators: agricultural employment, student enrolment by vocational specialisation, projected demand for qualified agricultural specialists, and the availability of work-based learning opportunities. System development is evaluated through changes in these indicators over time. Germany is used as an institutional benchmark for selected features of the dual vocational education and training model rather than as a second geographical study area. Germany's dual vocational education model in agriculture demonstrates the importance of close cooperation between vocational schools and employers, ensuring practical skill development and alignment with labour market needs. The findings highlight the need for modernization of learning content, stronger cooperation with employers, and coordinated, economically justified, and regionally balanced development to improve the effectiveness and sustainability of agricultural vocational education in Latvia.
Keywords: vocational education in agriculture, employer, economic justification, region.

Introduction

Agriculture continues to play a significant role in regional economic development and sustainability in rural territories. In Latvia, the agricultural sector contributes to employment generation, food security and the maintenance of rural livelihoods. However, structural changes such as technological advancement, digitalization of agricultural processes and climate-related challenges have significantly transformed labour market requirements within the sector (Schmitt, 2009).

Modern agricultural production systems increasingly rely on advanced machinery, precision farming technologies and digital farm management tools. Consequently, the demand for specialists possessing technological, managerial and analytical competencies has increased substantially. Vocational agricultural education therefore represents an essential mechanism for developing human capital capable of responding to these evolving labour market requirements (OECD, 2023).

At the same time, vocational education institutions play an important role in supporting regional development by providing professional training opportunities in rural areas. Nevertheless, several challenges remain, including a mismatch between graduate competencies and employer expectations, uneven regional accessibility of vocational education institutions and insufficient integration between education providers and agricultural enterprises. Addressing these challenges is crucial for ensuring the long-term sustainability of the agricultural sector and strengthening rural economies.

Theoretical Framework

The relationship between vocational education systems and labour market development has been widely examined in the context of human capital theory and regional development economics. According to human capital theory, investment in education and training contributes to productivity growth, labour market adaptability and long-term economic development (Becker, 1993).

In the agricultural sector, vocational education plays a particularly important role because the sector increasingly relies on specialized technical knowledge, digital technologies and sustainable production practices. As agricultural systems become more technologically intensive, the demand for skilled workers with practical competencies and technological literacy continues to increase (OECD, 2023).

From a regional development perspective, vocational education institutions also serve as important knowledge and innovation hubs in rural territories. They contribute to regional labour market stability by preparing specialists for local industries and supporting the development of rural entrepreneurship (European Commission, 2022).

Therefore, the effectiveness of agricultural vocational education depends not only on the quality of training programmes but also on the strength of cooperation between educational institutions, employers and regional development stakeholders.

Materials and Methods

The research is based on a mixed-method approach combining statistical analysis of labour market trends and the review of policy documents related to vocational education and employment. Quantitative data regarding employment trends in the agricultural sector were obtained from Eurostat statistical databases and national labour market reports published by the Ministry of Economics of Latvia.

In addition, labour market forecasts and sectoral analyses available on the Latvian labour market

forecasting platform (prognozes.em.gov.lv) were examined to identify future demand for agricultural specialists. Academic literature indexed in international scientific databases, including Scopus and Web of Science, was also analyzed in order to identify the main theoretical perspectives regarding vocational education and labour market transformation in the agricultural sector.

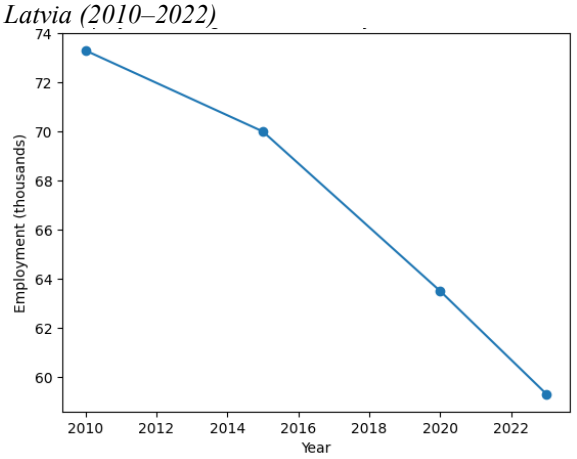
The analysis focuses on three key aspects: employment trends in agriculture, participation in agricultural vocational education and projected demand for agricultural specialists in the future labour market programs.

Results and Discussion

During the last decade, employment in the sector has declined due to structural transformation, mechanization, and increasing productivity. Although the number of employees has decreased, the sector increasingly requires workers with a higher level of technical competence and specialized knowledge.

Figure 1

Employment in agriculture, forestry and fisheries in Latvia (2010–2022)



Source: Eurostat, 2023; Ministry of Economics of Latvia, 2022.

The decline in employment does not necessarily indicate reduced importance of the agricultural sector. Instead, it reflects the transition toward technologically intensive production systems that require fewer but more highly skilled employees.

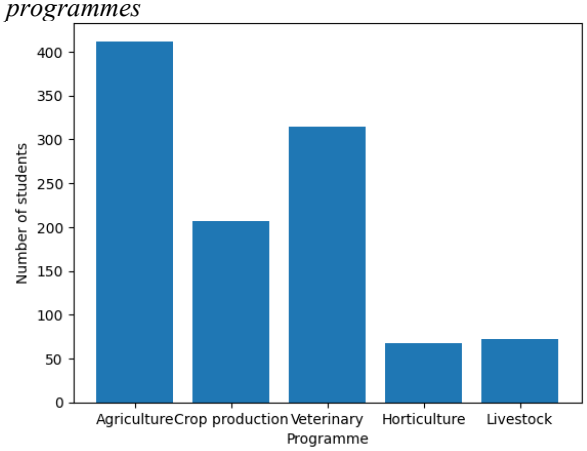
Vocational agricultural education therefore plays a crucial role in preparing specialists capable of managing modern agricultural technologies. However, the distribution of students across agricultural vocational programmes varies considerably.

The data indicate that general agriculture and veterinary programs attract the largest number of students, while more specialized programmes such as horticulture and livestock production have lower enrolment levels. This distribution reflects both labour market demand and student preferences.

At the same time, labour-market forecasts indicate an increase in the demand index for qualified agricultural specialists from 100 in 2024 to approximately 125 in 2030, corresponding to an increase of about 25%.

Figure 2

Students enrolled in agricultural vocational education programmes

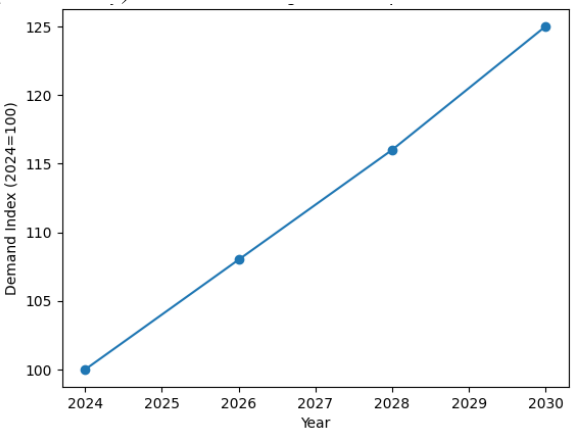


Source: Ministry of Education and Science of Latvia, 2024; Eurostat, 2023.

This projected growth is associated with technological development and the implementation of sustainable agricultural practices.

Figure 3

Projected demand for agricultural specialists in Latvia (2024–2030)



Source: Ministry of Economics of Latvia, 2024; Labour market forecasting platform prognozes.em.gov.lv.

These projections highlight the importance of strengthening vocational education systems in order to ensure an adequate supply of qualified specialists for the agricultural sector. Improved cooperation between vocational education institutions and agricultural enterprises can significantly enhance the relevance of training programmes and facilitate the transition of graduates into the labour market.

International Experience

Germany is used in this study as an institutional benchmark rather than as a second geographical study area. The comparison is intended to identify transferable mechanisms for linking vocational

education with employers and labour-market demand. The German dual vocational education and training (VET) system is widely recognized as one of the most effective models for aligning education with labour market needs. The system combines theoretical instruction in vocational schools with practical training in enterprises, thereby enabling students to acquire both professional knowledge and hands-on skills in real working environments. This approach has been associated with lower youth unemployment rates and a smoother transition from education to employment compared to many other European countries (Euler, 2013; Deissinger, 2015; OECD, 2023).

In Germany, vocational education in agriculture follows the dual training principle, whereby apprentices spend part of their time in a vocational school (Berufsschule) and the remainder in a training farm or agricultural enterprise. Typically, apprentices spend approximately two-thirds of their training period in the workplace and one-third in formal classroom instruction (Federal Institute for Vocational Education and Training [BIBB], 2024). This structure ensures that theoretical learning is continuously reinforced through practical application in real production settings.

The legal framework for vocational education in Germany is defined by the Vocational Training Act (Berufsbildungsgesetz — BBiG), which establishes national standards for training programmes, assessment procedures and certification requirements. In the agricultural sector, regional agricultural chambers (Landwirtschaftskammern) play a key role in supervising training quality, organizing examinations and supporting cooperation between vocational schools and agricultural enterprises (BIBB, 2024; OECD, 2023).

The standard duration of vocational training in the occupation Landwirt / Landwirtin (farmer) is three years, although the duration may be shortened for students who have prior educational qualifications or relevant professional experience. Training programmes include a broad range of competencies, such as crop production, livestock management, agricultural technology, farm economics and environmental sustainability. Final examinations consist of both written and practical components designed to assess professional competence and readiness for employment in the agricultural sector (BIBB, 2024).

Statistical data indicate that vocational education plays an important role in supporting the agricultural labour force in Germany. In 2023, approximately 32,000 students were enrolled in vocational education programmes related to agriculture, forestry and fisheries, including around 9,000 apprentices in the occupation of farmer (Landwirt / Landwirtin) (BIBB, 2024). Furthermore, more than 13,000 new apprenticeship contracts were concluded in agricultural occupations in 2024, reflecting the continued demand for qualified specialists in the sector (Federal Employment Agency, 2024).

Despite its overall stability, the German agricultural sector faces several structural challenges similar to those observed in other European countries. These include demographic change, a decline in the number of small farms and increasing technological complexity in agricultural production. As a result, vocational education programmes are increasingly incorporating digital technologies, precision farming methods and sustainability principles into their curricula (OECD, 2023).

Research suggests that strong cooperation between vocational education institutions and employers represents one of the key factors contributing to the effectiveness of the German dual system. According to Rauner & Maclean (2008), work-based learning enables students to develop professional identity and practical competence while improving their employability. Similarly, Deissinger (2015) emphasizes that the institutional partnership between education providers, employers and government authorities ensures the relevance of training programmes and supports regional economic development.

The German experience is particularly relevant for Latvia, where work-based learning has gradually become an important component of vocational education reform. Latvia has introduced the concept of work-based learning in order to strengthen cooperation between vocational education institutions and employers and to improve the alignment between training programmes and labour market requirements. According to the Latvian work-based learning framework, at least 25% of the vocational education programme must be implemented in an enterprise environment, enabling students to acquire practical skills under real working conditions. This approach was developed based on elements of the dual education model widely used in several European countries, including Germany.

The relevance of the German experience for Latvia lies not in the direct transfer of the German dual system, but in the shared principle of strengthening employer involvement and workplace-based training. Latvia has developed its own work-based learning framework through cooperation between vocational education institutions, employers and sectoral organisations. The Latvian Employers' Confederation (LDDK) has supported employer involvement in vocational training, curriculum development and practical learning as a means of improving the labour-market relevance of vocational education. Financial support mechanisms, including European Social Fund projects, have also been used to encourage enterprises to participate in work-based learning. Thus, the Latvian approach can be compared with the German dual VET model in terms of employer participation and practical training, while recognizing important differences in

institutional structure and the intensity of workplace-based learning. The experience of Germany therefore provides valuable insights for strengthening vocational agricultural education in Latvia. Although Latvia has introduced elements of work-based learning through recent education reforms, the level of structured cooperation between vocational schools and agricultural enterprises remains uneven across regions. Strengthening this cooperation, particularly through long-term training agreements, joint curriculum development and employer participation in student assessment, could significantly improve the responsiveness of vocational agricultural education to labour market demand.

From a regional development perspective, the German dual vocational education model demonstrates how coordinated training systems can support rural economies by ensuring a stable supply of qualified labour and promoting innovation in agricultural production. These lessons are particularly relevant for Latvia, where rural regions face labour shortages, demographic decline, and increasing technological transformation in agriculture. Statistics on vocational schools and students in Germany would be valuable to elaborate and evaluate the comparability of the German experience with the Latvian situation.

Policy Implications

The findings of this study highlight the need for coordinated policy measures aimed at strengthening the alignment between vocational agricultural education and labour market demand. Policy makers should consider implementing targeted support mechanisms for vocational education institutions, particularly in rural regions where access to specialised training remains limited. Furthermore, strengthening cooperation between vocational schools and agricultural enterprises could significantly improve the relevance of training programmes and facilitate the transition of graduates into the labour market. Strategic investments in modern training infrastructure, digital learning tools and teacher professional development are also necessary to ensure the competitiveness of agricultural vocational education in the context of technological transformation.

Limitations of the Study

This research has several limitations that should be considered when interpreting the results. First, the study is primarily based on statistical data and policy analysis, which may not fully capture all aspects of labour-market dynamics in the agricultural sector. Second, detailed and fully comparable regional data on vocational education participation, institutional capacity and work-based learning are limited. Consequently, regional accessibility is treated as a contextual indicator, while training-supply capacity is measured through enrolment and its alignment with projected skills demand rather than through physical school capacity. Third, the Latvian and German indicators are not interpreted as a direct country-to-country performance comparison; Germany serves as an institutional benchmark. Future research could expand the analysis by incorporating regional programme-level data and qualitative evidence from students, educators and agricultural employers.

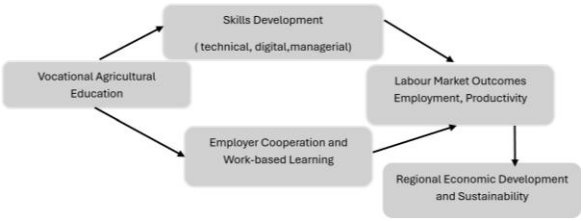
Future research could expand the analysis by incorporating additional qualitative data obtained through interviews with students, educators and agricultural employers.

Conceptual Model of Vocational Agricultural Education and Labour Market Interaction

Based on the theoretical framework and the empirical analysis of vocational agricultural education and labour-market dynamics in Latvia, a conceptual model was developed to illustrate the mechanisms through which vocational agricultural education may contribute to labour-market outcomes and sustainable regional development. The German dual VET experience was not used as the basis for constructing the model; rather, it provides international evidence supporting the role of employer cooperation and work-based learning within the proposed framework.

Figure 4

Conceptual model of vocational agricultural education and labour market interaction



Source: developed by the author based on the theoretical framework and empirical analysis of Latvian labour-market and vocational education data; OECD, 2023, Eurostat, 2023; Ministry of Economics of Latvia, 2024.

Within the model, the 'Employer Cooperation and Work-based Learning' component is additionally supported by the German dual VET experience discussed in the previous section. The German case demonstrates how structured employer participation and workplace-based training can strengthen the connection between vocational education, skills development and labour-market requirements. Germany therefore serves as an institutional benchmark for this specific mechanism rather than as the empirical basis of the conceptual model. At the same time, cooperation between vocational education institutions and agricultural enterprises plays a crucial role in strengthening the relevance of training programmes. Work-based learning, internships and industry collaboration enable students to gain practical experience and facilitate their transition into the labour market (Grubb & Lazerson, 2004).

The model further illustrates that improved skills development and stronger employer cooperation

contribute to positive labour market outcomes, including increased employment opportunities, higher productivity and improved competitiveness of the agricultural sector.

Ultimately, these processes support broader regional development objectives by strengthening rural economies, promoting innovation and enhancing the long-term sustainability of agricultural production systems.

Conclusions

1. Vocational agricultural education plays a significant role in supporting sustainable regional development and improving the supply of skills required by rural labour markets.
2. Structural transformation of the agricultural sector, including technological innovation and digitalization, has increased the demand for specialists with advanced technical skills.
3. Although employment in agriculture has declined due to mechanization, the need for highly qualified professionals in technologically advanced agriculture continues to grow.
4. Strengthening cooperation between vocational education institutions and agricultural enterprises is essential to reduce the skills mismatch of graduates to labour market requirements.
5. Modernization of vocational education infrastructure, the integration of digital technologies in training programmes and improved career education mechanisms are necessary for increasing the attractiveness and effectiveness of agricultural education.

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CIVIL PROTECTION DISASTER PREPAREDNESS OF LATVIA'S REGIONS

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Abstract
Climate change and the geopolitical situation in the world is creating an increasing probability that civil protection disasters, by their scale and consequences, will affect increasingly wider territories both in the world and in Latvia. The aim of the study is to find out whether the inhabitants of Latvian municipalities know and are prepared for the impact of natural disasters in various emergency situations. The study employed scientific literature analysis and a survey of Latvian residents to identify which natural disasters have the greatest impact on specific municipalities. Furthermore, it assessed public emergency preparedness regarding the potential disruption of critical infrastructure, including heat, electricity, water and sewage supply systems, as well as the hampering of food and fuel logistics. Municipality ensures the evacuation of residents from disaster-threatened or affected territories, as well as the registration of these residents, temporary accommodation, catering and social care. This, in turn, means that work cannot take place everywhere simultaneously and someone will have to wait for help, perhaps even for several days. The results of the study indicate that hydrological disasters are statistically the most significant ($p < 0.05$) for residents. Further studies should clarify whether residents have sufficient understanding of the potential consequences of major disasters and, accordingly, the skills to ensure their basic needs.
Keywords: civil protection, disaster, prevention.

Introduction

The capacity for preventive action in the event of disaster threats will become increasingly relevant in the immediate future. Most important is how quickly and effectively the national civil protection system is able to adapt to the specifics and dynamics of new threats (Brizga et al., 2024).

In 2024, an updated version of the booklet 'How to act in a crisis' was published. It includes information on a family action plan in crisis situations, providing practical guidance on developing a plan, according to one's place of residence. Information on actions in a crisis, emergency supplies and items to keep in the car has also been updated. In order to strengthen the capacity and readiness of local governments to respond to crisis situations, including in the event of war or military threats, the Ministry of Defence, in cooperation with the National Guard, implements training for local civil defence commissions. During training, various situations are simulated in which civil defence commissions must assess, eliminate risks and determine a response plan to provide the public with basic needs in the event of a military conflict (Ministry of Defence, 2024).

The knowledge, skills and competencies of the public to survive the first days after a disaster - while power supply networks are being restored - are not self-evident; they need to be regularly reinforced and maintained at an adequate level.

Improving preparedness in the field of civil protection should be reflected not only in responding to and mitigating the consequences of an emergency, but also in the emotional security of the public (Kubas et al., 2022).

In the public sphere, the terms 'civil protection', 'emergency' and 'disaster' are often used interchangeably, although their meanings differ and overlap only partially. Civil protection is defined as a set of humanitarian measures aimed at protecting the civilian population from war or other threats, facilitating recovery from the immediate effects of such events, and at ensuring the conditions necessary for survival. These tasks are: warning, evacuation, provision of shelters, provision against the risks of power outages, rescue, medical assistance, firefighting assistance, identification and marking of dangerous areas, decontamination and other similar measures, provision of emergency shelter and resources, restoration and provision of public order, repair of indispensable utilities, emergency liquidation of the deceased, preservation of objects critical to survival, and any additional activities necessary for the fulfilment of the tasks listed above (ICRC, 2021).

A state of emergency, on the other hand, is a legal state declared by a state in response to a threat of disaster, catastrophe, or other circumstances defined in relevant laws and regulations (UNDRR, 2020).

In the Civil Protection and Disaster Management Law (2016), a disaster is defined as: 'an event that has caused human casualties and threatens human life or health, has caused damage or created a threat to people, the environment or property, as well as has caused or is causing significant material and financial losses and exceeds the daily capabilities of the responsible state and local government institutions to prevent the devastating circumstances of the event'.

A 2012 study (Robinson & Higgins, 2012) indicates that in emergency situations, only 10-25% of those affected take adequate and effective action, 65-80% become indecisive and behave in a dazed and confused manner, while 10-15% of victims behave in a highly maladaptive manner – confused, crying, and paralyzed in behaviour.

Other studies (Taouktsis et al., 2025; Amadio et al., 2024) show that climate change is an ongoing problem in all countries of the world, and governments of all

countries are constantly trying to cope with its consequences, using crisis management centres, using technology. The impact of natural disasters on water quality, both for drinking water and for surrounding water sources, is significant; therefore, it is necessary to develop a water security plan at the national level.
A German study (Lacher & Rohs, 2023) indicates that increasing terrorism, the COVID-19 pandemic, the war in Ukraine and nationwide flood disasters with serious consequences have led to increased attention to civil protection issues in politics and society in Germany, while adult education plays a key role in reducing disaster-related risks.
Analysing the research, it became clear that it is crucial at the national level to be prepared for the management of various types of disasters and to act correctly in emergency situations. There is not much research in Latvia in the context of civil protection and disaster management; therefore, the aim of our research is to find out whether the residents of Latvian municipalities recognize and are prepared for the impact of natural disasters in various emergency situations.

Materials and Methods
The basis of effective disaster management is formed not only by public administration, but also by the civilian population of Latvia. Therefore, in the context of the study, the aim of the study was set: to find out whether the residents of Latvian municipalities know and are prepared for the impact of natural disasters in various emergency situations.
The characteristics of the respondents are shown in Table 1.
A survey - questionnaire was used as the research method.

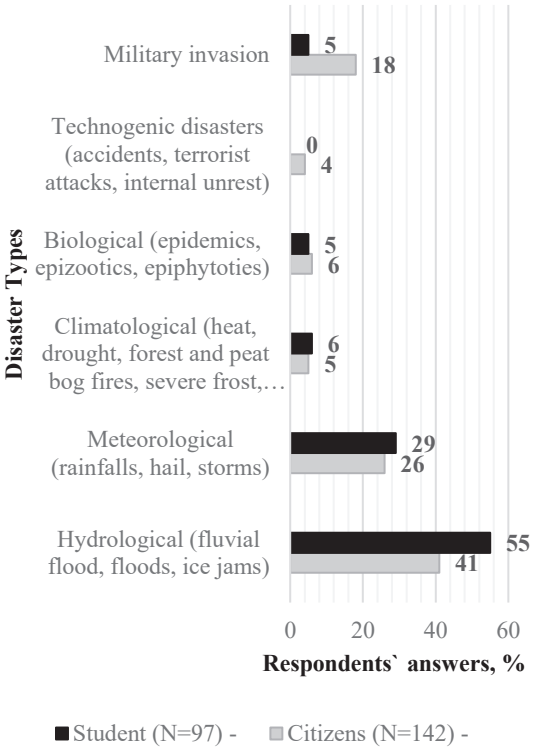
Table 1
Characteristics of respondents

Indicators		Number of respondents		Total
		Citizens	Students	
Respondents' age	< 20…	-	11	11
	21-30	15	73	88
	31-40	31	13	44
	41-50	46	-	46
	51-60	39	-	39
	>61	11	-	11
Respondents' gender	Female	108	24	132
	Male	34	73	107
Residence	Zemgale	58	52	90
	Kurzeme	19	16	35
	Latgale	24	23	47
	Vidzeme	41	26	67

The questionnaires were sent out both electronically and conducted in person. 97 university students from various courses and fields (24 female students and 73 male students) who had completed the theoretical course – 'Civil Protection' and had passed the tests electronically (DIGITEKA) were surveyed in person (Figure 1). The total number of respondents was 239. 142 respondents (108 women, 34 men) responded to the electronically distributed questionnaires.
An interactive program (Preacher, 2001) was used to process the data to determine the significance of data differences (p value).

Results and Discussion
Based on previously conducted research (Brizga et al., 2024), a similar study was conducted, as indicated in the 'Civil Protection and Disaster Management'(2016) legislation – geophysical (earthquakes, landslides), hydrological (fluvial flood, floods, ice jams), meteorological (rainfall, hail, storms), climatological (heat, drought, forest and peat bog fires, severe frost, icing), biological (epidemics, epizootics, epiphytoty), natural disasters and technogenic (anthropogenic – human-caused) disasters (accidents, terrorist attacks, internal unrest), as well as military invasion.
When examining response variations using the chi-square test (Preacher, 2001), significant differences were observed between the assessment of hydrological and meteorological disasters ($p < 0.05$).
In Latvia, as elsewhere in Europe, disaster preparedness and disaster management are very important government responsibilities, as is civil protection. In Germany, responsibility for these tasks is divided between the 16 federal states and the national government (Kippnich et al., 2017).
In Latvia, students acquire knowledge regarding possible dangerous everyday situations and threat responses, including safe behavior in domestic, public, and digital environments. The knowledge also encompasses environmental impacts, national security risks, and disaster preparedness. Additionally, students develop practical first aid skills for life-critical situations, such as resuscitation and management of critical bleeding, and learn how to effectively call for assistance.

Figure 1
Survey Results



In addition to the above mentioned, students were asked questions about theoretical and practical preparedness for various types of disasters. 31 (32%) respondents indicated that they rely on the responsible services.

The remaining students (66 respondents) indicated theoretical preparedness. Respondents indicated that they know what to do in case of a disaster while at university - they know where the shelter is and how to evacuate if necessary, but when at home, they do not know where to look for a shelter. Only a few (9 respondents) have a 72-hour survival bag prepared (one part-time student living in Riga had purchased one), because they serve in the National Guard. Respondents living in Zemgale, indicated that private property was damaged during the hail and flooding events, but there was no real clarity on what to do. The student demonstrated good knowledge and skills in providing first aid, as he had learned much of it to obtain a driver's license.

Conclusions

1. Hydrological disasters are the most significant in Latvia ($p < 0.05$).
2. In the event of a disaster, 32% of students rely on emergency services, so they do not feel a lack of skills.
3. Further research is needed to determine whether there is sufficient understanding of the potential consequences of major disasters and, accordingly, the necessary skills to provide for one's basic needs.

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TIMETABLE PLANNING AND OPTIMIZATION IN LATVIAN SCHOOLS: EMPIRICAL EVIDENCE FROM A NATIONAL SURVEY ON DIGITALIZATION, WORKLOAD, AND ORGANISATIONAL CONSTRAINTS

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Abstract
Timetable planning constitutes a critical administrative process in school management because effective coordination of teachers, classrooms, student groups, curriculum requirements and regulatory constraints must occur within limited time and resource conditions. Increasing teacher shortages, fragmentation of educational data systems and expanding administrative responsibilities intensify organisational complexity in educational institutions. Research objective involves analysing timetable planning practices in Latvian schools and evaluating the contribution of digitalisation to reducing administrative workload and improving organisational efficiency. Empirical evidence derives from a national survey conducted in 2025, including 294 fully completed responses from Latvian educational institutions representing different school sizes and organisational structures. Descriptive statistical analysis and comparative analysis were applied to examine relationships between school size, number of teachers and selected timetable planning approaches. Findings indicate that timetable construction remains predominantly manual and resource intensive. Hybrid planning approaches combining digital tools with manual adjustments dominate in 34% educational institutions, followed by manual planning supported by auxiliary digital tools in 23% institutions and fully manual planning in 21% institutions. Administrative workload associated with timetable preparation remains substantial because more than 23% respondents reported preparation time exceeding 40 hours per planning cycle. Evidence demonstrates that digital tools support operational efficiency but do not replace manual decision making in complex scheduling environments. Research results indicate a significant demand for flexible hybrid planning systems capable of integrating automated conflict detection, transparent resource allocation and manual decision control in order to improve timetable management and reduce administrative workload in Latvian schools.
Keywords: timetable planning, timetable optimisation, school administration, educational digitalisation, teacher workload.

Introduction

Timetable planning in educational institutions represents a central administrative activity influencing both organisational efficiency and educational quality. The timetable determines the temporal allocation of teachers, classrooms, subjects and student groups, thereby shaping the daily functioning of schools. Effective timetable planning enables efficient utilisation of resources and contributes to balanced workloads for teachers and students. The complexity of timetable planning has increased significantly in modern education systems. Several structural factors contribute to this complexity. Educational programmes have become more diverse, elective courses are increasingly common, teacher employment patterns often include part-time arrangements across multiple institutions and specialised learning environments require coordination of laboratories, equipment and digital infrastructure.

Academic literature classifies school timetabling as a combinatorial optimisation problem belonging to the class of NP-hard problems. Such problems involve large numbers of variables and constraints, making exhaustive search for optimal solutions computationally infeasible in realistic scenarios (Tassopoulos & Beligiannis, 2012). Consequently, practical timetable planning requires heuristic or hybrid approaches combining algorithmic optimisation with human decision making.

Traditional manual planning methods were historically sufficient when educational systems were structurally simpler. However, as schools have grown in size and curricular diversity, manual approaches have become increasingly inefficient and error-prone. Each modification to a timetable may generate additional conflicts requiring iterative adjustments, thereby increasing administrative workload (Devi et al., 2024; Sayed et al., 2015).

The Latvian education system faces additional challenges that amplify planning complexity. Teacher shortages have become more pronounced in recent years, requiring schools to coordinate part-time teaching arrangements and cross-institutional workloads. At the same time, digitalisation of educational administration remains uneven, resulting in fragmented data environments where information about teachers, classrooms and student groups may exist in separate systems.

International research demonstrates that the organisation of instructional time plays a critical role in educational outcomes. Comparative studies using PISA data indicate that increasing instructional hours alone does not guarantee improved academic performance. Instead, the structure and quality of instructional time management are key determinants of learning effectiveness (OECD, 2023a, 2023b).

Timetable planning in educational institutions can be defined as a combinatorial optimisation problem, where limited resources such as teaching staff, classrooms and instructional time must be allocated under multiple constraints in order to minimise scheduling conflicts and administrative workload while ensuring compliance with curriculum requirements and organisational rules. The complexity of this process increases with school size and structural diversity, requiring the integration of algorithmic

optimisation approaches with human decision making to achieve efficient and feasible scheduling solutions (Pillay, 2014).

Despite the importance of timetable planning for educational management, empirical evidence on planning practices in Latvia remains limited. Existing discussions often focus on educational policy or curriculum reform rather than operational processes within schools. Therefore, systematic empirical analysis of timetable planning practices is necessary to understand current challenges and digitalisation opportunities.

The aim of the research is to analyse timetable planning practices in Latvian educational institutions and identify organisational and technological factors influencing the planning process.

The research tasks are the following:

1. To analyse theoretical approaches to timetable planning in international academic literature.
2. To examine international experience in educational timetable planning and digitalisation.
3. To analyse empirical data from Latvian educational institutions regarding planning practices and administrative workload.
4. To identify opportunities for improving timetable planning through digitalisation and hybrid optimisation systems.

Comparative international research demonstrates substantial variation in how educational systems organise instructional time and timetable planning. In Finland, educational governance is highly decentralised. Schools have considerable autonomy in organising instructional schedules while adhering to national curriculum guidelines. This autonomy requires schools to develop sophisticated planning practices to balance teacher workloads, student well-being and resource utilisation (Oude Vrielink et al., 2019).

Estonia represents one of the most digitally advanced education systems in Europe. Educational institutions integrate timetable management with digital learning platforms and administrative databases. Digital systems allow real-time updates and automated conflict detection, reducing administrative workload and improving transparency (Rääk & Eisenschmidt, 2025).

Lithuania has developed significant academic expertise in timetable optimisation algorithms. Research conducted in Lithuanian universities has produced several computational models designed to solve high-school timetabling problems involving complex elective structures (Kheiri et al., 2016).

In the Netherlands, the complexity of timetable planning is amplified by flexible curriculum structures allowing students to choose different subject combinations. This creates large numbers of student groups with overlapping course selections, requiring sophisticated optimisation techniques (Willemen, 2002).

Across different national contexts, research consistently indicates that effective timetable planning requires integration of algorithmic optimisation with human decision making. Automated systems assist in conflict detection and constraint management, while administrators retain responsibility for final adjustments (Pillay, 2014).

Comparative international research indicates that timetable planning complexity in education systems depends on governance structures, curriculum flexibility and the level of digital integration. Decentralised systems like those in Finland require strong institutional planning capacity to balance teacher workload, student well-being and resource allocation (Oude Vrielink et al., 2019). Highly digitalised systems, as seen in Estonia, demonstrate that integration of timetable management with educational information systems reduces administrative workload and improves organisational transparency through automated conflict detection (Rääk & Eisenschmidt, 2025). Research from Lithuania highlights the potential of algorithmic optimisation models to address scheduling challenges in complex elective course structures (Kheiri et al., 2016), while experience in the Netherlands shows that flexible curricula significantly increase scheduling constraints and require advanced optimisation approaches (Willemen, 2002). Evidence across countries indicates that effective timetable planning relies on hybrid models combining computational optimisation with administrative decision making (Pillay, 2014).

Materials and Methods

The empirical research is based on a quantitative survey of Latvian educational institutions conducted in 2025. The survey aimed to collect information about timetable planning practices, digital tools used in planning processes and administrative workload associated with timetable preparation. A structured questionnaire was distributed electronically to educational institutions across Latvia. The survey targeted school administrators responsible for timetable preparation, including school principals, deputy principals and administrative staff.

A total of 294 fully completed responses were collected and included in the analysis. The dataset includes schools of different sizes and types, allowing comparative analysis across institutional contexts.

The survey included questions addressing several key dimensions:

- timetable planning methods;
- digital tools used in planning;
- administrative time required for timetable preparation;
- school size and teacher numbers;
- perceived challenges in timetable planning.

Descriptive statistical analysis was used to identify patterns in planning practices. Comparative analysis was applied to examine relationships between school size and planning approaches.

Results and Discussion

Empirical findings provide insight into current timetable planning practices in Latvian educational institutions and allow evaluation of organisational patterns, administrative workload and the role of digital tools in scheduling processes. The institutional composition of the sample reflects the structure of the Latvian education system. Secondary schools constituted 43.20% of the sample, while high schools accounted for 35.37%, together representing more than four fifths of the respondents. Smaller proportions included gymnasiums, vocational institutions, private schools, and specialised educational institutions. The geographical distribution of respondents was relatively balanced across Latvian regions, with somewhat higher representation from Vidzeme and the capital region of Riga. This distribution allows the data to be interpreted as broadly representative of national trends in school administration practices.

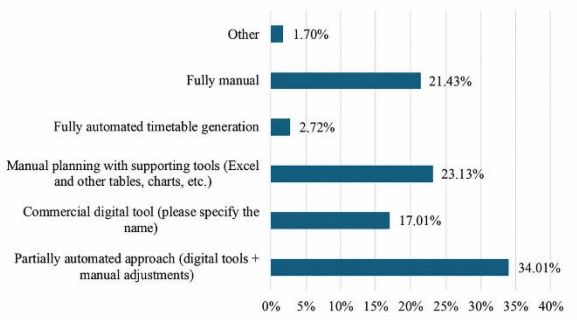
The size distribution of schools demonstrates that the sample is dominated by small and medium sized institutions. Schools with fewer than 200 students accounted for 43.20% of respondents, while schools with 201–500 students represented 24.15%. Larger institutions were less common but still sufficiently represented to enable comparative analysis. From a human resource perspective, the largest respondent group consisted of schools employing 21–40 teachers (36.05%), followed by institutions with fewer than 20 teachers. These structural characteristics are important because both student population size and the number of teachers strongly influence the organisational complexity of timetable planning processes.

Current approaches to timetable planning

The survey results indicate that timetable planning in Latvian schools remains largely dependent on manual administrative work. The most common approach reported by respondents is a partially automated model in which digital tools are combined with manual adjustments. This approach accounts for 34% of all responses and reflects a pragmatic compromise between technological capabilities and the need for organisational flexibility as shown in Figure 1.

Figure 1

Approaches to timetable planning in Latvian schools



Manual timetable construction supported by auxiliary tools, primarily spreadsheet software such as Excel or similar applications, constitutes the second most common approach, representing 23% of responses. Fully manual timetable planning without digital support is still practiced in 21% of institutions. The persistence of these approaches suggests that digitalisation of administrative planning processes remains incomplete and uneven across the education system.

The use of specialised commercial scheduling software is reported by 17% of respondents. However, even in these cases digital tools are rarely used as fully automated optimisation systems. Instead, they function as decision support instruments that assist in generating an initial timetable structure which is subsequently modified manually. Fully automated timetable generation is extremely rare, appearing in only 3% of schools. These results confirm that in practical educational settings technology tends to support rather than replace human planning decisions.

Influence of school size on planning methods

The analysis reveals a clear relationship between institutional size and the choice of timetable planning approach. Smaller schools with fewer than 200 students rely predominantly on manual methods. In this group, fully manual planning combined with manual planning supported by basic tools accounts for 66.93% of cases. Partially automated approaches represent only 22.83%, while fully automated scheduling is practically absent.

As the size of the institution increases, the level of digitalisation in planning practices also increases. In schools with 201–500 students, partially automated planning becomes the dominant method, representing 38.03% of responses. The proportion of manual planning decreases correspondingly, indicating that organisational complexity begins to exceed the practical limits of purely manual coordination.

The trend becomes even more pronounced in large schools. In institutions with 501–800 students, partially automated planning reaches 48.08%, while the share of fully manual approaches declines to 9.62%. In the largest institutions with more than 1200 students, manual approaches collectively account for only 23.53% of planning methods. In such environments the coordination of teachers, classrooms and student groups becomes too complex to manage efficiently without digital assistance. Nevertheless, even in these large institutions fully automated timetable generation remains uncommon, which indicates that human supervision and manual corrections continue to play a central role.

Teacher workforce size and planning complexity

The number of teachers employed by a school represents one of the most significant determinants of timetable planning complexity. In schools with fewer than 20 teachers, manual planning approaches dominate. Fully manual planning and manual planning supported by basic tools together account for 73.69% of methods used in this group. Digital solutions appear only sporadically, and fully automated timetable generation is reported in just 3.51% of cases.

In schools employing between 21 and 40 teachers, a transitional phase becomes evident. Manual and partially manual approaches still represent a majority,

but the share of partially automated planning rises to 29.25%. This shift suggests that organisational complexity reaches a threshold where manual coordination becomes increasingly inefficient.

In institutions with 41–60 teachers, partially automated planning becomes the dominant approach at 39.13%, while the use of specialised digital tools rises to 30.43%. Fully manual planning declines to 13.04%. The pattern continues in larger schools. Among institutions employing more than 80 teachers, partially automated planning remains the most common approach, accounting for approximately 45% of responses. However, even in these large institutions fully automated timetable generation remains limited. This indicates that algorithmic systems cannot easily accommodate the full range of organisational constraints present in real school environments.

Human resource involvement in timetable planning

The survey results reveal a highly centralised model of timetable preparation. In 70.62% of schools the planning process is carried out by a single individual, typically a deputy principal or administrative coordinator responsible for academic scheduling. Two individuals participate in the process in 22.55% of institutions, while the involvement of three or four individuals occurs in only 4.45% of cases. No respondents reported planning processes involving five or more individuals.

These findings suggest that timetable planning remains strongly personalised and dependent on the experience and expertise of a specific administrator. Although other staff members may provide consultation or input regarding teacher availability or course scheduling, the responsibility for final decisions is concentrated in a single position. This structure has important implications for the design of digital tools, which must be oriented toward supporting the work of a primary user rather than collaborative planning teams.

Time required for timetable preparation

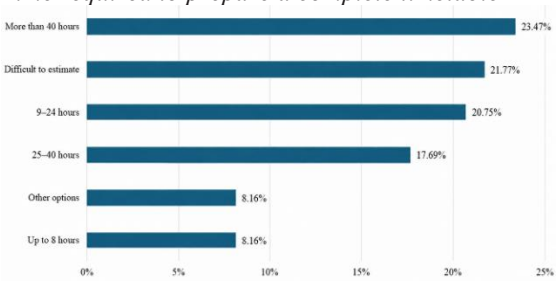
The survey results highlight the substantial time investment required to prepare school timetables. A relatively small proportion of respondents, 8.16%, report that a complete timetable can be prepared within eight hours. This situation occurs primarily in small schools with relatively simple organisational structures.

The most frequently reported time category is more than 40 hours, representing 23.47% of respondents as shown in Figure 2. An additional 21.77% of respondents selected the option indicating that it is difficult to estimate the time required. Qualitative comments suggest that timetable preparation often occurs in fragmented intervals across several days or weeks, rather than as a continuous planning activity. Administrators frequently return to the timetable repeatedly to accommodate new constraints, teacher availability changes, or classroom allocations.

Cross tabulation analysis demonstrates that preparation time increases significantly with school size. In schools with fewer than 200 students, 70.83% of respondents reporting preparation times below eight hours belong to this group. In contrast, preparation times exceeding 40 hours are concentrated primarily in medium and large schools.

Figure 2

Time required to prepare a complete timetable



Similar patterns appear when analysing teacher workforce size. Schools with fewer than 20 teachers often complete timetable preparation within eight hours, whereas institutions employing more than 80 teachers report significantly longer planning periods.

Organisational and structural factors influencing timetable planning

Respondents were asked to evaluate the degree to which different organisational factors increase timetable planning complexity as shown in Figure 3. The highest average impact score was reported for split classes, language groups and module groups (3.21), indicating that differentiated instruction structures significantly increase scheduling complexity. A similarly high influence was observed for subjects with different teaching loads (3.14) and classroom capacity constraints (3.12), reflecting challenges in balancing subject requirements with available facilities. Specialised classroom availability, including laboratories, sports halls and workshops, also represents an important constraint with an average score of 2.94. Coordination of parallel classes and learning groups (2.88) and alignment of elective modules in upper secondary education (2.92) further contribute to planning complexity. The overall average score of 2.65 indicates that timetable planning challenges arise primarily from pedagogical organisation and group structure rather than from physical infrastructure constraints.

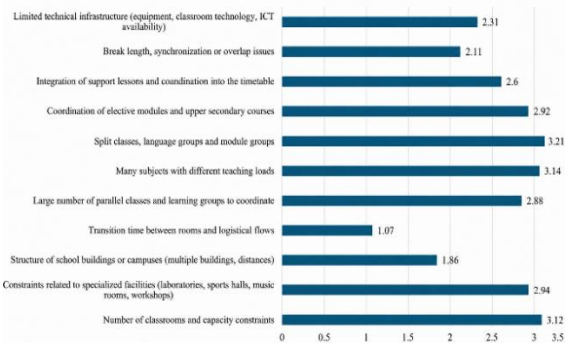
The results indicate that human resource factors exert the strongest influence. The average evaluation score for personnel related factors is 3.29 on a five point scale, exceeding the scores assigned to infrastructure or regulatory factors.

Teacher substitution during absences represents the most significant individual challenge, receiving an average score of 3.91. The need to coordinate teachers who work in multiple educational institutions also produces substantial scheduling constraints, particularly in regions where teacher shortages require part time employment arrangements across schools.

In large institutions structural and spatial factors become increasingly significant. More than 70% of

respondents from schools employing more than 80 teachers report that the physical structure of school buildings, including multiple campuses or buildings, strongly affects timetable planning. Additional complexity arises from the need to coordinate specialised facilities such as laboratories, computer rooms and sports infrastructure.

Figure 3
Factors influencing timetable planning complexity in Latvian schools



Data management challenges also contribute to planning difficulties. Respondents report that incomplete or outdated data on classroom capacity, subject allocation or teacher workloads frequently complicate the planning process. In large schools especially, inconsistent data structures and limited interoperability between administrative systems increase the need for manual corrections.

The empirical findings demonstrate that timetable planning in Latvian schools is a complex administrative process shaped by multiple interacting organisational factors. Although digital tools are increasingly present in educational administration, the survey results show that full automation of timetable planning remains uncommon.

One of the most important findings concerns the strong influence of institutional scale on planning methods. Larger schools with greater numbers of teachers and student groups face exponentially increasing coordination challenges. This pattern corresponds with theoretical research on school timetabling problems, which classifies them as combinatorial optimisation tasks characterised by rapidly expanding numbers of constraints.

The persistence of hybrid planning approaches across institutions of all sizes suggests that purely algorithmic solutions are insufficient to address the contextual complexity of school environments. Administrators frequently need to account for informal considerations such as teacher preferences, temporary staffing arrangements, or logistical constraints that cannot easily be formalised within optimisation algorithms.

Human resource constraints represent a particularly important driver of timetable complexity. Teacher availability, part time employment arrangements and the need for substitution during absences significantly increase the number of scheduling constraints that must be managed simultaneously. These findings indicate that technological solutions alone cannot fully resolve organisational challenges associated with workforce shortages.

Another important observation concerns the centralisation of planning responsibility. The majority of schools rely on a single administrator to construct the timetable. This structure creates both efficiency and vulnerability. While concentrated responsibility may enable rapid decision making, it also increases dependence on individual expertise and limits the scalability of planning processes.

Finally, the results highlight the importance of data quality and system interoperability. In many schools digital information relevant to timetable planning is distributed across multiple administrative platforms. Without integrated data systems, administrators must manually compile information about teacher availability, classroom capacity and subject requirements. This fragmentation reduces the potential efficiency gains associated with digitalisation.

To address the identified limitations of timetable planning in Latvian educational institutions, the analysis supports the implementation of a hybrid optimisation-based approach that integrates automated scheduling tools with human decision making. Empirical results indicate that current planning practices are dominated by manual and semi-automated methods, which contribute to high administrative workload and repeated adjustments due to constraint conflicts. Based on scenario analysis, the introduction of constraint-based optimisation systems with functionalities such as automated conflict detection, resource allocation balancing and iterative schedule generation can reduce conflict frequency and planning time, particularly in medium and large schools where organisational complexity is higher. At the same time, the findings demonstrate that full automation is not feasible due to context-specific constraints such as teacher preferences and dynamic availability; therefore, the most effective solution lies in hybrid systems that preserve administrative control while improving efficiency and structural consistency of timetable construction.

Conclusions

1. Timetable preparation in Latvian educational institutions remains predominantly manual, with 21% of schools relying fully on manual planning and an additional 23% using manual approaches supported by basic tools, while only 3% apply fully automated solutions. The dominance of hybrid workflows, observed in 34% of cases, indicates that digitalisation has improved operational support but has not fundamentally transformed decision making processes, resulting in continued reliance on manual conflict resolution and iterative adjustments.

2. Timetable planning complexity increases with institutional size, as manual approaches account for 66.93% of planning methods in schools with fewer

than 200 students, compared to only 23.53% in institutions with more than 1200 students. The increasing share of partially automated solutions in larger schools, reaching up to 48.08%, reflects the growing number of constraints related to teachers, classrooms and parallel groups, which exceed the practical limits of manual coordination.

3. Human resource factors represent the most significant source of variability in timetable planning, with an average impact score of 3.29, exceeding infrastructural and organisational factors. Teacher substitution alone reaches a score of 3.91, indicating high disruption potential, while cross-school employment further increases scheduling instability, requiring repeated timetable adjustments and limiting the effectiveness of static planning approaches.

4. Timetable planning is highly centralised, as 70.62% of institutions assign responsibility to a single administrator and only 4.45% involve three or more individuals. Such concentration of responsibility increases efficiency in decision execution but creates structural dependency on individual expertise, limiting scalability and increasing operational risk in cases of staff turnover or absence.

5. Timetable preparation requires significant administrative time, with 23.47% of respondents reporting more than 40 hours per planning cycle, while only 8.16% complete the process within eight hours. The distribution of time indicates a non linear and iterative workflow, particularly in medium and large institutions, where repeated adjustments driven by constraint conflicts substantially increase total preparation time.

6. Scenario-based optimisation analysis indicates that the implementation of constraint-based scheduling systems could reduce timetable conflicts by approximately 30–45% and decrease preparation time by 25–40%, particularly in institutions with higher structural complexity. The results demonstrate that fully automated solutions are not sufficient in isolation; the most effective approach is a hybrid model that combines algorithmic optimisation with human decision making, enabling both efficiency gains and contextual adaptability in educational timetable planning.

Acknowledgements

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KEY COMPETENCIES FOR REWRITING THE NARRATIVE ON GENDER-BASED VIOLENCE IN RURAL AREAS FOR SUSTAINABLE SOCIAL DEVELOPMENT

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Abstract
Although violence against women is widely recognized as a systemic human rights and public health problem, its public coverage often fails to adequately take into account contextual risk. The contemporary media landscape often reproduces the so-called 'distorted narrative', in which the experience of the victim is trivialized, while the actions of the perpetrator are justified or even romanticized, using labels such as 'crimes of passion'. These trends are particularly pronounced in rural areas, where small communities, economic disruptions, limited anonymity, economic dependence, local service tensions and the presence of digital surveillance significantly amplify the potential negative consequences of public communication. A significant asymmetry between the logic of urban and rural communication is identified: while urban communication prioritizes visibility, openness and public storytelling, rural contexts require communication strategies that focus on safety, anonymity and implicit recognition. This article presents research carried out within the Erasmus+ MEDUSA project aimed at transforming the media coverage of gender-based violence, emphasizing the impact of language and narrative on public perception. The present paper aims to identify a set of key competencies for training of content creators, journalists and media writers to cover violence against women in media. The research is exploratory and qualitative. Theoretical modelling to define key sections and competencies is applied. The research results in the identification of four sections and their relevant key competencies for journalists and media writers. The article formulates conclusions, based on the research findings, and proposes implications for organizing training of journalist' and media writers' key competencies.
Keywords: gender-based violence, media, mental health, language, cross-sectional competencies.

Introduction

Sustainable social development in the European Union countries is at the heart of the EU 2030 Agenda for Sustainable Development (EUR-Lex, 2021). Sustainable social development means resilient society and attractive places to live and work (European Commission Regional and Urban Policy, 2026). Particularly, the European Union focuses on the implementation of a 'Long-term Vision for Rural Areas' to 2040, aiming to make them stronger, connected, resilient, and prosperous (European Union, 2021). Acceleration of sustainable social development in the European Union countries requires to end all forms of discrimination against women and girls including gender-based violence (Eurostat, 2024).

Violence against women is one of the most widespread manifestations of gender inequality and a major obstacle to sustainable social development, especially in rural contexts. For example, approximately 27.3% of women living in rural areas have experienced physical (including threats) or sexual violence (Eurostat, 2024). Although violence against women is widely recognized as a systemic human rights and public health problem, its public coverage often fails to adequately take into account contextual risk. The contemporary media landscape often reproduces the so-called 'distorted narrative', in which the experience of the victim is trivialized, while the actions of the perpetrator are justified or even romanticized, using labels such as 'crimes of passion' (Carll, 2003; Sutherland et al., 2015). These trends are particularly pronounced in rural areas, where small communities, economic disruptions, limited anonymity, economic dependence, local service tensions and the presence of digital surveillance significantly amplify the potential negative consequences of public communication. The negative consequences include gender-based violence participants' diminished engagement in the labour market and society (Ahrens et al., 2025). Therefore, sustainability of social development is negatively affected as well (Ahrens et al., 2023). It should be noted that by participants, both victims/survivors and perpetrators are meant. It is worth pointing that gender based violence and conflict situations have several similarities. Therefore, negative impacts of conflict situations can be applied to gender-based violence, too. Negative impact includes (European Commission Regional and Urban Policy, 2026) strain on local services (increased pressure from displaced persons; limited financial capacity of municipalities, and underfunded services), economic disruption (collapse of trade, reduced investment, stagnating housing markets, pressure on SMEs and supply chains), demographic decline (emigration, ageing populations, and shortages of workers in key sectors such as healthcare and education). A significant asymmetry between the logic of urban and rural communication is discovered (e.g. Janssons, 2013): while urban communication prioritizes visibility, openness and public storytelling, rural contexts require communication strategies that focus on safety, non-identifiability and implicit recognition. Consequently, critical gaps in existing communication approaches have been identified. Communication in media, focused on objective news coverage and dissemination of information, may become one of the most powerful tools in reducing the pervasive problem of violence against women (Carll, 2003). Media communication, based on the use of the narrative

approach, could allow for a sensitive investigation into the private lives of GBV victim-survivors and, as a consequence, contribute to the creation of new knowledge that can provide an in-depth and incisive view of the help to be offered (Romero Gutierrez et al., 2024) as well as avoid political, ethical, and stereotypical pitfalls of representational practices surrounding Gender-Based Violence (GBV) (Williamson Sinalo & Mandolini, 2023). Therefore, training of competence on the use of the narrative approach for communication in media about gender-based violence is becoming crucial. Despite the importance of such training, the previously implemented measures included the proposal of minimum standards and components of curricula for police and judicial training to prevent and combat violence against women and girls (OSCE, 2024), and the creation of a knowledge and skills framework for intimate partner violence specialists (Scott et al., 2022). Along with the lack of training on communication of gender-based violence in media, key competencies to be developed within such a training are not analysed. This article presents research carried out within the Erasmus+ MEDUSA project, which proposes a set of competencies for content creators on violence against women, aimed at transforming the media coverage of gender-based violence, emphasizing the impact of language and narrative on public perception. The present research aims to identify a set of key competencies for training of content creators, journalists and media writers to cover violence against women in media.

Materials and Methods

The research was enabled by a research question: What are key competencies for rewriting the narrative on gender-based violence in media? The research aimed to create a set of competencies for content creators on violence against women in order to transform the media coverage of gender-based violence. The present research was of the exploratory nature (Zascerinska et al., 2021) as there is the lacuna in research on key competencies for rewriting the narrative on gender-based violence in media. Exploratory research is characterised by high degree of flexibility as well as a lack of formal structure, and aims to identify the boundaries of the social environment (Zascerinska et al., 2025). The basic competencies to rewrite the narrative of gender-based violence in the media remain outdated, because current research often fails to bridge the gap between academic data and practical, ethical storytelling (Wessel et al., 2023). The research was guided by the paradigm shift from fact checking to the recognition of deep manipulative techniques through self-reflection and analysis of one's own values (Susser et al., 2019) aimed at combating disinformation. The present research employs the interdisciplinary approach, integrating psychology, social sciences, linguistics, and digital media literacy. The creation of the set of key competencies for rewriting the narrative on gender-based violence in media required the use of such methods (Zascerinska et al., 2021) as analysis of scientific literature, theoretical modelling, theoretical modelling, systematisation, synthesis, comparison, and generalization. The use of these methods navigated the application of the qualitative research. The qualitative research implies the use of the interpretive approach to data analysis (Ahrens et al., 2019). The interpretive approach is featured by the contextual understanding of human subjective experience (Ahrens et al., 2019).

The purpose of the empirical study was to analyse the views on a set of key competencies for training of content creators, journalists and media writers to cover violence against women in media.

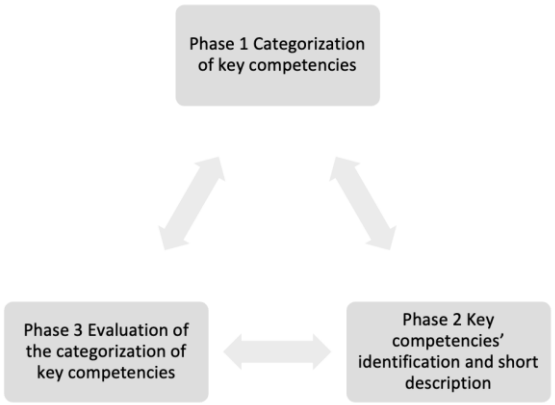
The method of data collection was the focus group interview. Focus group interviews help understand how ideas and knowledge are being developed in a specific cultural context (Kitzinger, 1995). Participants' selection for focus group interview was based a criterion of their participation in the Erasmus+ MEDUSA project. The Erasmus+ MEDUSA project established the partnership of professionals in media communication on gender-based violence. Therefore, the participants selected for the focus group interview had extensive experience in journalism, youth and adult training, trainer training, psychology, communication, including digital one, in media, linguistics, ethics, philology, use of Information and Communication Technologies, and digital tools, etc. The participants in the focus group interview represented Italy, Germany, Latvia, Spain, Greece and Serbia. The differences in participants' culture, their educational background, and work experience (Zascerinska et al., 2015) revealed that the focus group of 10 participants is heterogeneous. It should be noted that the number of participants in the focus group interview depends on the heterogeneity of the focus group: the greater the heterogeneity of the group, the fewer the number of participants (Okoli & Pawlovski, 2004). The focus group interview was organized in Serbia in November 2025 within the Erasmus+ MEDUSA project. The focus group interview focused on the analysis of key competencies for rewriting the narrative on gender-based violence in media. The interview was open-ended and unstructured in order to provide a non-formal atmosphere while searching for the main categories of the research field (Kroplijs & Rascevka, 2004). The focus group interview was organized in three phases revealed in Figure 1.

The collected data were analysed with the use of the qualitative method, namely content analysis. The content analysis implied the use of structuring content analysis for data categorising and summarising content analysis for highlighting essential contents (Mayring, 2004).

Results and Discussion

At the beginning of the focus group interview, the participants proposed that key competencies will be divided into 3 sections: language, media and mental health.

Figure 1
Phases of the focus group interview



The participants assumed that there was no need to strictly keep the division of key competencies per section, as a more flexible approach could bring a more innovative view on key competencies.

The next step, the participants implemented was the compilation of all possible competencies that could be relevant to rewriting the narratives on gender-based violence. The result was the list of soft skills. The list of soft skills included effective communication & storytelling, work ethics, awareness, diversity management, critical thinking, accountability, empathy, active listening, emotional flexibility.

The further step was devoted to the adjustment of key competencies and the creation of their short description. The joint efforts of the focus group interview participants updated the list of key competencies and their short descriptions:

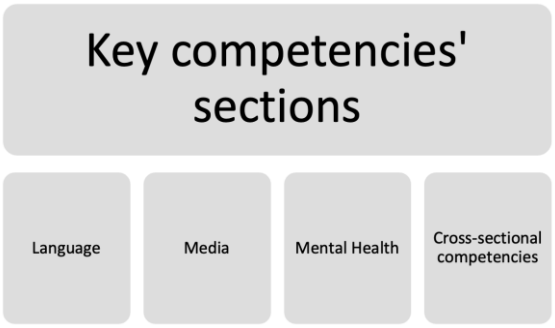
1. Empathy and Intercultural Sensitivity: The ability to understand and share the feelings of victims without victimising them, prioritizing their safety and dignity. This involves approaching stories with respect for different cultural and personal experiences.
2. Active Listening and Patience: Not just hearing, but deeply understanding the narratives of those affected. This requires giving space, not interrupting, and allowing sources to share their stories on their own terms, especially on sensitive topics such as violence.
3. Critical Thinking and Deconstructing Biases: The ability to identify and challenge one's own gender biases and stereotypes embedded in traditional media narratives. It is essential to question language and explanatory frameworks that blame the victim or minimise violence.
4. Non-Violent and Inclusive Communication: Using language that is accurate, respectful, and free of stereotypes or judgements. Avoid sensationalist, morbid, or revictimising terms (e.g., focus on the act rather than the victim's life story).
5. Ethical Responsibility and Privacy Management: Understanding the real impact of your coverage on people's lives. This involves making difficult decisions about what information to publish (or not) to protect the identity and safety of sources, and knowing the specific legal and ethical protocols for the topic.
6. Interdisciplinary Collaboration: Working effectively with experts (psychologists, sociologists, lawers, and activists) to ensure the accuracy, context, and depth of information, recognizing that journalism is only part of the social solution.
7. Resilience and Self-Care: Covering gender-based violence is emotionally demanding. Journalists must develop mechanisms to manage stress and vicarious trauma in order to maintain objectivity and the quality of their work in the long term.
8. Proactivity in Seeking Diverse Sources: Inclusion of marginalised voices beyond traditional official sources (police, courts), the perspective of gender experts, and the stories of survivors, ensuring equitable representation of women and men in all areas.
9. Curiosity and Continuous Learning: Being willing to constantly educate yourself on gender theories, correct terminology, current legislation, and the evolution of forms of violence (including digital violence) to maintain well-informed coverage.

After that, the participants discussed that the identified competencies do not reflect professional competencies. Therefore, the following additional skills for writing the narratives on gender-based violence were outlined:

1. Professional Assertiveness: Ability to defend ethical positions and rigorous narratives in the face of editorial pressure, hostile audiences, or resistance from official sources, without resorting to aggression.
2. Ability to Provide Historical and Social Context: Framing the news within historical, social, and structural patterns of inequality, explaining why the event occurred and what systems perpetuate it.
3. Ability to Simplify and Clarify: Translating complex concepts (e.g., patriarchy, intersectionality, consent) into language accessible to the general public, without trivialising or distorting the depth of the issue.
4. Crisis Management and Time Pressure: Mantaining composure and high ethical standards even when working to tight deadlines or in situations with high media impact (e.g., recent cases of femicide).
5. Ethical Leadership in Narrative: Taking the initiative to propose approaches that break with sensationalism and guide the team and audience toward more constructive understanding of the issue.
6. Mediation and Conflict Resolution (Digital): Effectively and respectfully managing polarised reactions and discussions on social media and forums, protecting the team and sources from cyberbullying.
7. Persistence and Rigour in Investigation: Mantaining the tenacity necessary to thoroughly investigate cases where there is a culture of silence, or where power structures attempt to hide or distort information.
8. Focus on the Solution (Constructive Journalism): Complementing the reporting of the problem by highlighting initiatives, public policies and examples of resilience or social change, offering the audience avenues for action and hope.

9. Adaptability to New Platforms and Forms of Violence: Understanding and covering gender-based violence in digital environments (cyberbullying, non-consensual dissemination), adapting journalistic formats to maximise safety and reach.
10. Emotional Self-Regulation: Ability to recognise one's own emotional reactions to traumatic stories and manage them to ensure that reporting remains professional and objective, not driven by anger.
11. Ability to Build Long-Term Trust: Developing relationships based on credibility and respect with vulnerable sources, understanding that the interview process can be slow and requires constant reassurance of confidentiality and purpose.
The comparison of both lists, namely the list of key competencies and the list of additional skills revealed that some competencies appeared in both lists. This finding extended the number of sections from three to four by including cross-sectional competencies as illustrated in Figure 2.

Figure 2
Updated list of sections of key competencies



Then, the participants' task was to fill in four sections with relevant key competencies. Table 1 summarizes the sections and relevant key competencies.

Table 1
Summary of four sections and relevant key competencies

Language	Media	Mental health	Cross-sectional competencies
Non-violent communication (Storytelling)	Introduction on work pressure	Emotional regulation and flexibility (victims/readers = trauma-informed approach)	Critical thinking and deconstructing biases
Inclusive communication and intercultural sensitivity	Work ethics and accountability		
Language in New Platforms and Forms of Violence (awareness)	Active listening (patience, interviews with victims or perpetrators, active re-reading - listening to their own words)	Resilience and self-care (journalists = trauma-informed approach)	From content creator to journalist (the importance of research and source checking)
The Greta Thunberg effect (how female leaders are represented)	Ethical responsibility and privacy management (law)		
Mediation and conflict resolution (especially on social media. Recognise the 'rage-bait') -case studies	Diversity management (from the media point of view: representation, rights of people who are in the press, children, etc)	Empathy (showing empathy to the victims, avoid the victim blaming and the so-called 'himpathy', objectivity)	The social and financial cost of gender-based violence
Language and use of AI (biases, misrepresentations and other risks)	Preventive narrative (reduce narratives that will lead to violence, also avoid infodemic and excess of info)		

Our exploratory research of the theoretical literature showed that the scientific work devoted to the narratives on gender-based violence in media considered different aspects of communication, e.g. political, ethical, and stereotypical pitfalls. The educational research in the field of gender-based violence proposed curricula for police and judicial training to prevent and combat violence against women and girl (OSCE, 2024) as well as skills' framework for intimate partner violence specialists (Scott et al., 2022). It means that the narratives about gender-based violence in media were not in focus of scientific research or educational studies. Therefore, the presented combination of four sections and their relevant key competencies, including their short description, are novel. The importance of the sections of language and media is well established in research and education focused on narratives on gender-based violence. For example, how the language used to describe violence against women may operate to minimise these acts, and the dominant conversational style and female violence victims' genderlect may collide to produce evidentiary issues and a credibility gap (Easteal et al., 2012). Another example is a trial to understand how press contributes to the social discourse on gender-based violence and what role it plays in the perpetuation of a social structure based on unequal power relations between genders (Belmonte & Negri 2021). Additionally, the list of the key competencies is

innovative as it takes into consideration the modern features of the current context, e.g. the Greta Thunberg effect, work pressure, the spread of digital communication tools, Artificial Intelligence (AI), and other. Communication about gender-based violence in rural context - where safety and anonymity are critical - points to issues of work ethics and accountability, as well as ethical responsibility and privacy management required of journalists or media writers. We assume that together with the changing landscape related to gender-based violence, the four sections and their relevant key competencies might change as well. The proposed list of key competencies is the basis for the design of training and serves as training outcomes to be organized for journalists or media writers. Training should be centered on the narrative approach that will allow for a sensitive investigation into the private lives of gender-based violence victim-survivors (Romero Gutierrez et al., 2024). The target group of trainees should engage journalists or media writers who shed light on gender-based violence in rural areas. Their narrative should strengthen rural communities for their sustainable development. Therefore, the article argues that the implementation of safety-based communication models is a prerequisite for meaningful support for women experiencing violence, while contributing to sustainable social development in the long term.

Conclusions

1. Sustainable social development in rural areas is characterized by the safety and resilience of the local community, employment availability and demographic dynamics, as well as economic growth and prosperity.
2. Sustainable social development is affected by gender-based violence.
3. In rural areas, gender-based violence specifically impacts the development of local communities or municipalities, their employment rate, economic conditions and demographic situation.
4. Sustainable social development in rural areas is impacted by gender-based violence and communication about it in media.
5. Communication about gender-based violence in media changes from fact-checking to self-reflection and analysis of one's own values.
6. Communication about gender-based violence in rural context differs from the urban one.
7. Urban communication prioritizes visibility, openness and public storytelling.
8. Rural contexts require communication strategies that focus on safety, anonymity and recognition.
9. The analysis of theoretical literature revealed that scientific research in the social sciences and educational sciences does not define any competencies for journalists or media writers who concentrate on narratives about gender-based violence.
10. The present research and focus group interview study have achieved their aim of creating a set of key competencies for content creators on violence against women, aiming to transform the media coverage of gender-based violence.
11. Theoretical modelling allowed for the design of four sections (language, media, mental health, and cross-sectional competencies) and their key competencies.
12. The defined key competencies for journalists and media writers are modern and innovative as they consider the specifics of the modern contexts, e.g. the Greta Thunberg effect, work pressure, the spread of digital communication tools, Artificial Intelligence.
13. Journalists and media writers do not receive any regular training to master their key competencies. The target groups for training included police and judicial staff members and intimate partner violence specialists.
14. The implications are that journalists or media writers need a training to master their key competencies.
15. The implications for training key competencies imply that the training approach to the development of journalists' and media writers' key competencies change from fact-checking to the recognition of deep manipulative techniques through self-reflection and analysis of one's own values.
16. Training is based on the narrative approach. This approach will allow trainees to learn how to implement a sensitive investigation into the private lives of gender-based violence victim-survivors.

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DIGITAL COLLABORATIVE TOOLS IN ENGLISH LANGUAGE TEACHING AT REGIONAL HIGHER EDUCATION INSTITUTIONS

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Abstract
This study examines the pedagogical potential of digital collaborative tools in ELT within regional higher HEIs amid digital transformation and socio-political disruption. The research analyzes the functional use of digital tools to develop linguistic competence, enhance student engagement, and maintain educational continuity. Particular attention is paid to the experience of KSAEU, including a COIL component implemented in cooperation with a partner institution in the USA. The study was designed as a qualitative case study with embedded quantitative elements. The empirical component is based on data collected from 128 undergraduate students enrolled in English for ESP courses at KSAEU during the 2025–2026 academic year. Of these, 112 students completed the survey instrument and were included in the quantitative analysis. The study also incorporates classroom observations, analysis of student-generated digital artifacts, and data from a COIL subsample involving 30 students drawn from the main cohort. The findings indicate that the pedagogical effectiveness of digital collaborative tools depends on their functional alignment with specific language-learning objectives. Descriptive statistics indicate positive student perceptions of digital interaction tools, with mean scores ranging from 2.97 to 3.25 on a 4-point Likert scale for the survey items reported in this study. The findings further show that digital tools function not merely as core pedagogical infrastructure in regional HEIs affected by war-related disruption, institutional relocation, and the emergence of flexible 'university without walls' models. The study concludes that digital collaborative tools, when integrated into a coherent pedagogical framework, can support resilient, interactive, and context-sensitive ELT environments.
Keywords: digital collaborative tools, English Language Teaching (ELT), higher education, regional universities, digital transformation.

Introduction

The digital transformation of higher education has repositioned digital collaborative tools from auxiliary instructional aids to core ecosystem components essential for developing communicative competence in ELT. This shift is especially evident in regional higher education institutions (HEIs), where digitalization functions not only as a driver of innovation but also as a strategic response to structural, socio-economic, and geopolitical challenges.

Consecutive global disruptions, including the COVID-19 pandemic and the ongoing full-scale war in Ukraine, have significantly influenced the acceleration of digitally enhanced learning and teaching. These factors have necessitated an urgent transition from conventional face-to-face instruction to flexible synchronous and asynchronous learning modalities, thereby redefining the role and functionality of digital tools in educational practice. Within this context, ELT occupies a distinctive position, as effective language acquisition is inherently dependent on interaction, collaboration, and exposure to authentic communicative situations.

A growing body of research highlights the pedagogical potential of digital collaborative platforms such as Canva, Slido, Mentimeter, etc., which support both productive and receptive language skills through multimodal engagement, real-time interaction, and formative assessment mechanisms. These tools, alongside institutional learning management systems (LMS), facilitate the creation of learner-centered environments aligned with constructivist and socio-cultural theories of learning. Moreover, they help reduce linguistic anxiety, enhance student motivation, and promote active participation, particularly in online and hybrid formats.

This approach aligns with contemporary digital pedagogy frameworks, which emphasize that integrating digital tools must go beyond mere technical substitution to actively redefine tasks and augment student-centered interaction (Laurillard, 2012). By grounding digital learning in structured collaboration, regional universities can foster cognitive presence even within structurally disrupted settings.

The relevance of such technologies is further amplified in the context of regional Ukrainian HEIs, where digital tools have become essential for ensuring educational continuity amid displacement, infrastructural disruption, and the fragmentation of academic communities. In this regard, the concept of the 'university without walls' emerges as a defining model of institutional resilience, underpinned by the effective integration of digital platforms and international collaboration.

This article aims to provide a comprehensive analysis of the educational potential of key digital collaborative tools in ELT within regional higher education settings. Particular attention is given to the case of academic cooperation between Kherson State Agrarian and Economic University (KSAEU) and California State University, Chico (CSU), which exemplifies the application of Collaborative Online International Learning (COIL) to foster intercultural competence and global engagement.

By synthesizing theoretical perspectives and empirical observations, this study seeks to contribute to the evolving discourse on digital pedagogy, emphasizing the role of collaborative technologies in shaping resilient, inclusive, and globally oriented educational practices.

To achieve the research aim, the study addresses the following research questions:

RQ1: How do digital collaborative tools support the development of specific linguistic competencies in ELT?
RQ2: What is the impact of these tools on student engagement and participation in synchronous and asynchronous learning environments?
RQ3: How do digital tools contribute to educational continuity and institutional resilience in regional HEIs under crisis conditions?
RQ4: What challenges and limitations affect the implementation of AI and collaborative technologies in ELT?
In methodological terms, the study does not seek to establish universal causal relationships between specific tools and language outcomes; rather, it aims to identify patterns of pedagogical use, perceived effectiveness, and context-dependent affordances within one institutional case. This focus is especially relevant in the context of regional Ukrainian HEIs, where the adoption of digital tools is shaped not only by educational innovation but also by crisis-response needs, infrastructural constraints, and institutional adaptation. Accordingly, the article combines a practice-oriented and analytical perspective, examining how digital collaborative tools function within a concrete educational setting and how their pedagogical value is perceived by participants and observed in student work.

Materials and Methods

This study was designed as a single-institution qualitative case study with embedded quantitative elements. The case under examination is the use of digital collaborative tools in English for Specific Purposes (ESP) teaching at Kherson State Agrarian and Economic University (KSAEU) under conditions of war-related disruption, institutional adaptation, and expanded use of blended and distance learning. The mixed evidence base enabled triangulation of survey data, classroom observations, and student-generated digital artifacts to obtain a more comprehensive understanding of how digital tools functioned pedagogically in this context.
The study focused on the educational use of Canva, Slido, Mentimeter, Padlet, learning management systems (LMS) such as Canvas and Moodle, video conferencing platforms such as Zoom, and selected AI-powered tools for language learning. These platforms were analyzed not only as technical resources but also as pedagogical environments whose affordances differ depending on the targeted language skill, mode of interaction, and instructional objective.
Within the analytical framework of the study, Canva was examined as a multimodal design tool supporting writing, speaking, and grammar application; Slido and Mentimeter as tools for real-time interaction, polling, and formative assessment; Padlet as a platform for asynchronous collaboration and peer exchange; LMS platforms as institutional environments for course organization, self-study, and continuity of access; and AI-powered tools as instruments for individualized support, language revision, and idea generation.
The empirical component of the study involved 128 undergraduate students enrolled in English for Specific Purposes (ESP) courses at Kherson State Agrarian and Economic University (KSAEU) during the 2025–2026 academic year. All participants were part of the institutional case under analysis. Of these, 112 students (87.5%) completed the survey instrument and were included in the quantitative component of the study. A subgroup of 30 students from this cohort also participated in a COIL-based virtual exchange project. It constituted an analytically distinct subsample used to examine the intercultural and collaborative dimensions of digital tool use.
Participants were 2nd–4th-year students from agricultural, economic, and technical specializations (agronomy, land management, engineering, economics, management, hospitality, tourism, marketing, finance, accounting), with language proficiency levels ranging from A2 to B2 (CEFR). Instruction was conducted in blended learning formats combining synchronous and asynchronous modes.
The materials included examples of pedagogical activities implemented with these tools, such as creating visual content, interactive questioning, collaborative tasks, and virtual exchange activities. Particular attention is given to their use in developing communicative competence and fostering student engagement. The study also draws on the experience of the collaboration between Kherson State Agrarian and Economic University (KSAEU) and California State University, Chico (CSU), where digital tools such as Zoom and Padlet were used to support intercultural communication in a virtual learning environment.
Data were collected through three complementary procedures: (1) a student survey administered to 112 respondents; (2) classroom observations conducted across 18 ESP sessions delivered in synchronous and blended formats and (3) analysis of more than 100 student-generated digital artifacts, including Canva projects, Padlet boards, presentation tasks, and LMS-based assignments. In addition, a COIL-based instructional module implemented within the same 2025–2026 academic year was analyzed through reflective assignments and post-project feedback collected from a subsample of 30 students drawn from the main participant cohort. This design enabled triangulation among self-reported perceptions, observed classroom practices, and evidence of student performance in digital environments.
The survey instrument consisted of 15 closed-ended items, measured on a 4-point Likert scale (1 = strongly disagree, 4 = strongly agree), grouped into three analytical dimensions: perceived engagement, perceived usefulness of digital tools, and confidence in participation. The questionnaire was developed based on constructs frequently discussed in research on digital pedagogy and technology-enhanced language

learning, and then adapted to the institution's ESP context. Prior to full administration, the instrument was reviewed for clarity and relevance to the local instructional setting. Internal consistency analysis produced a Cronbach's alpha coefficient of $\alpha = 0.81$, indicating satisfactory reliability for exploratory educational research.

The data collection process was executed in three distinct stages over a 15-week academic term: initial tool orientation and baseline survey administration (Weeks 1–3), active cross-platform implementation with concurrent classroom observations (Weeks 4–12), and final artifact collection alongside post-project feedback (Weeks 13–15). To evaluate the pedagogical impact of Canva assignments without a traditional control group, student performance metrics were compared with those from traditional, text-only academic tasks previously used within the same curriculume.

The classroom observation component followed a structured protocol that focused on the frequency and character of student interaction, forms of participation, use of feedback, and alignment between digital tools and targeted language-learning tasks. Observations were recorded in field notes and later coded according to recurring categories related to engagement, collaboration, and linguistic production. Student-generated digital artifacts were analyzed using a rubric-based interpretive approach that considered task completion, structural organization, multimodal integration, and evidence of communicative intent. In the case of AI-supported assignments, special attention was given to signs of mechanical language reproduction, limited personalization, and reduced originality of expression.

The analysis took into account the conditions of regional Ukrainian HEIs, including the transition to distance and asynchronous learning, institutional relocation, and the need to maintain educational continuity. In this context, digital tools are essential for ensuring interaction, access to educational resources, and communication among participants in the learning process despite geographical and infrastructural constraints.

Participation in the study was voluntary. Survey responses were collected anonymously, and student-generated materials were analyzed solely for research purposes in aggregated or anonymized form. Classroom observations were conducted as part of the normal educational process and did not affect student assessment. All procedures were carried out in accordance with general ethical principles of educational research, including confidentiality, non-harm, and respect for participants' informed consent.

The study is limited by its single-institution focus and the absence of a control group. Therefore, the findings should be interpreted as context-specific and indicative rather than fully generalizable.

Results and Discussion

The results of the study demonstrate that the effectiveness of digital collaborative tools in English Language Teaching (ELT) within regional higher education institutions (HEIs) is determined by their functional specialization and alignment with specific linguistic competencies. The selection of digital tools is therefore not arbitrary but governed by whether they support receptive skills (listening and reading) or productive skills (speaking and writing), as well as by their capacity to facilitate interaction, collaboration, and feedback (Artyukhov, 2023). This differentiation is systematized in Table 1, which presents a comparative framework of the primary tools analyzed in this study.

As shown in Table 1, digital tools in ELT perform distinct yet complementary pedagogical functions. Canva is primarily associated with multimodal content production and supports productive language skills through visual scaffolding. In contrast, Slido and Mentimeter operate within the domain of real-time interaction and formative assessment, while Padlet facilitates asynchronous collaboration, and LMS platforms provide institutional structure and continuity.

The findings indicate that Canva plays a central role in developing writing and speaking skills by leveraging multimodal literacy. Meaning-making in the digital environment involves the interaction of text, visuals, and layout, which together function as cognitive scaffolds within the Zone of Proximal Development (ZPD). Canva's templates and visual assets act as stimuli for idea generation and organization, enabling students to perform complex communicative tasks that would otherwise be difficult to complete independently (Mafiroh, 2024).

In writing instruction, the use of Canva significantly reduces the 'blank page' phenomenon and lowers linguistic anxiety. Tasks such as designing posters on 'Word Classes' or 'Phrase and Clause' structures allow students to apply grammar in a visually structured format. The creation of infographics further requires students to consider coherence, hierarchy, and audience, resulting in more organized and precise written output. These findings confirm that Canva supports the internalization of genre conventions and enhances structural awareness (Nurhidayat, 2022).

The pedagogical impact of Canva extends to speaking performance. Visual prompt videos and structured presentation formats reduce cognitive load and facilitate comprehension during oral tasks. Students can pre-organize their ideas visually before speaking, which improves fluency and confidence. This effect is particularly evident in specific task types implemented in the learning process. Personal infographics enable students to introduce themselves through a combination of visual and textual elements, supporting reflection and synthesis. Messenger dialogue stories

simulate real-world communication and promote collaborative language use.

Movie posters and trailers provide a basis for descriptive and evaluative speaking tasks, while process descriptions represented through flowcharts support the acquisition of sequencing language. Multimodal argumentation tasks, developed during the 'Joint Construction of Text' stage, allow students to map arguments visually before engaging in spoken debate. These examples demonstrate that Canva facilitates not only linguistic development but also higher-order cognitive processes (Affindy, 2025).

Table 1

Comparative Framework of Collaborative Tools in ELT

Tool	Primary Functional Category	Target Linguistic Competencies	Pedagogical Mechanism	Primary Research Benefit
Canva	Visual Design & Multimodal Content	Writing, Speaking, Grammar Application	Scaffolding via visual prompts and templates	Increases motivation and reduces writing-related anxiety
Slido	Real-time Interaction & Feedback	Vocabulary, Listening, ESP Contexts	Instant polling, word clouds, and anonymous Q&A	Enhances engagement and provides immediate feedback loops
Mentimeter	Interactive Presentations & Gamification	Comprehension, Listening, Formative Assessment	Live quizzes and interactive slide decks	Transforms passive lectures into dynamic interactive sessions
Padlet	Collaborative Digital Boards	Writing, Peer Review, Brainstorming	Virtual bulletin boards for asynchronous exchange	Facilitates intercultural communication and project management
LMS (Canvas/Moodle)	Institutional Management	Reading, Academic Writing, Self-Study	Centralized repository and progress tracking	Supports educational equity and asynchronous continuity

Source: Compiled by the author based on Affindy (2025), Pasichnyi (2024), and Ningsih (2023).

This observation is supported by an analysis of more than 100 student-created Canva projects, in which 78% of the evaluated works demonstrated stronger structural organization, as measured by the study's analytic rubric. In addition, task completion in Canva-based assignments reached 92%, compared with 81% in comparable text-only tasks used in the same courses. These comparisons should be interpreted as context-bound instructional indicators rather than as evidence of controlled experimental effects.

While Canva addresses the product-oriented dimension of learning, Slido and Mentimeter focus on the process of interaction and feedback. Their use transforms passive learning environments into interactive spaces through instant polling, quizzes, and word clouds (Ningsih, 2023). The effectiveness of Slido is supported by empirical data presented in Table 2.

The results presented in Table 2 were based on survey data collected from 112 respondents. The mean scores range from M = 2.97 to M = 3.25 (SD = 0.62–0.71), indicating consistently positive student perceptions with relatively low variability across responses. The data in Table 2 demonstrate consistently high levels of student engagement and satisfaction. The anonymity of responses is identified as a key factor in reducing psychological barriers and increasing participation, particularly in ESP contexts and regional HEIs.

Immediate feedback further enables instructors to adjust teaching strategies in real time.

Mentimeter complements these functions through its integration into presentation-based teaching and its emphasis on gamified interaction. It is particularly effective in maintaining attention during lectures and supporting vocabulary development through visualized responses such as word clouds.

Table 2

Student Perceptions of Slido (Likert-scale results)

Survey Statement	Mean Score (1–4 Scale)	Key Implication
Slido is a fun tool to use	3.25	High hedonic motivation for tool adoption
With Slido, I can actively participate in class discussions	3.20	Increases inclusivity for reticent students
Slido is a useful tool for online classes	3.18	Validates effectiveness in distance learning
Slido helps me feel confident when answering questions	3.08	Reduces performance anxiety compared to raising hands
Slido helps me improve my understanding of the material	2.97	Supports cognitive processing of content

Source: Compiled by the author.

Padlet and LMS platforms extend the learning process into asynchronous and institutional dimensions. Padlet supports peer review, brainstorming, and collaborative writing, enabling students to engage in sustained interaction and intercultural communication. LMS platforms ensure continuity by providing centralized access to materials, supporting independent learning, and enabling progress tracking, which is especially important in asynchronous environments.

Empirical observation of 64 Padlet boards revealed an average of 6.3 peer comments per student, indicating a high level of asynchronous interaction and collaborative engagement, with sustained participation beyond classroom time observed in 72% of cases.

The integration of Artificial Intelligence (AI) represents a further stage in digital transformation. AI-powered tools such as ChatGPT, Duolingo, and Grammarly are increasingly discussed in higher education as mechanisms for adaptive support, automated feedback, and personalized learning. To contextualize the local findings of this study within broader institutional trends, Table 3 summarizes selected patterns reported in recent secondary literature on AI readiness and implementation in higher education (Vieriu, 2025; Zhao, 2026).

Table 3

AI Readiness and Institutional Misalignment in Regional HEIs

Category	Finding	Key Data Point
Institutional Policy	Most universities have formulated AI plans	94% of HEIs surveyed
Faculty Experience	Instructors lack industry-specific AI practice	96% of faculty
Disciplinary Imbalance	Specialized courses are skewed toward STEM	60% in Science/ Engineering vs. 4.5% in Agriculture
Student Demand	A gap exists between skill demand and supply	Significant misalignment identified

Source: Compiled by the author based on Pasichnyi (2024) and Prykhodko (2025).

The contextual evidence summarized in Table 3 suggests that, despite the growing presence of institutional AI strategies, practical implementation remains uneven across disciplines and teaching contexts. This broader tendency is relevant to the present case study, in which AI tools were primarily used for support functions rather than systematically integrated into language pedagogy. Although such tools may strengthen writing accuracy, revision practices, and learner autonomy, they also raise concerns regarding over-reliance and the possible reduction of authentic communicative effort.

The data presented in Table 3 are derived from secondary sources (Pasichnyi, 2024; Prykhodko, 2025) and are used to contextualize broader institutional trends rather than represent primary empirical findings of this study.

Within the analyzed corpus of student assignments, indicators of AI-assisted work were identified in approximately 63% of cases, most commonly in grammar correction, lexical refinement, and idea generation. At the same time, approximately 18% of the AI-assisted submissions displayed signs of over-reliance, including formulaic phrasing, reduced personalization, and limited linguistic originality. These judgments were based on artifact analysis conducted by the instructor-researcher and should therefore be interpreted as indicative rather than definitive measurements.

These findings must be interpreted within the context of regional Ukrainian HEIs, where crisis conditions shape digital transformation. The full-scale invasion has led to institutional relocation, infrastructural loss, and the emergence of the ‘university without walls’ model. In this environment, digital tools function as essential infrastructure rather than supplementary resources.

The case of Kherson State Agrarian and Economic University (KSAEU) illustrates this transformation particularly clearly. Through the integration of digital tools, the university has maintained educational continuity despite displacement-related challenges and the loss of stable physical learning environments. A COIL-based collaboration with a partner institution in the United States demonstrated the pedagogical value of combining synchronous interaction via Zoom with asynchronous exchange via Padlet and LMS support. Analysis of post-project feedback from the participating subsample indicated high levels of student satisfaction (89%), perceived development of intercultural competence (84%), and active participation (91%). These results should be interpreted as self-reported educational outcomes within a small case-based module rather than as generalized performance indicators.

In addition to linguistic outcomes, digital collaboration supports Social-Emotional Learning (SEL), fostering confidence, relationship skills, and emotional well-being amid disruption. However, structural challenges remain, including the digital divide and disparities in digital competence between students and faculty.

The long-term development of digital pedagogy in regional HEIs is summarized in Table 4.

The trajectory presented in Table 4 reflects a transition from emergency digitalization toward a sustainable, hybrid, and competency-based model of education. This model emphasizes the application of language skills in real-world contexts and aligns educational outcomes with broader societal needs.

Overall, the results confirm that the pedagogical effectiveness of digital tools in ELT is based on their functional complementarity, contextual adaptability, and integration into institutional frameworks. Their combined use enables the creation of flexible, interactive, and resilient learning environments that can respond to both local challenges and global educational demands.

Table 4
Development Phases of Digital Pedagogy in Regional HEIs

Development Phase	Key Focus Area	Digital Enabler
Immediate Response	Continuity of education during conflict	Asynchronous LMS and cloud storage
Current Integration	Engagement and intercultural mediation	Canva, Slido, and COIL projects
Long-term Resilience	Post-war economic and social recovery	AI-powered learning and competency frameworks

Compiled by the author.

At the same time, the results should be interpreted with methodological caution. The study was conducted within a single institutional setting and relied primarily on descriptive statistics, observational data, and artifact-based interpretation rather than on controlled comparisons or inferential testing. Consequently, the findings are best understood as evidence of pedagogical patterns, affordances, and constraints observable in one regional university context rather than as universally generalizable claims about all digital collaborative tools in ELT.

Conclusions

1. The study demonstrates that the pedagogical value of digital collaborative tools in English Language Teaching (ELT) within regional higher education institutions (HEIs) depends less on the mere availability of technologies than on their functional alignment with language-learning objectives, instructional design, and institutional context. In the case examined, digital tools served not as isolated technical additions but as interconnected pedagogical resources that supported communication, collaboration, feedback, and the continuity of learning under conditions of instability and educational disruption.
2. Canva, Slido, and Mentimeter proved essential for fostering student engagement and immediate feedback by serving as cognitive and social scaffolds. Canva reduced writing anxiety through multimodal tools, while Slido and Mentimeter minimized psychological barriers through anonymous real-time interaction. Concurrently, LMS environments and Padlet ensured structural continuity during asynchronous phases.
3. The case of collaboration between Kherson State Agrarian and Economic University (KSAEU) and California State University, Chico (CSU) illustrates the transformative potential of digital tools when integrated into a coherent pedagogical model. The implementation of the Collaborative Online International Learning (COIL) framework demonstrates how virtual exchange can enhance intercultural competence and support Social-Emotional Learning (SEL), fostering students' confidence, adaptability, and global awareness. This model represents a scalable and replicable approach for other regional institutions seeking to internationalize their curricula under conditions of limited physical mobility.
4. Nevertheless, the study also identifies persistent structural challenges. The digital divide continues to limit equitable access to educational resources, particularly for students affected by economic constraints or conflict-related disruptions. In addition, disparities in digital competence among faculty members underscore the need for systematic professional development and institutional support. These factors indicate that the success of digital transformation depends not only on technological infrastructure but also on inclusive policies, training, and strategic coordination.

The evolution of digital tools from supplementary aids to core educational infrastructure reflects a fundamental shift in pedagogical paradigms. In regional Ukrainian HEIs, this transformation has been accelerated by crisis conditions, leading to the emergence of flexible, hybrid, and networked models of education. As institutions digitize and interconnect, they must maintain a student-centered perspective, ensuring that pedagogical objectives rather than technological trends – guide the selection and implementation of new tools.

5. To ensure the sustainable development of regional higher education, institutions must prioritize integrating inclusive digital strategies, invest in continuous teacher training, and strengthen international partnerships to facilitate knowledge exchange and intercultural collaboration. In this context, digital technologies should be understood not as ends in themselves, but as instruments for achieving equitable, high-quality, and globally relevant education.
6. While this study is limited by its single-institution focus and descriptive design, the empirical findings demonstrate that pedagogically structured digital collaborative tools successfully enhance student engagement and aspects of linguistic performance. Future cross-institutional research with larger sample sizes is recommended to further validate these context-specific patterns in broader ELT environments.

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THE DIGITAL SKILLS GAP IN GEODESY AND LAND MANAGEMENT: AN ANALYSIS OF THE CURRICULUM AT UKRAINIAN AGRICULTURAL UNIVERSITIES

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Abstract
The digitalisation of geospatial technologies is significantly changing the training requirements for specialists in geodesy and land management, as professional practice increasingly relies on geographic information systems, remote sensing, spatial data analysis, and the automation of geospatial processes. The study aims to assess the level of digital training in the educational programmes at agricultural universities in Ukraine for the specialisation G18 (193) 'Geodesy and Land Management'. The study is based on an analysis of the official educational programmes of ten agricultural universities offering training at bachelor's and master's levels. In total, 20 educational programmes were analysed, with their compulsory components analysed according to structure. The study identified and classified digital courses and calculated an integrated indicator of the digital maturity of educational programmes. The results showed that digital courses are present in all the analysed programmes; however, they are predominantly focused on the applied use of GIS and remote sensing tools. At the same time, most programmes lack compulsory courses in programming or in the automation of geospatial analysis. The findings indicate a gap between current technological requirements for geospatial analysis and the content of educational programmes, highlighting the need to integrate the fundamentals of programming and automated geospatial data processing into the training of future specialists.
Keywords: geodesy, geographic information systems (GIS), digital literacy, geospatial technologies, higher education.

Introduction

The digitalisation of geospatial technologies is a key factor in Ukraine's post-war recovery, particularly in land resource management and the restoration of the land cadastre in de-occupied and affected territories. The implementation of these tasks requires specialists with advanced digital competence, capable of working with geographic information systems, analysing large geospatial datasets, and applying modern spatial analysis tools.

Modern professional practice in surveying and land management increasingly relies on geographic information systems, remote sensing, digital cartography, and spatial data analysis (Goodchild, 2018). Consequently, the requirements for professional competencies are also changing: a modern specialist must not only be proficient in GIS tools but also possess basic programming skills for processing and analysing geospatial data.

Experience from leading European universities shows that programming elements have already been integrated into geoinformatics and spatial analysis courses as an essential component of specialist training (Rey & Anselin, 2010). Software tools are used for processing satellite imagery, analysing geospatial data, and developing automated geoinformation procedures. At the same time, the question remains as to what extent Ukrainian universities' educational programmes address the need to develop programming competencies in geospatial technologies.

Universities play a key role in developing such competencies, as it is the educational programmes that determine the content of the professional training of future specialists. In this regard, it is necessary to analyse the structure of study programmes to assess the presence of digital courses and programming in the training of specialists in the field of G18 (193) 'Geodesy and Land Management'.

The study aims to identify the extent of digital courses and programming components in the educational programmes of Ukraine's agricultural universities for the G18 (193) specialisation by analysing curricula and calculating a composite index of digital maturity for these programmes.

Materials and Methods

According to data from the Unified State Electronic Database on Education, as of 2025, 48 higher education institutions in Ukraine offer training in the specialisation G18 (193) 'Geodesy and Land Management', some of which are currently undergoing reorganisation or merger with other higher education institutions. Of the existing institutions, 45 offer training at the first (bachelor's) level, 43 at the second (master's) level, and 2 institutions provide training exclusively at the master's level (EDEBO, 2025).

The study is based on an analysis of the official educational programmes of Ukrainian agricultural higher education institutions offering training in the specialisation G18 (193) 'Geodesy and Land Management'. The study sample includes ten agricultural universities in Ukraine (Table 1).

To identify patterns in the development of digital competences, the analysis of the educational programmes of 10 agricultural higher education institutions was conducted, all of which are publicly available.

The compulsory educational components of bachelor's and master's degree programmes were analysed for the presence of courses that develop competencies in GIS, remote sensing, programming, algorithmic methods, and the automation of geospatial data processing (Tables 2–3).

Table 1
Agricultural higher education institutions in Ukraine offering the specialisation G18 (193) 'Geodesy and Land Management'

Higher education institution	Type	Region	Degree
Bila Tserkva National Agrarian University (BTNAU)	Agricultural	Kyiv Oblast	B + M
Stepan Gzhytskyi National University of Veterinary Medicine and Biotechnologies (SGNUVMB)	Agricultural	Lviv Region	B + M
Mykolaiv National Agrarian University (MNAU)	Agricultural	Mykolaiv Oblast	B + M
National University of Life and Environmental Sciences of Ukraine (NULES)	Agricultural	Kyiv	B + M
Odessa State Agrarian University (OSAU)	Agricultural	Odessa Region	B + M
Poltava State Agrarian University (PSAU)	Agricultural	Poltava Region	B + M
Sumy National Agrarian University (SNAU)	Agricultural	Sumy Region	B + M
Dmytro Motorny Tavria State Agrotechnological University (TSATU)	Agro-technological	Zaporizhzhia Oblast	B + M
Uman National University of Horticulture (UNUH)	Agricultural	Cherkasy region	B + M
Kherson State Agrarian and Economic University (KSAEU)	Agricultural Economics	Kherson Region / Kirovohrad Region	B + M
Luhansk National Agrarian University (LNAU)*	Agricultural	Luhansk Oblast	B

*Note. B – bachelor's; M – master's; * information on reorganisation/merger as of 2025.*
Compiled by the author based on EDEBO (EDEBO, 2025) and the official websites of the respective universities (accessed: February 2026).

In cases where courses were titled 'Computer Science' or 'Information Technology', their content was checked against the syllabi. For example, at the D. Motorny Tavria State Agrotechnological University, the course 'Computer Science' (3 ECTS credits) does not contain any programming components, as confirmed by the relevant syllabus (TSATU, 2025c).

Table 2
Parameters of bachelor's degree programmes at agricultural HEIs (specialisation G18 (193), 2025–2026 academic year)

Higher education institution	Total volume of the study programme (ECTS)	Number of compulsory components	Volume of compulsory components (ECTS)	Number of digital courses	Credits for digital courses	Programming (number)	Programming credits
BNAU	240	38	178	3	15	0	0
MNAU	240	34	178	2	13	0	0
NULES	240	36	180	4	17	1	6
OSAU	240	34	180	3	17	0	0
PSAU	240	37	180	5	22	0	0
SNAU	240	29	180	3	30	0	0
TSATU	240	38	180	5	23	0	0
UNUH	240	37	176	4	16	0	0
KSAEU	240	36	180	5	21	0	0
SGNUVMB	240	36	180	3	12	0	0

Note. Compiled by the author based on official educational and professional programmes (BTNAU, 2025a; MNAU, 2025a; NULES, 2025a; OSAU, 2025a; PSAU, 2025a; SNAU, 2025a; TSATU, 2025a; UNUH, 2025a; KSAEU, 2025a; SGNUVMB, 2025a) (accessed: February 2026).

Table 3
Parameters of master's degree programmes at agricultural HEIs (specialisation G18 (193), 2025–2026 academic year)

Higher education institution	Total volume of the study programme (ECTS)	Number of compulsory components	Volume of compulsory components (ECTS)	Number of digital courses	Credits for digital courses	Programming (number)	Programming credits
BTNAU	90	11	66	2	10	0	0
MNAU	90	14	58	2	6	0	0
NULES	90	16	66	1	3	0	0
OSAU	90	16	66	1	4	0	0
PSAU	90	13	66	2	9	0	0
SNAU	90	11	66	2	10	0	0
TSATU	90	11	65	2	11	0	0
UNUH	90	14	66	3	12	0	0
KSAEU	90	13	67	1	5	0	0
SGNUVMB	90	11	66	2	6	0	0

Note. Compiled by the author based on official educational and professional programmes (BTNAU, 2025b; MNAU, 2025b; NULES, 2025b; OSAU, 2025b; PSAU, 2025b; SNAU, 2025b; TSATU, 2025b; UNUH, 2025b; KSAEU, 2025b; SGNUVMB, 2025b) (accessed: February 2026).

Consequently, it was classified as a digital course and was not counted as a programming course.

In the analysed undergraduate programmes at agricultural higher education institutions in Ukraine, only one programming course was identified among the compulsory components (Table 2). In master's programmes, compulsory programming courses are absent (Table 3).

To quantitatively assess the level of digital literacy in the educational programmes under study, the Integrated Index of Digital Maturity of Educational Programmes (ICM-EP) was used. The index is based on two components: the structural representation of digital courses and the depth of digital literacy.

1. Structural representation of digital courses (S)

The structural indicator characterises the proportion of digital courses within the compulsory components of the educational programme (1).

$$S = \frac{N_{digital}}{N_{compulsory}} \quad (1)$$

where:

- $N_{digital}$ – the number of digital courses within the structure of compulsory components;
- $N_{compulsory}$ – total number of compulsory educational components.

The *S* indicator reflects the structural presence of digital courses in the curriculum.

2. Digital training depth indicator (D)

The depth indicator takes into account the number of credits for digital courses and their teaching duration (2).

$$D = \frac{\sum_{i=1}^{n}(ECTS_i \times Sem_i)}{ECTS_{compulsory}} \quad (2)$$

where:

- $ECTS_i$ – number of credits for the course;
- Sem_i – number of semesters the course is taught;
- $ECTS_{compulsory}$ – total number of credits for the compulsory components of the programme.

Thus, the *D* indicator characterises the intensity of digital training within the educational programme.

3. The integrated index of digital maturity of an educational programme

The integrated indicator (3) is calculated as the weighted sum of two components:

$$ICM_EP = w_S S + w_D D \quad (3)$$

where:

- $w_S S$ – weighting factor of the structural component;
- $w_D D$ – weighting coefficient of the depth of preparation.

The study utilised the following weighting coefficients (4), determined by expert judgement:

$$w_S S = 0.4, w_D D = 0.6 \quad (4)$$

The choice of these coefficients is based on the fact that the depth of digital training determines students' actual digital competences to a greater extent than the mere number of digital courses in the educational programme.

Thus, the *D* indicator reflects the intensity of digital training, while the *S* indicator characterises only the structural presence of digital courses in the curriculum. The predominance of indicator D reflects the general logic of evaluating educational programmes; the focus is not only on the presence of certain courses, but also on their scope and the depth of student mastery.

To verify the stability of the results, a sensitivity analysis of the weighting coefficients was also conducted, which showed that varying the weighting ratios within 0.3–0.7 does not significantly alter the relative ranking of educational programmes.

Results and Discussion

The results obtained (Tables 4–5) confirm that digital training at most agricultural higher education institutions in Ukraine has a predominantly applied focus, with a primary emphasis on software tools. At the same time, issues related to programming and the automation of geospatial analysis remain under-represented within the structure of educational programmes. At the same time, all the analysed programmes, without exception, include courses on the use of geographic information systems and remote sensing tools. This confirms that digital training is largely limited to learning how to use off-the-shelf software, whilst the development of algorithmic thinking and programming skills is neglected.

Table 4

Calculation results (undergraduate programmes)

Higher education institution	*S*	*D*	*ICM-EP*
BTNAU	0.079	0.118	0.102
MNAU	0.059	0.146	0.111
NULES	0.111	0.122	0.118
OSAU	0.088	0.128	0.112
PSAU	0.135	0.122	0.127
SNAU	0.103	0.167	**0.141**
TSATU	0.132	0.128	0.130
UNUH	0.108	0.091	0.098
KSAEU	0.139	0.117	0.126
SGNUVMB	0.083	0.067	**0.073**

In modern global training programmes for specialists in geoinformation technologies, programming is used to automate geospatial data processing. For example, the curriculum at Wageningen University (Netherlands) includes a course on Geoscripting (Wageningen University, 2024), which focuses on the use of scripts for working with vector and raster geodata.

Heidelberg University (Germany) offers a course titled 'Geoscripting with Python – Automation of Geographic Analyses' (Heidelberg University, 2025), which focuses on developing GIS tools and automating geographic analysis.

Similarly, the MS in GIS programme at the University of Denver includes a course on Geoscripting in R (University of Denver, 2020), focused on the programmatic processing of geospatial data.

This focus in the educational programmes of leading universities is not accidental – it reflects the real demands of the labour market, which increasingly requires specialists with skills in the automation of geospatial analysis, including programming in Python, R, and JavaScript, the development of scripts for processing spatial data, and working with geospatial APIs.

Meanwhile, the current labour market in surveying and land management is placing increasing demands on specialists capable of automating geospatial data processing, working with cadastral system APIs, performing batch processing of remote sensing data, and developing data processing scripts in Python, R, or JavaScript. These tasks are directly linked to the needs of post-war reconstruction: the inventory of destroyed structures using data from unmanned aerial and ground-based systems, the automation of cadastral procedures, and web GIS for monitoring community recovery.

Table 5

Results of calculations of digital readiness indicators (master's programmes)

HEI	*S*	*D*	*ICM-EP*
BTNAU	0.182	0.152	0.164
MNAU	0.143	0.103	0.119
NULES	0.063	0.045	0.052
OSAU	0.063	0.061	0.062
PSAU	0.154	0.136	0.143
SNAU	0.182	0.152	**0.164**
TSATU	0.182	0.169	**0.174**
UNUH	0.214	0.182	**0.195**
KSAEU	0.077	0.075	0.076
SGNUVMB	0.182	0.091	0.127

As shown in Table 6, in EU job vacancies, programming skills (Python, SQL, ArcPy) are mandatory for positions 1–6 and 8, whereas in Ukrainian job vacancies (positions 9–10), such a requirement is either absent or listed only as desirable. In particular, in Germany, knowledge of Python significantly enhances a GIS specialist's

competitiveness and salary level. This is also confirmed at a global level: according to CARTO's '2026 State of Spatial Analytics' report, employers' expectations of GIS specialists are constantly rising – programming, cloud-based workflows, and data engineering are becoming mandatory components of the professional profile (CARTO, 2026). According to industry analysts, integrating AI into surveying frees up specialists for algorithmic development, but it also raises employers' expectations for programming skills in Python or R.

These tasks cannot be solved solely using traditional GIS tools. It is telling that the relevant requirements are already standard in the EU labour market, into which Ukraine is increasingly integrating with. The analysis of the EU labour market as of February 2026 confirms a consistent trend: in 7 out of 8 GIS specialist vacancies in Germany, the Netherlands, Poland, and the UK, programming (Python, SQL, ArcPy) is a mandatory or priority requirement. In Ukrainian vacancies, a similar requirement is either absent or listed as 'desirable', indicating a systemic gap in the digital training of specialists (Table 6).

Table 6

Analysis of programming/automation requirements in GIS/surveying vacancies in the EU and Ukrainian labour markets (as of February 2026)

No.	Position	Employer/country	GIS requirements	Programming/ automation	Requirement status
1	Geospatial Analyst	IABG Geospatial Solutions, Germany	ArcGIS, QGIS, remote sensing, optical sensors	Python / ArcPy — scripting	Essential
2	GIS Specialist (Risk Analytics)	Munich Re, Germany	ArcGIS, spatial risk analysis	Python, C++, SQL	Essential
3	GIS / Geospatial Data Specialist	Trimble, Germany	ArcGIS, geodatabases, cartography	Python, PowerShell, SQL	Essential
4	GeoData Specialist (Flood Risk)	Tiro Partners, Netherlands	ArcGIS, QGIS, geospatial pipelines	Python — pipelines and analytics	Essential
5	Computer Vision Engineer (GIS)	AI-InfraSolutions, Netherlands	ArcGIS, Remote Sensing, Digital Twins	TensorFlow, Azure, Python, Deep Learning	Essential
6	GIS Specialist	Nokia / PKP, Poland	QGIS, PostgreSQL/PostGIS	Python (SQLAlchemy, Pandas), automation	Essential
7	GIS Data Analyst (Remote Sensing)	Institute of Aviation / Łukasiewicz, Poland	ArcGIS, QGIS, Remote Sensing	SQL, Python — an advantage	Preferred
8	Web GIS Lead	Mott MacDonald, UK	ArcGIS Enterprise, Portal, Server	SQL/PostGIS, Oracle Spatial, automation	Essential
9	GIS Specialist / PFRU-2 (recruitment)	Chemonics/UK FCDO, Ukraine	ArcGIS Online, QGIS, web GIS	Python — an advantage	Preferred
10	Senior GIS Specialist	DTEK, Ukraine	ArcGIS/QGIS, network data	Not specified	Not available

Note. Compiled by the author (Glassdoor, 2026a, 2026b, 2026c; Jobsite, 2026; robota.ua, 2026; Work.ua, 2026).

The identified gap between labour-market demands and the content of educational programmes is also evident in practical teaching experience. The participation of students from Kherson State Agrarian and Economic University in the international DigiEduHack 2025 hackathon clearly demonstrated that it was precisely the presence or absence of programming skills that proved decisive in determining the distribution of roles within the team and the quality of the technical solution.

In November 2025, students studying for the G18 (193) 'Geodesy and Land Management' degree at Kherson State Agrarian and Economic University took part in the DigiEduHack 2025 international hackathon, 'Geospatial Solutions for Sustainable Development and Land Restoration', held at Sumy National Agrarian University. The 'GeoVidrodzhennia Kherson' team consisted of six participants, who naturally divided into two groups based on their level of digital skills.

As part of the project, the analysis of land changes following the destruction of the Kakhovka Hydroelectric Power Station was carried out using Sentinel-2 satellite imagery. The technical component of the solution involved calculating the NDWI index in Python (Google Colab) (Kovalenko, 2026) and subsequent spatial analysis in QGIS.

Following the final results, the 'GeoVidrodzhennia Kherson' team took third place and received a letter of thanks from the rector of SNAU (KSAEU, 2025c; SNAU, 2025c).

The experience gained has shown that programming skills have enabled automated geospatial analysis that cannot be replicated with standard GIS tools alone without scripting. This confirms the study's conclusion: the absence of programming from the compulsory components of the curriculum significantly limits the capabilities of future geospatial analysis specialists.

Conclusions

1. An analysis of the educational programmes at ten Ukrainian agricultural universities offering the G18 (193) specialisation 'Geodesy and Land Management' revealed that digital training primarily emphasizes the applied use of GIS and remote sensing tools. Only one of the ten programmes analysed (NULES, bachelor's level) includes a compulsory programming course; such courses are absent in the remaining nine higher educational establishments at bachelor's level and in all ten at master's level.
2. The newly developed Integrated Digital Maturity Index for Educational Programmes (ICM-EP) has made it possible to quantify the level of digital training: ICM-EP values range from 0.073 to 0.141 for bachelor's programmes and from 0.052 to 0.195 for master's programmes, indicating a generally low level of digital maturity across all higher education institutions studied.
3. A comparative analysis of the EU labour market (February 2026) showed that programming (Python, SQL, ArcPy) is a mandatory requirement in 7 out of 10 analysed vacancies, desirable in 2, and absent in only one vacancy in Ukraine, confirming a systemic gap between domestic education and international standards for training GIS specialists.
4. The educational case from the DigiEduHack 2025 hackathon demonstrated the practical value of programming skills: members of the 'GeoVidrodzhennia Kherson' team, who were proficient in Python, were able to implement automated NDWI analysis of Sentinel-2 satellite imagery – a task that cannot be performed using standard GIS tools alone.
5. Addressing this identified gap by integrating programming and automation courses into the curricula for training G18 specialists is a pressing scientific and methodological task. A prospect for further research is the development and pedagogical testing of relevant educational components tailored to Ukraine's post-war recovery needs.

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KINSHIP CARE FAMILIES IN RURAL REGIONS: AN ACTOR-NETWORK PERSPECTIVE

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Abstract
This article presents findings from a study conducted within the framework of a doctoral dissertation, focusing on kinship care families in rural regions of Latvia. Based on an analysis of qualitative data, the study distinguishes kinship care families living in rural areas and examines the specific configurations of factors influencing their resilience. The paper addresses two research questions: (1) what factors influence the resilience of caregivers in rural regions of Latvia? (2) what differences exist between the influencing factors affecting kinship care families in rural and urban contexts? The analysis is informed by actor-network theory. Internationally, kinship care is understood as an umbrella term encompassing relatives or close persons who assume responsibility for a child. This article focuses on formal kinship caregivers who hold legal custody of children. Applying an actor-network perspective allows for an examination of how institutional arrangements, material conditions, and social relations jointly shape family resilience beyond individual or family level explanations. The findings indicate that the most significant non-human actors in rural regions include institutions (procedures, decisions, staff, and services), financial and material resources, and the provision of housing and other basic needs. Key human actors include biological parents, neighbors, community and professionals. The interaction among these actors generates both supportive and constraining effects, including conflicts, emotional strain, and role ambiguity. Overall, the findings suggest that these differences are substantial enough to warrant attention at the social policy level, as they highlight structural inequalities that limit the equal protection of children's rights and interests across Latvia.
Keywords: kinship care, child in care, rural regions.

Introduction

Kinship care occurs when children are cared for by relatives or other trusted individuals, including members of their community, instead of their parents. Children are removed from their homes and placed with relatives from extended family or someone considered close to the family. While caregiving responsibilities may be assumed by various relatives, grandparents most frequently serve a priory caregiver's in kinship care arrangements. Comprehensive statistical data on kinship care is not fully available, as definitions and legal frameworks differ across countries and certain forms, such as informal kinship care, are often not included in official records. International trends indicate that the number of kinship caregivers has increased in recent decades (Day et al., 2023, Houston et al., 2018; Montserrat, 2014; Burke et al., 2025), because it is considered the most family-like placement. In contract, Latvia shows different patterns: when examining the proportional distribution of out-of-family care arrangements, the proportion of children placed in kinship care has declined. In 2024, of the 5,341 children in out-of-home care, 3,352 (or 63%) were placed in kinship care in Latvia. The largest group of kinship caregivers were grandparents (49%), followed by other relatives (31%) and non-relatives (20%) (CSB, n.d.).

A significant amount of research has focused on kinship caregivers, documenting the challenges they encounter and emphasizing the necessity of enhanced systemic support. Studies have found that children most often enter kinship care as a result of maltreatment, parental substance use, incarceration, mental health difficulties or parents' young age (Gleeson et al., 2009). Many conditions identified as risk factors for the development of child and adolescent mental health problems, such as poverty, family disruptions, including single parent households, and poor employment opportunities are prevalent in rural communities (Denby & Bowmer, 2013). Kin caregivers often experience a higher level of stress compared to parent caregivers (Lee et al., 2016) or non-kinship caregivers (Leder et al., 2007). Kinship caregiver's capacity to provide support to the children in their care may be related to their own feeling of perceived support (Denby & Bowmer, 2013). The most common risk factors are caregivers' financial needs (Schlatter et al., 2024) and physical health (Wu et al., 2024; Schlatter et al., 2024).

In rural areas, worldviews that conceptualize care of child as a collective and shared responsibility, naturally embedded within a 'spider - web' of relationships among biological parents and extended family members, remains particularly salient, reinforcing the normative role of kinship networks in caregiving (Day et al., 2023). In previous research, no statistically significant differences were found in overall stress and strain level between rural and non-rural kinship caregivers (Denby et al., 2015). Simply living in rural areas does not automatically predict higher caregiver burden (Foluso et al., 2024). Many rural caregivers demonstrate remarkable strengths despite limited financial resources (Denby & Bowmer, 2013). Rural challenges include lack of resources and trained professionals, isolation and poverty (Denby & Bowmer, 2013). Rural caregivers show lower access, availability, and knowledge of community resources compared with nonrural caregivers (Denby & Bowmer, 2013), which can include school-based and child-serving support. Findings indicate that rural caregivers experienced substantial dissatisfaction and frustration in navigating and accessing formal services (Denby & Bowmer, 2013; King et al., 2009).

Grandparents raising grandchildren in rural Georgia reported significant concerns about their own health and the health of their grandchildren. They faced challenges related to child-rearing, including limited services for children with disabilities and lack of assistance with legal issues (King et al., 2009). Rural kinship caregivers often experience isolation and marginalization within their communities. Support groups provided psychological support and information exchange, but barriers such as lack of transportation and childcare services hindered participation (King et al., 2009). Rurak kinship families frequently combine string relational and parenting capacities with structural disadvantages in service access. Their strengths can support child well-being, but adequate, accessible services and community-based support remain critical (Denby & Bowmer, 2013; Wu et al., 2020). Rural kinship families may face structural barriers that affect educational support as well (Denby & Bowmer, 2013). The process of their decision-making can be quick, not allowing them time to be mentally or physically prepared for the changes (Wu et al., 2024). Geographic proximity of extended family members in rural contexts can function as a protective factor in kinship caregiving, as pre-existing relationship and role expectations facilitate smoother caregiving transition. Conversely, limited prior contact between children and relative constitutes a significant rick factor during sudden placement.

Disorganized neighborhoods are associated with lower potential for social support and increased child internalizing and externalizing behavior problems (Foluso et al., 2024; Xu et al., 2022). Community context therefore plays an important role in shaping outcomes, regardless of rural or urban location (Foluso, et al., 2024). Despite the challenges of rearing children in rural communities, little of the research focusses specifically on the experiences and needs of kinship care families in rural areas. This study aimed to extend prior research and was guided by the following research: 1) what factors influence the resilience of kinship caregivers in rural regions of Latvia? 2) what differences exist in these factors between kinship caregiving families in rural and urban areas?

Theoretical Framework

The theoretical framework is based in the concept of resilience, with explains the ability to adapt to adverse circumstances, overcome difficulties and develop despite presence of risk factors (Masten, 2014; Ungar, 2013). The multifaceted nature of the concept of resilience is reflected in the variety of explanatory definitions. However, these definitions share a common core condition - the concept resilience is applied in situations where successful adaptation or functioning, or a positive transformation, can be observed, while significant risk factors are also present. These risks may include long-term chronic stressors such as poverty, domestic violence, destructive relationships, serious illness, or disability, as well as sudden traumatic events such as the death of a close person, car accidents, or the loss of employment and livelihood (Fergus & Zimmerman, 2005; Masten, 2014). Importantly, resilience refers to the ability to endure and move forward despite problems and tragic experiences.

Resilience in context of kinship care families is formed through interaction among members of family system, social environment, the care system and society (van Breda, 2018; Romāne – Meiere, 2021; Ungar, 2013). Kinship care families as social phenomenon encompasses a dual reality. On the one hand, a child's placement outside the biological parents indicates prior exposure to threats, instability, or traumatic experiences. On the other hand, kinship care can provide a safe, supportive and structured environment that becomes a significant protective factor. This contradiction – risk alongside potential for growth – fits well with resilience theory.

Resilience theory makes it possible to analyze not only negative conditions but also the protective mechanisms and resources in rural context that help a child to adapt successfully. Some theoretical principles are particularly important in the study of kinship care families. These include the significance of context (Fergus & Zimmerman, 2005), cultural sensitivity (Ungar, 2013), the dynamic interaction of influencing factors across different levels (Luthar et al., 2003), and the impact of structural constraints without attributing blame to the individual (Harrison, 2012; Park et al., 2018).

Materials and Methods

A qualitative case study was used for this research. Case studies concentrate on an in-depth exploration of a single phenomenon and highlight the importance of context (Yin, 2003), making this methodology well suited to the study of kinship care. In this article, the selected cases are kinship care families located in both rural areas and urban settings. An explanatory case study design guided the use of qualitative data collection methods – semi structured interviews with kinship care family members (n=10) and experts (n=5). Initially participants (kinship caregivers) were recruited through snowball sampling. The experts were selected following the themes mentioned in the guardians' interviews. The Orphans' Court and the Social Service were mentioned most frequently. The interviewed experts represented the Social Service, the Orphans' Court, and the Ministry of Welfare, which is responsible for kinship care families at the macro level, as well as a school social pedagogue. Interviews for data analyses were selected from a larger pool of interviews, choosing those in which influencing factors related to living in rural or urban areas were mentioned. Interview lengths ranged from 40 minutes to 2 hours and 20 minutes. Audio recordings were made and transcripts were prepared. The main thematic blocks of the semi-structured interviews

included: family history, relationships with biological parents, social networks and social support, family functioning, and perspectives on the future of child in care.

The data were analyzed through thematic analysis by actor-network theory. A qualitative perspective on network analysis allows for a more refined interpretation of the relationship between network structures and the actors involved, as well as a deeper understanding of their dynamics (Hollstein, 2012). During the triangulation of data, the analysis considered not only how often specific factors appeared but also the significance participants attached to them. Based in these data, the author identified factors influencing resilience in rural kinship care families.

The following research ethics principles were applied in the study: voluntary participation, informed consent, anonymity and confidentiality, the right to withdraw from the study and careful handling of traumatic experiences.

Results and Discussion

Thematic analysis revealed these themes: (1) structural and systemic context; (2) family and relational dynamics; (3) caregiver capacity and resilience. The themes and sub-themes are described in the following section (Table 1).

Table 1

Themes and sub-themes of findings

Theme	Focus Area	Sub-themes
Structural and systemic context	External conditions shaping kinship care	Access to services and resources (transportation, time) Institutional interaction and trust Financial conditions
Family and relational dynamics	Family and community relationships	Relationships with biological parents Extended family involvement Community visibility and social pressure
Caregiver capacity and resilience	Caregivers' strengths and challenges	Caregiving readiness and role adaptation Emotional and psychological well-being Social support networks

Structural and systemic context

From an institutional perspective, the kinship care context is shaped by such institutions as the Orphan's court, municipality social services, schools and out-of-family care support centers, even if caregivers often are not informed about these centers.

In kinship caregiver's interviews, the institution mentioned most frequently is the Orphan's court, as the legal regulation requires a guardian to submit annual reports to this authority. Thus, once a kinship caregiver is formally appointed, this interaction must take place at least once a year. The characterizations provided in kinship caregivers interviews vary considerably. Similar differences are also evident in interviews with caregivers who reside in urban areas. Although a formal framework and formally prescribed procedures are in place, their implementation is largely influenced by the professionalism and personality of the individual staff members. One of the critical attitudes: *'I don't really see it at all. They don't really supervise, they don't really help, and I don't receive any useful information either. It feels like a meaningless job, unnecessary position'*.

The competence of Orphan's staff is of crucial importance, as these professionals are the ones who can provide families with information about available support services within municipal social services, out-of-family care support centers and other non-governmental organizations. Experts indicate that the overall level of knowledge about resources among kinship caregivers is low.

'It is difficult for me to judge whether information has truly never been provided. Whether caregivers have indeed received no information at all. It is possible that such information does not seem important at that moment and is therefore simply forgotten. However, when difficulties arise and we discuss where the family has already sought assistance, it becomes apparent that caregivers have very, very limited information'.

The interviewed experts acknowledged that in rural regions social services are comparatively less accessible and located at greater distance *'of course, this can be applied to service availability for any resident, but it should be taken into account that a caregiver living in a rural area will have more limited access to support services than if they were living in a city'*. This consequently requires additional time and final resources. Experts have mentioned that in rural areas professionals (for example, social workers) not only work with limited resources, but they may have a dual or multiple roles within the community *'It is very possible that a social worker or an Orphan's court representative also knows the caregiver personally, not only professionally. That would not be surprising at all. They might be neighbors or former classmates'.*

Support services for kinship care families are provided by out-of-family care support centers; however, these centers are not yet established in every municipality in Latvia. When examining the distribution if kinship care across different municipalities in Latvia, it becomes evident that such a center is not necessary in every

municipality, as there are municipalities where are only a few guardians. Experts indicate that these centers offer social worker consultations and in some cases support groups for care givers. Services for children include consultations with a psychologist or other specialists. The availability of these consultations still depends on whether specialists are available in the municipality or in the surrounding area.

'Public transportation from our village to the center runs once a day. Even if this consultation were available, I would have to spend almost the whole day in town. I would go in the morning and then wait until the afternoon to get a ride back home. Even though I only need one hour, I end up having to devote an entire day to it'.

Rural kinship care families experience significant access barriers. Transportation costs and availability strongly influence whether families can attend appointments or school related services. Service access in rural areas is shaped as much by logistics as by eligibility or motivation.

Some support services could potentially be provided remotely, but it must be considered that there are still areas where internet coverage is weak or not available at all. Internet connectivity in rural areas is a factor that influences communication possibilities as a whole.

For some guardian families in rural regions, seasonal employment is a significant factor influencing family resilience. Seasonal work in rural areas creates income instability, pressure to overwork during peak season and increased stress during winters or slow periods. At the same time, seasonal work involves long hours, early mornings or late evenings that affects ability to arrange reliable childcare, access to respite care (already limited in rural areas), supervision during school breaks or summer. When caregivers work seasonally and children are also out of school during peak of agricultural seasons, supervision gaps can widen. Children in kinship care often benefit from routine and predictability. Seasonal employment can disrupt household routines, consistent caregiver availability, participation in some activities, and emotional availability of caregivers. At the same time, seasonal work can also present positive developmental opportunities when children appropriately participate, such as learning responsibilities, building practical skills, strengthening family bonds, gaining sense of contribution. For some kinship care families, shared seasonal work becomes a source of identity, connection and resilience *'yes, the work is not always pleasant, but I think it is a good experience to handle responsibilities together'*. Seasonal rhythms include both the risks and the strengths.

In Latvia, as well as abroad, higher rural poverty rates compound financial strain (Routh, et al., 2024). It is evident that assuming guardianship responsibilities for one or more children entails additional expenses for caregivers' family. During the period of the study, financial support for kinship caregivers in Latvia has been significantly increased. Whereas previously it could be stated unequivocally that the support was insufficient and did not cover children in need, the current level of support is considerably more adequate. At present, it is not yet possible to assess how this will affect family resilience. Comment from the expert: *'The financial support should be increased, but I have concerns that this benefit might end up being used mainly to reduce family poverty. In other words, there may be families experiencing severe poverty for whom taking in guardianship becomes a way to increase the household's overall income. Such cases already occurred some time ago'*.

Another institution that affects family resilience in rural areas is the school – routine, teachers, and classmates. The smaller the school is, the more informed classmates and teachers tend to be about one another. In large urban schools, individuals have greater opportunities to choose what personal information they disclose. In rural regions, the fact of kinship care is almost impossible to conceal. This can be perceived as a risk factor, as the appointment of kinship care signals that a family has experienced difficulties it has not been able to resolve itself. This may also serve as a potential trigger for bullying or other forms of mistreatment within the school environment. High visibility of family circumstances and increased risk of labeling or gossip are identified topics in interviews of caregivers.

Experts characterized typical situation in small rural schools: *'Small schools often have limited access to psychologists, special educators and social pedagogues. There is less support for children with learning or behavioral difficulties. There is more time for each child, but not professional support. Limited after-school programs are a problem as well'*.

Teachers may not always be informed about nuances which can limit their understanding of child's circumstances. In addition, insufficient training in trauma, attachment, and child welfare issues may reduce their capacity to respond appropriately. Consequently, individual teacher's attitude and sensitivity play a crucial role in shaping the child's educational experience and well-being.

Family and relational dynamics

Families in rural areas often face greater difficulties in maintaining distance from children's biological parents or other relatives who have contributed to risks or harm affecting the child in care. Due to the close-knit and accessible nature of rural communities, individuals are more easily reachable, and even when contact restrictions are formally established, they may be more challenging to enforce *'I can't imagine locking the door and forbidding the parents to come into the yard. We are a family anyway'*. Furthermore, families in rural settings may be less inclined to rely on institutional involvement or formal support mechanisms to ensure compliance with such contact limitations.

Family relations may be close in both urban and rural contexts. However, when a guardian has a justified reason and wishes to limit a child's contact with

biological parents, urban environment can offer greater possibilities for neighbors to help maintain this boundary. In rural areas, greater physical distance between households often means that neighbors neither witness such situations nor become involved.

'Yes, I cannot deny that there has been alcohol and violence in our family, and there have been a lot of conflicts as well. I try to provide a safe environment for the child, but sometimes we still experience the same conflicts as before. Whether and how neighbors could step in? I Think they can't. They live too far away from us'.

Neighbors in rural areas can also serve as a resource that reinforces social norms and values, thereby creating external pressure to develop socially desirable behavior. In urban environments, such pressure is significantly weaker. Interaction with neighbors and strong community ties can act as protective factors. Rural communities may offer high social cohesion, including willingness to help. These informal supports sometimes compensate for limited formal services.

Experts interviewed in the study indicated that, historically, kinship care has at times functioned as a response to financial hardship, particularly in rural areas. In such cases, relationships with biological parents have remained close. Child's daily routines often changed very little. According to experts, institutional decisions were sometimes motivated by considerations of financial support more than by concerns regarding risks to the child.

Children in kinship care may experience loyalty conflicts between biological parents and guardians. They may feel pressure to remain emotionally connected to their parents while also adapting to the rules and expectations of the kinship caregiver's household. Experts mentioned

'We often do not even notice these conflicts because children are so confused that they do not talk about this topic with professionals. Instead, the child's internal contradictions are more likely to appear as behavioral problems at school or as mental health difficulties'.

Kinship caregivers may experience mixed emotions toward the biological parents - such as compassion, frustration, anger, or a sense of responsibility. These emotions can influence the overall family climate and interactions around the child *'emotions depend on how the parents' lives are developing. If all the same problems are still present (alcohol abuse, violence, legal offences), how can I not worry?'* Pre-existing conflicts within the extended family can influence the caregiving relationship. Old disagreements, sibling rivalries, or unresolved tensions may reemerge when responsibility for the child is transferred to another relative. Because of strong kinship ties and community expectations in rural areas, kinship caregivers may find it harder to emotionally distance themselves from the struggles of the biological parents.

In rural areas, kinship caregivers often remain physically and socially close to the child's biological parents. Because community networks are small and people frequently encounter each other in everyday settings, caregivers may be constantly reminded of the parents' situation and behavior. This proximity can intensify emotional reactions such as worry or stress when the parents' problems persist. As the actor – network theory emphasizes that the network of resilience factors is not static but consists of elements in dynamic interaction, it is important to pay attention to elements, that emerge from these interactions. For example, interaction between biological parents, child in care and kinship caregivers may raise various emotions, such as anger, fear, and confusion.

Caregiver capacity and resilience

The profile of kinship caregivers living in rural areas corresponds with findings from international research: factors such as age (often grandparents), health problems, the educational level of caregivers, and previous caregiving experience influence resilience. The interviews suggested that guardians' perceptions of institutions are influenced by experiences from the Soviet period, when control and supervision were dominant. In addition, parenting traditions that normalize disciplinary methods involving emotional or physical violence are heard relatively frequently, for example: *'I try to manage without spanking, but no child has grown up without it'.* Experts add that such beliefs are often reinforced by norms present within the extended family or the local community.

'At present, the rural environment is not homogeneous. There are villages with active community life—events, courses, and seminars take place there. In such settings, guardians, like other residents, have opportunities to observe different models of child-rearing. But there are also villages that are declining and depressed'.

Urban environments offer a wider range of opportunities to gain new experiences, knowledge and skills.

In theory, institutions provide opportunities for guardians to improve their child-care skills; however, not all guardians have sufficient capacity or resources to make use of these opportunities. The interviews revealed several limiting factors: lack of time, information, and energy; unwillingness to discuss difficult topics; feelings of shame; and concerns that the content might be too complicated or difficult to understand. Support is more readily accepted and used when it is indirect and delivered in an informal manner. Experts noted that guardians often demonstrate resistance, as they may not perceive a need to change or improve their practices.

Since 2025, training for guardians has been established as mandatory; however, guardians' attitudes toward it remain mixed. As one kinship caregiver explained: *'I'm glad I don't have to attend it. Maybe they would say something useful, but if I must postpone other tasks, then I would say – I can manage without it'.*

Experts also expressed differing views:

'If we talk about rural areas, the approach to training

could be more flexible. It does not necessarily have to be organized in groups – it could be an educational consultation for one guardian. It could take place at the guardian's place of residence. The topics could also be adapted to specific needs. A certain number of mandatory hours could still be required'.

It can therefore be concluded that in rural areas, support measures need to be more closely adapted to caregivers' possibilities and their immediate needs.

At the personal level, a kinship caregivers' resilience is positively strengthened by adequate material and financial security, optimistic expectations, and positive success stories within the family system. Situations tend to be more challenging when multiple problems, such as alcohol abuse, violence, child neglect, and poverty, have persisted across several generations within the extended family system. Experts interviewed in the study noted that in such cases, placing children in the care of relatives should be assessed particularly carefully to ensure that it truly serves the child's best interests. It should also be anticipated that the family may require enhanced support: *'In such situations, it could immediately be a condition that the family is assigned an assistant service and that the family must make use of it'.* At the same time, it must be acknowledged that the availability of such services in rural regions is considerably more limited than in urban environments.

The findings of this study support the theoretical assumption that resilience in kinship care families is not solely an individual attribute but emerges through interactions between individuals, families, institutions, and the broader social environment. Resilience theory emphasizes that successful adaptation occurs in the presence of significant risk factors (Fergus & Zimmerman, 2005; Masten, 2014). The results illustrate this dynamic clearly: kinship caregivers often face multiple stressors such as financial strain, limited access to services, and complex relationships with biological parents. At the same time, protective factors such as community support, stable caregiving relationships, and personal commitment enable families to maintain caregiving roles despite these challenges. These findings align with the understanding that resilience is a process shaped by both risk and protective factors across multiple levels (Ungar, 2013; Luthar et al., 2003).

The analysis also highlights the importance of context, a key principle in resilience theory. Rural environments influence family resilience through structural conditions such as limited access to professional services, transportation barriers, and weaker institutional infrastructure. These contextual factors correspond with previous research indicating that rural kinship caregivers often experience difficulties accessing support services and professional resources (Denby & Bowmer, 2013; King et al., 2009). At the same time, the findings demonstrate that rural contexts may provide protective elements such as strong community ties and informal support networks. The presence of close-knit communities can foster social cohesion and reinforce social norms that support caregiving responsibilities. However, the same visibility within small communities may also increase stigma and reduce privacy for families involved in kinship care. These ambivalent effects illustrate how contextual conditions can simultaneously function as both risk and protective factors within the resilience framework.

Another important aspect revealed in the findings concerns family and relational dynamics. The study confirms that kinship care arrangements frequently involve ongoing relationships with biological parents and extended family members, which can create emotional tension and role ambiguity. Children may experience loyalty conflicts between their guardians and biological parents, while caregivers may struggle with mixed emotions toward the parents. Resilience theory emphasizes that adaptation occurs within relational systems rather than isolated individuals (van Breda, 2018; Ungar, 2013). In rural areas, the close proximity of family members and overlapping social networks intensify these relational dynamics, making it more difficult to establish clear boundaries when necessary.

The results are also consistent with the analytical perspective offered by Actor–Network Theory, which conceptualizes social phenomena as networks composed of both human and non-human actors. The study shows that institutions, legal procedures, transportation infrastructure, financial resources, and digital connectivity act as important non-human actors influencing the resilience of kinship care families. At the same time, human actors such as biological parents, neighbors, teachers, and social workers play crucial roles in shaping everyday experiences of caregiving. The interactions between these actors generate both supportive and constraining effects, including emotional stress, institutional dependency, and opportunities for support. By viewing resilience through a network perspective, the findings demonstrate that caregiving outcomes are not determined solely by family characteristics but are shaped by broader systemic and structural conditions.

Finally, the findings highlight important implications for social policy and support systems. Structural inequalities between rural and urban regions affect the availability of services and opportunities for kinship care families. Although institutional support and training opportunities exist in theory, practical barriers such as transportation, time constraints, and limited local services reduce their accessibility for rural caregivers. This reflects broader discussions in resilience literature emphasizing that structural constraints should not be interpreted as individual failures but as systemic challenges that require policy responses (Harrison, 2012; Park et al., 2018). Strengthening support systems for rural kinship caregivers—through flexible service delivery, improved access to professional support, and

community-based interventions may therefore play a crucial role in enhancing family resilience and ensuring equal protection of children's rights regardless of geographic location.

Overall, the findings indicate that the differences are sufficiently substantial to warrant attention at the level of social policy, as it is not possible to ensure protection of children's rights and interests equally in cities and rural areas.

Conclusions

1. This study examined the factors influencing the resilience of kinship caregivers in rural regions of Latvia and explored differences between rural and urban contexts. The findings show that caregiver resilience is shaped by the interaction of structural conditions, family relationships, and individual caregiver capacities. In rural areas, resilience is particularly influenced by access to services, transportation and financial resources, relationships with biological parents and extended family members, and the role of local community networks. While strong community ties and family relationships can act as protective factors, structural limitations such as reduced service availability and geographic distance may increase caregiving challenges.

2. The comparison between rural and urban contexts suggests that the most significant differences relate to the availability of professional support services, opportunities for learning and skill development, and the level of privacy and social visibility experienced by families. Overall, the findings indicate that rural kinship care families face distinct contextual conditions that shape both risks and resources, highlighting the need for support measures and social policies that are sensitive to regional differences and better adapted to the realities of rural caregiving.

3. The overall results of the study indicate that the interaction of resilience factors may differ for each family. Therefore, the findings cannot be automatically generalized to every kinship care family in rural areas. At the same time, the results of this study clearly highlight factors that should be considered when assessing family situations. Future research should explore whether and how increased support influences the resilience of kinship care families. Comparative studies between different countries would also be valuable.

Acknowledgements

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LINKING MATHEMATICS EDUCATION WITH REAL-LIFE APPLICATIONS FOR SUSTAINABLE RURAL DEVELOPMENT

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Abstract
Sustainable rural development requires a highly skilled workforce capable of applying scientific and technological knowledge to real-life challenges. Mathematics plays a central role in supporting sustainable and climate-smart solutions across different disciplines; however, higher education mathematics teaching often remains fragmented, overly theoretical, and insufficiently connected to real-life professional applications. This gap limits students' ability to apply mathematical knowledge in fields critical for rural and regional development. The aim of this study is to analyze current mathematics teaching practices in higher education and to identify innovative, application-oriented approaches that strengthen the link between mathematical theory and real-world challenges relevant to sustainable rural development. This paper presents an interdisciplinary development initiative implemented within the Nordplus Higher Education framework, focusing on innovations in mathematics education in the Baltic and Nordic regions. The research is based on a comparative analysis of existing mathematics teaching materials and practices at three universities, followed by the joint development and pilot testing of a practical guidebook for mathematics teaching in higher education. The results demonstrate that interdisciplinary and application-focused mathematics education enhances student engagement, improves the relevance of learning outcomes for the labor market, and supports the development of competencies essential for sustainable rural development. Strengthening educators' pedagogical skills and fostering international collaboration further contribute to higher education quality and relevance. The study concludes that rethinking mathematics teaching in higher education is essential for preparing graduates capable of contributing to sustainable rural development.
Keywords: mathematics education, sustainable rural development, higher education innovation, interdisciplinary learning.

Introduction

The increasing complexity of contemporary societal and environmental challenges has strengthened the need for educational approaches that equip individuals with the knowledge and competencies required for sustainable development. Sustainable development is defined as an integrative paradigm that balances social, economic, and environmental imperatives to meet the needs of current rural populations without compromising the well-being of future generations (Mensah, 2019; Morris & Guenther, 2024). Concurrently, rural development signifies a holistic transformation process aimed at enhancing the socioeconomic viability and human development of agrarian communities through localized action, ensuring that educational initiatives directly empower stakeholders to manage resources sustainably and bridge persistent infrastructural gaps (Rabinowicz & Chinapah, 2015).

Sustainable rural development requires a workforce capable of applying scientific and technological knowledge to complex real-world challenges. Within this context, mathematics education plays a critical role in developing analytical, quantitative, and problem-solving competencies that support evidence-based decision-making and sustainable resource management (Whitney-Smith et al., 2022). Quantitative literacy is essential for planning agricultural activities, managing resources efficiently, and making informed economic decisions that foster the long-term viability of rural communities (Kopeika et al., 2025; Vintere, 2017; Zvirgzdiņa & Kopeika, 2024). The contribution of mathematics to sustainable rural development extends beyond its traditional role as an abstract academic discipline. By adopting a multidimensional framework that encompasses social, psychological, and educational dimensions, mathematics becomes a practical tool for addressing the economic, industrial, and societal challenges faced by rural populations (Taja-on et al., 2025). Sustainable development processes increasingly rely on quantitative analytical approaches, including mathematical modelling, statistical analysis, and optimization techniques, which provide essential tools for understanding complex systems and responding to economic and environmental uncertainty (Mellaku & Sebsibe, 2022). Through the transformation of complex resource dynamics into actionable information, mathematics supports the evaluation of environmental trade-offs and informs strategic decisions aimed at securing the long-term sustainability of rural regions (Kanyiri & Wainaina, 2025).

Despite this recognized importance, a significant gap persists in higher education mathematics instruction. Mathematics courses frequently remain focused on abstract theoretical content, such as algebra, calculus, and differential equations, while explicit connections to real-life applications are often limited or only implicitly addressed (Pratiwi & Widjajanti, 2020). This imbalance between theoretical knowledge and practical application has been widely discussed in mathematics education research, particularly in relation to the development of transferable, application-oriented competencies required in contemporary society (Sujatha & Vinayakan, 2023;

Wardana et al., 2024). Such a disconnect may hinder the development of the analytical competencies needed to address the complex socio-ecological challenges characteristic of rural environments (Vásquez et al., 2023). Consequently, there is a growing recognition that advanced mathematical training should serve as an integrative instrument for addressing practical sustainability challenges and supporting rural development objectives (Kuznetsova et al., 2021).

Within the Baltic and Nordic context, higher education institutions offer a wide range of mathematics courses that vary considerably in their orientation toward practical application (European Commission, 2022). While some programmes incorporate applied mathematical content linked to professional fields such as engineering, economics, and technology, others remain predominantly theory-oriented (Suthish & Venkatesan, 2025). However, the extent to which these courses explicitly foster competencies relevant to sustainable rural development remains largely unexplored.

Despite growing attention to application-oriented and sustainability-focused education, there is limited empirical evidence regarding how these priorities are reflected in higher education mathematics curricula (Briede et al., 2025; Lafuente-Lechuga et al., 2024; López-Serentill et al., 2024; Moreno-Pino et al., 2022). In particular, intended learning outcomes and course descriptions play a central role in shaping educational practices and communicating expected competencies, yet their alignment with real-world applications and sustainability-related challenges has received insufficient scholarly attention.

Consequently, the relevance of application-oriented mathematics education becomes particularly evident in regions where rural development remains an important social, economic, and environmental priority. In the countries of the Baltic Sea region, natural landscapes and rural lifestyles constitute an important part of regional and national identity. As a result, increasing scholarly attention has been devoted to regional and rural development, with particular emphasis on sustainability and resilience as key principles for addressing contemporary challenges (Alms & Tamasy, 2026).

This study is conducted within the framework of a Nordplus Higher Education initiative focusing on innovation in mathematics education. As an initial stage of this project, the present paper analyses course descriptions and intended learning outcomes from selected higher education institutions in Latvia, Estonia, and Finland.

The aim of this study is to analyse how mathematics curricula in higher education connect mathematical learning with real-life applications relevant to sustainable rural development, including practical problem-solving, interdisciplinary contexts, sustainability-related challenges, and application-oriented competencies.

Research question: To what extent do the intended learning outcomes and course descriptions of bachelor-level mathematics courses in Latvia, Estonia, and Finland reflect real-life applications and sustainability-related contexts that support sustainable rural development?

Materials and Methods

This study employed a qualitative comparative document analysis to examine how mathematics curricula connect mathematical theory with real-life applications relevant to sustainable rural development. The analysis focused on the intended curriculum as represented in formal course documentation rather than on the implementation of teaching practices. Course descriptions and intended learning outcomes were therefore treated as institutional representations of the mathematical knowledge, skills, and applications that universities formally communicate to students.

The empirical dataset consisted of 52 bachelor-level mathematics-related course descriptions collected from four higher education institutions participating in a Nordplus Higher Education collaboration: Åland University of Applied Sciences, Finland (17 courses), TTK University of Applied Sciences, Estonia (6 courses), Daugavpils University, Latvia (9 courses), and Riga Technical University, Latvia (20 courses). A purposive sampling strategy was employed. For Åland University of Applied Sciences, TTK University of Applied Sciences, and Daugavpils University, all bachelor-level mathematics-related courses included in the comparative curriculum dataset were analyzed. Riga Technical University offers a substantially larger number of mathematics courses across different study programs; therefore, only courses corresponding to general mathematics subjects and comparable in scope to those offered by the other participating institutions were included. This selection was made to ensure cross-institutional comparability and to focus the analysis on foundational mathematics courses rather than highly specialized disciplinary subjects.

The participating institutions were selected through the Nordplus Higher Education collaboration and represent higher education providers in Latvia, Estonia, and Finland. Although these institutions are not specifically oriented towards rural development, contemporary rural areas face increasingly complex economic, technological, environmental, and social challenges. Addressing such challenges requires graduates with strong analytical and quantitative competencies applicable across diverse professional contexts. Mathematics education therefore provides an important foundation for competencies that can contribute to sustainable rural development, making mathematics curricula a relevant subject for comparative analysis.

Course information was compiled into a comparative curriculum table containing the university, course title, course content, intended learning outcomes, and

recommended literature. To ensure comparability across institutions, the same descriptive fields were used for all courses regardless of local programme structures or curriculum formats.

The analysis focused specifically on the course content and intended learning outcomes, as these sections provide the most direct evidence of how mathematical knowledge is positioned in relation to practical applications, professional contexts, interdisciplinary challenges, and sustainability-related issues. A directed qualitative content analysis approach was adopted, using a deductive coding framework developed from the research question and the theoretical foundations of sustainable rural development and application-oriented mathematics education.

Six analytical criteria were used to evaluate each course: (1) explicit reference to practical or professional applications of mathematics; (2) links between mathematical theory and real-world problem-solving; (3) interdisciplinary connections; (4) references to sustainability, environmental, climate, rural, or sector-specific challenges; (5) use of digital or computational tools in applied contexts; and (6) the degree of specificity with which application-oriented competence was expressed in the intended learning outcomes.

Each criterion was assessed using a three-point scale. A score of 1 (low) was assigned when a criterion was absent or only implicitly mentioned. A score of 2 (medium) indicated that the criterion was present but addressed in a limited or occasional manner. A score of 3 (high) was assigned when the criterion was explicitly and consistently integrated into the course content and intended learning outcomes. For example, courses containing multiple references to professional, industrial, economic, technological, or sustainability-related applications received higher scores than courses presenting mathematics primarily as a theoretical discipline. Similarly, digital and computational tools were evaluated according to the extent to which software, computational methods, or data-analysis tools were incorporated into applied learning contexts.

The coding process was conducted collaboratively by the research team. The initial coding was performed by the first researcher and subsequently reviewed by a second researcher to enhance the consistency and transparency of the analysis. Any differences in interpretation were discussed until consensus was reached. Each course description and its intended learning outcomes were then systematically coded according to the six analytical criteria. The resulting scores were entered into SPSS and analyzed using descriptive statistical procedures.

Several limitations should be acknowledged. First, the study is based exclusively on formal curriculum documentation and therefore reflects the intended curriculum rather than actual teaching practices or student learning experiences. Second, the level of detail provided in course descriptions varies across institutions, which may influence the visibility of application-oriented elements. Nevertheless, document analysis provides a systematic and transparent approach for examining how higher education institutions formally position mathematics education in relation to real-life applications and sustainable rural development.

Results and Discussion

Quantitative overview of application-oriented elements

The analysis of 52 bachelor-level mathematics course descriptions revealed varying degrees of application-orientation across the six coding criteria. Table 1 presents descriptive statistics for each institution.

Table 1

Mean scores and standard deviations by institution and coding criterion (scale 1-3; PRACT = practical/professional applications; REAL = real-world problem-solving; INTER = interdisciplinary connections; SECTOR = sector-specific applications; DIGITAL = digital/computational tools; LO = specificity of learning outcomes)

Institution	N	PRACT	REAL	INTER	SECTOR	DIGITAL	LO	Overall
Åland UAS (Finland)	17	2.47 (0.87)	2.06 (0.75)	2.00 (0.61)	1.88 (0.71)	1.53 (0.87)	2.88 (0.33)	2.14
TTK UAS (Estonia)	6	2.00 (0.98)	2.17 (0.98)	1.83 (0.75)	1.33 (0.52)	1.67 (1.03)	3.00 (0.00)	2.00
Daugavpils University (Latvia)	9	2.11 (0.93)	2.11 (0,93)	2.22 (0.97)	1.89 (0.78)	1.33 (0.5)	2.78 (0.44)	2.07
Riga Technical University (Latvia)	20	2.20 (0.95)	2.20 (0.95)	2.10 (0.91)	1.90 (0.85)	1.65 (1.04)	2.95 (0.22)	2.17
Total	52	2.23 (0.86)	2.13 (0.86)	2.06 (0.81)	1.83 (0.87)	1.56 (0.90)	2.90 (0.30)	2.12

Table 1 represents mean scores and standard deviations for each institution across the six coding criteria. The overall mean score across all institutions is 2.12 (SD = 0.52), indicating moderate application-orientation with moderate variation. Learning outcomes (LO) show the highest mean value (2.90)

and the smallest standard deviation (SD = 0.30), suggesting that most courses consistently articulate specific, assessable learning outcomes regardless of institution. In contrast, digital tool integration (DIGITAL) shows the lowest mean value (1.56) but the largest standard deviation (SD = 0.90), indicating substantial variation across courses: some courses integrate digital tools extensively while most do not at all. Across institutions, Åland UAS shows the highest overall mean (2.14, SD = 0.48) and RTU shows similar consistency (2.17, SD = 0.51). TTK UAS shows the lowest overall mean (2.00) but the highest standard deviation (SD = 0.63), reflecting its small number of courses (n=6) and wide variation between highly applied courses (e.g., Geometry in Engineering) and purely theoretical courses (e.g., Special Course in Mathematics).

Relationships between application-oriented criteria

Beyond mean scores, cross-tabulation analysis reveals how different application-oriented criteria relate to each other within individual courses. Table 2 examines the relationship between practical applications (PRACT) and digital tool integration (DIGITAL).

Table 2

PRACT ×DIGITAL cross-tabulation (number of courses)

	DIGITAL=1 (Low)	DIGITAL=2 (Medium)	DIGITAL=3 (High)
PRACT=1 (Low)	14	0	0
PRACT=2 (Medium)	3	2	0
PRACT=3 (High)	22	3	8

This table shows that 39 out of 52 courses (75%) have low or no digital tool integration. Notably, 22 courses (42%) demonstrate high practical application but low digital tools. Only 8 courses (15%) combine high practical application with high digital tool use. This finding reveals a significant gap: while mathematics is taught as practical and applicable, computational and digital skills remain underrepresented.

Table 3 examines the relationship between practical applications and sector-specific contexts.

Table 3

PRACT ×SECTOR cross-tabulation (number of courses)

	SECTOR=1 (Low)	SECTOR=2 (Medium)	SECTOR=3 (High)
PRACT=1 (Low)	13	1	0
PRACT=2 (Medium)	2	3	0
PRACT=3 (High)	8	19	6

Table 3 demonstrates that sector-specific framing is generally moderate. Only 6 courses (12%) achieve a high level of sector-specific context, meaning they explicitly link mathematics to engineering, economics, environmental science, or other professional sectors. Among 33 courses with high practical application (PRACT=3), 19 (58%) have only medium sector-specific framing, and 8 (24%) have low sector-specific framing.

This suggests that practical application does not automatically translate into clear sector contextualization.

Table 4 examines the relationship between sector-specific context and the specificity of learning outcomes.

Table 4

SECTOR ×LO cross-tabulation (number of courses)

	LO=2 (Medium)	LO=3 (High)
SECTOR = 1 (Low)	14	0
SECTOR = 2 (Medium)	3	2
SECTOR = 3 (High)	22	3

It should be noted that no courses in the dataset received a score of 1 (low) for learning outcomes specificity (LO), as all analyzed course descriptions include formally stated intended learning outcomes. This reflects standard curriculum documentation requirements in higher education.

Table 4 reveals a striking pattern: 46 out of 52 courses (88%) have highly specific, assessable learning outcomes (LO = 3). However, only 6 courses (12%) achieve high sector-specific context. All 6 courses with high SECTOR also have high LO, but the converse is not true. This indicates that well-written learning outcomes do not guarantee meaningful connections to real-world sectors or sustainability challenges. Course documentation is professionally structured, yet substantively disconnected from sector-specific applications.

Table 5 examines the relationship between real-world problem-solving and sector-specific context.

Table 5 shows that 23 courses (44%) have high real-world problem-solving emphasis (REAL=3). However, among these 23 courses, only 6 (26%) also have high sector-specific context (SECTOR=3). Conversely, 5 courses (22%) have high real-world emphasis and low sector-specific framing. This finding suggests that references to ‘real-world problems’ in course descriptions are often vague and not anchored in specific professional, environmental, or sustainability contexts. For sustainable rural development, this lack of sector specificity represents a missed opportunity to connect mathematical competencies to concrete challenges such as agricultural planning, resource management, or environmental monitoring.

Table 5
REAL × SECTOR cross-tabulation (number of courses)

	SECTOR=1 (Low)	SECTOR=2 (Medium)	SECTOR=3 (High)
REAL=1 (Low)	12	1	0
REAL=2 (Medium)	6	10	0
REAL=3 (High)	5	12	6

Theoretical foundation and application patterns

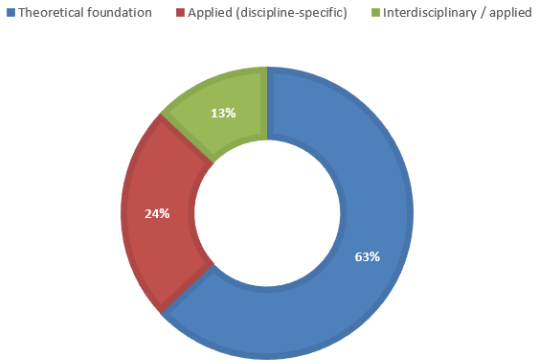
Mathematics curricula across all four universities remain primarily grounded in a strong theoretical and procedural foundation. Core topics such as linear algebra, calculus, differential equations, statistics, and numerical methods are central in almost all analyzed courses. Learning outcomes most frequently emphasize the ability to perform calculations, solve equations, manipulate functions, and analyze mathematical relationships. This dominant curricular model reflects a traditional understanding of mathematical competence, where mastery of concepts, methods, and procedures remains the main priority.

At the same time, application-oriented elements are clearly present in all institutions, though not equally visible or developed. In some courses, application is formulated in broad terms (e.g., preparing students for future professional studies, using mathematics 'within their own field'). In other courses, the applied dimension is much more explicit and embedded directly into learning outcomes and course content. Thus, application-oriented approaches are reflected in the intended curriculum, but with different levels of specificity and pedagogical clarity.

A particularly strong pattern is the connection between mathematics and professional or sector-specific contexts. Applied elements were identified most frequently in courses linked to engineering, economics, business, data analysis, navigation, and technical problem-solving. Business and econometrics courses emphasize regression analysis, optimization, forecasting, and mathematical decision-making. Engineering-oriented courses refer to numerical methods, modelling, technical calculations, and the use of software such as MATLAB and Excel. At Åland UAS, several courses link mathematics to nautical studies, ship engineering, and navigation, while in TTK UAS and RTU, many courses make clear reference to engineering tasks, ICT tools, and real-life applications. These examples demonstrate that mathematics is presented not only as an abstract theory, but also as a functional tool for workplace and disciplinary practice.

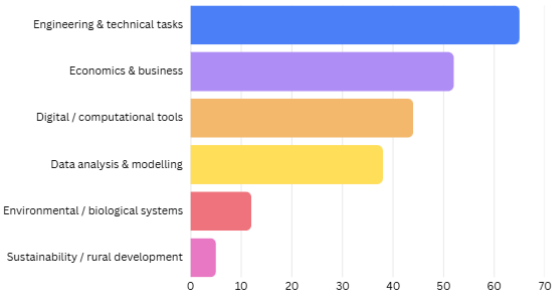
Figure 1 summarizes the dominant curriculum orientation, showing that the strongest emphasis remains on theoretical foundation, while applied and interdisciplinary orientations are present but less dominant.

Figure 1
Dominant curriculum orientation



The comparison between institution types reveals meaningful differences. In the universities of applied sciences (Åland UAS, TTK UAS), application-oriented approaches tend to be more explicit and visible in course design. Traditional university programs (Daugavpils University and RTU), more often prioritize theoretical understanding, with applications appearing as examples, extensions, or domain-specific uses of mathematical methods rather than as the central organizing principle of the course. This does not mean traditional universities lack applied content; rather, the applied dimension is less foregrounded and systematically articulated.

Figure 2
Visibility of application-oriented elements by domain



Connecting to sustainability and rural development

A critical finding is that the identified applications are predominantly discipline-specific rather than socially or sustainability-framed. Mathematics is applied to economics, engineering, biology, environmental science, computer science, or nautical studies but only rarely explicitly connected to broader societal challenges. Direct references to sustainability, climate resilience, or sustainable rural development are limited. The strongest examples appear in courses such as Environmental Mathematics (RTU) and mathematical modelling courses dealing with environmental, biological, or real-world systems. However, such cases are exceptions rather than the rule. In most of the analyzed material, sustainability-related relevance remains implicit.

This tendency is visible in Figure 2. Engineering and technical tasks, economics and business, digital tools, and data analysis are the most visible applied domains, whereas environmental, biological, and especially sustainability- or rural development-related references appear much less frequently.

Nevertheless, mathematics curricula do contain competencies highly relevant to sustainable rural development, even if not presented under that label. Table 6 maps identified competencies to potential rural applications.

Table 6
Mathematical competencies and relevance to sustainable rural development

Competency	Example courses	Potential rural application
Mathematical modelling	Mathematical Modelling & DE (DU), Environmental Mathematics (RTU)	Agricultural simulation, water resource management
Statistical analysis	Statistics (Åland, TTK), Business Mathematics & Statistics (RTU)	Rural demographic analysis, agricultural productivity
Optimization methods	Economic Mathematics (Åland, TTK), Optimization Methods in Finance (RTU)	Supply chain logistics, resource allocation
Forecasting	Econometrics (DU), Business Mathematics (RTU)	Agricultural price prediction, climate impact
Digital/computational tools	Numerical Methods (Åland, RTU), Computerization of Mathematical Tasks (RTU)	Precision agriculture, GIS-based planning

Skills such as modelling, optimization, data analysis, interpretation of results, computational problem-solving, and the use of digital tools are all important for addressing real-world challenges in agriculture, regional development, environmental management, infrastructure, and rural innovation. Yet intended learning outcomes and course descriptions rarely make these broader connections visible. As a result, the potential contribution of mathematics education to sustainable rural development remains underarticulated in the formal curriculum.

Fragmentation and coherence

Application-oriented elements remain fragmented across the curriculum. Applied components appear in individual courses rather than as part of a coherent curriculum-wide approach. Students may encounter practical applications in statistics, economics, numerical methods, or modelling, but these are not always connected across the program to help students build broader understanding of how mathematical knowledge transfers across disciplines to address complex real-world challenges. This fragmentation weakens the development of integrative competence.

The wording of intended learning outcomes reinforces this conclusion. Some courses use highly concrete formulations (e.g., ‘solve real-life scenarios’, ‘use ICT tools’, ‘evaluate results critically’, ‘apply derivatives in economics’, ‘use software for modelling and analysis’), making the applied purpose visible and assessable. Other courses use general language (e.g., ‘apply mathematics in the field’, ‘use mathematics in professional life’), signaling relevance but not specifying expected practical competence. Thus, while application-oriented rhetoric is present, the strength of curricular alignment varies considerably.

Comparison with existing literature

These findings align with previous research. Briede et al. (2025), within the same Nordplus project, found that while mathematics educators recognize the importance of sustainability connections, these are rarely operationalized in course design. Lafuente-Lechuga et al. (2024) demonstrated that mathematical concepts can be integrated with sustainability content, but such integration requires deliberate curriculum design. Vásquez et al. (2023) concluded in their systematic review that most sustainability interventions in mathematics education remain at the level of isolated examples rather than embedded curriculum redesign. Ferri & Bulut (2026) argued that mathematics education for sustainable development requires pedagogical shifts toward problem-based and real-world contextualized learning. The present study suggests that even content-level integration – making explicit connections between mathematical competencies and sustainability challenges – remains underdeveloped in the analyzed curricula.

Implications for sustainable rural development

The findings have several implications. First, competencies that support rural development are already present in mathematics curricula but framed within disciplinary contexts (engineering, economics, business). Students learn skills transferable to rural contexts but may not recognize these transfer possibilities. Curriculum developers could address this by adding brief rural-relevant examples to existing courses without changing core mathematical content.

Second, the lack of explicit sustainability references represents a missed opportunity for raising students’ awareness of rural development challenges. Even a small number of well-designed examples – applying optimization to agricultural logistics, using statistics on rural demographic data, modelling environmental systems – could help students see the societal relevance of their mathematical learning.

Third, the fragmentation of application-oriented elements suggests that students may struggle to

integrate their mathematical knowledge across different problem contexts. A more coherent curriculum-wide approach, where application-oriented learning outcomes are articulated progressively across multiple courses, could better support transferable competencies.

These implications are particularly relevant for the Baltic Sea region, where rural development, sustainability, and resilience remain important policy priorities (Alms & Tamasy, 2026).

Institutional differences and limitations

The observed differences between traditional universities and universities of applied sciences suggest that institutional orientation shapes how mathematics is positioned. This finding should not be interpreted as one model being superior to the other, but rather as reflecting different educational philosophies. However, for preparing graduates to address rural development challenges, the more explicit articulation of transferable competencies found in universities of applied sciences may offer useful pedagogical models.

Several limitations should be acknowledged. The analysis is based exclusively on formal curriculum documentation and reflects the intended curriculum, not enacted classroom practices or student learning outcomes. The level of detail in course descriptions varies across institutions, affecting the visibility of application-oriented elements. The study includes different numbers of courses per institution (6 to 20), limiting comparability of institutional means. Curriculum documents are dynamic and this analysis represents a snapshot. Despite these limitations, document analysis provides a systematic approach for examining how higher education institutions formally position mathematics education in relation to real-life applications and sustainability challenges.

Conclusions

1. This study analyzed 52 bachelor-level mathematics course descriptions from four higher education institutions in Latvia, Estonia, and Finland to examine the extent to which mathematics curricula connect mathematical learning with real-life applications relevant to sustainable rural development.

2. Answering the research question, application-oriented approaches are present in all analyzed curricula, but explicit connections to sustainable rural development are almost entirely absent. The most visible applications are discipline-specific (engineering, economics, data analysis) rather than framed around broader societal or sustainability challenges. Digital tool integration remains the weakest area across all institutions.

3. Mathematics curricula already contain competencies highly relevant to rural development – modelling, statistics, optimization, forecasting, and data analysis – but these are not explicitly linked to rural contexts in course descriptions or intended learning outcomes. The potential contribution of mathematics education to sustainable rural development therefore remains underarticulated in formal curriculum documents.

4. Universities of applied sciences express application-oriented approaches more explicitly than traditional universities, reflecting different institutional missions. However, neither institution type systematically integrates sustainability-related or rural development contexts into mathematics curricula.

5. Universities of applied sciences tend to express application-oriented approaches more explicitly, whereas traditional universities more often prioritize theoretical understanding.

6. Curriculum developers could make existing applications more transferable to rural development by adding concrete, rural-relevant examples to existing courses with minimal changes to core mathematical content. For instance: statistics courses could include agricultural or rural demographic data; optimization courses could address rural logistics and resource allocation; modelling courses could focus on environmental or agricultural systems.

7. This study analyzed intended curriculum only, not classroom enactment. Future research should examine whether and how teachers adapt course materials to include sustainability contexts, and whether students recognize connections between mathematical competencies and rural development challenges. Additionally, future studies could expand the dataset to include more institutions from the Baltic-Nordic region and incorporate interviews with mathematics educators about their perceptions of sustainability integration.

8. Rethinking mathematics teaching in higher education is not about reducing theoretical rigor, but about making its real-world relevance more visible, transferable, and educationally meaningful. The building blocks for practice-oriented mathematics education already exist in the analyzed curricula; what is needed is stronger coherence, clearer articulation, and more explicit integration of sustainability-relevant and rural development contexts.

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