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FOREWORD

From May 14 to 16, 2025, Latvia University of Life Sciences and Technologies hosted the 31st 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 108 presentations were successfully delivered at the conference. Registered participants represented 10 different countries, and 122 participants attended the event in person.

We believe that these Proceedings will be an excellent reference volume for researchers worldwide and will stimulate further research in agriculture, forestry, food and veterinary sciences, engineering, ICT, environment, economics, and education.

We would like to thank all authors and reviewers for their contribution in international scientific level.

We also sincerely thank all section moderators for their dedication and professionalism, which helped make the discussions smooth and meaningful throughout the sessions: Z. Vītoliņa, K. Furmanova, E. Dubrovskis, T. Ķince, S. Zeverte-Rivza, L. Duckena, D. Grabuža, L. Feldmane, J. Kaneps, U. Skadins, V. Tetere, J. Pilecka-Ulcugaceva, A. Pilvere, G. Mazure, T. Rubina, T. Sinkus, P. Miezaka. 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 in support of innovation and sustainability in rural regions.

We hope to see you at the Latvia University of Life Sciences and Technologies next year during the 32nd International Scientific Conference 'Research for Rural Development 2026', which will take place on May 13–15, 2026!

Natalija Sergejeva
Chairperson
Annual 31st International Scientific Conference
'Research for Rural Development 2025'

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YIELD POTENTIAL OF ALFALFA CULTIVAR UNDER LITHUANIAN ENVIRONMENT CONDITIONS

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Abstract
Seeking to achieve a balanced functioning of agrocenoses, it is vital to maintain a high productivity level of the crops grown with organic management practices, which major problem is yield losses due to poor soil quality. Alfalfa (*Medicago* spp.) is one of the most valuable forage crops of leguminous family, whose root system penetrates to deeper layers of the soil, improving physical and chemical soil properties. However, the use of alfalfa is limited due to its sensitivity to soil conditions. The aim of this study was to assess alfalfa's agro-biological properties under various soil conditions. Field experiments were conducted in four different locations with optimal management. Agro-biological properties of six alfalfa (*Medicago sativa* L. and *M. varia* Marth.) cultivars of various geographic origin were evaluated in a high productivity *Cambisol* and *Luvisol*. It was determined that cultivar 'Milda' distinguished for good overwintering, plants of cultivars 'Antanė', 'Malvina' and 'Skriveru' were taller at the beginning of flowering, cultivar 'Birutė' distinguished for the highest grass yield, while 'Antanė' and 'Birutė' distinguished for the dry matter (DM) yield. In a low productivity *Retisol*, the pH and mobile aluminium concentration had a major influence on overwintering, fresh matter and DM yields of the examined alfalfa cultivars. Alfalfa overwintering was 10.1–20.7% while fresh matter and dry matter yields were 2.0–2.4 and 2.8 times lower compared to alfalfa grown in high productivity soil.
Keywords: *Medicago* spp., agro-biological traits, productivity, soil type.

Introduction

In Lithuania, agricultural land soils markedly differ in productivity. Nearly 40% of the soils are insufficiently fertile (Tripolskaja & Šidlauskas, 2010); moreover, those in the western part of the country are characterised by an acid reaction (Repšienė & Skuodienė, 2010). *Retisols* have a low buffering capacity and sorption, leading to rapid acidification, nutrient depletion, and reduced water retention (Repšienė & Karčauskienė, 2016). Acidic soils are the most significant barrier to agricultural productivity because of the direct effects of pH on root environment and plant growth (Tomchuk, 2018). Acidity limits root growth and, as a result, the absorption of water and mineral nutrients. The topsoil layer, which contains more organic matter, is dominated by H^+, while Al^{3+} toxicity is more evident in the layer below. Acidic soil conditions induce plant stress, leading to symptoms such as slowed growth, weak tillering, sparse crop coverage, delayed developmental stages, and heightened susceptibility to diseases (Goulding, 2016; Wang et al., 2016).

Alfalfa is valued for the crop longevity, high fertility, good forage quality and beneficial characteristics for the environment (improves soil physical properties, accumulates valuable nutrients and atmospheric nitrogen). Alfalfa distinguishes from the other legume grasses for its resistance to drought, because strong roots enable easier nutrients and water accessibility from deeper layers of the soil. Growing pure alfalfa crops or their mixtures together with the other grasses and legumes, the soil is enriched by nitrogen (Arlauskiene & Maikštėnienė, 2004). Therefore, alfalfa is a good forecrop (Skuodienė & Nekrošienė, 2012). Moreover, it is worth to plant alfalfa on the hill slopes of 10–20° steepness (Jankauskas & Jankauskienė, 2003).

Alfalfa, as well as the other legume grasses, prefers soil pH of 6.5–7.2. They can grow in more acid soil as well, where limy layer is not deep in the subsoil. However, in acid soils, alfalfa becomes more sensitive for overwintering, drought and diseases circulating during the vegetation period (Daugėlienė, 2010).

Not only in Lithuania, but also in other countries around the world, alfalfa breeding programmes focus on winter hardiness, seed and grass yields increase, crop longevity, and resistance to abiotic and biotic stresses. Various breeding and selection methods are currently being used to develop alfalfa varieties for different purposes, with higher grass and seed yields, resistance to diseases, tolerance to acid soils and mobile aluminium (Liatukienė et al., 2024).

When selecting alfalfa, it is very important to compare the new varieties being developed with those developed in Lithuania and in other countries. Foreign varieties of alfalfa have good grass and seed yields but are sensitive to the climatic conditions of our country (Liatukienė, 2012). In addition, the newly developed varieties must not only be higher yielding than previously developed varieties, but also distinguished by other desirable traits such as plant height at the beginning of flowering, leaf and inflorescence shape, colour, stem thickness, etc.

The study was aimed to evaluate and compare the productivity traits of alfalfa varieties in different genesis soils.

Materials and Methods

Experimental trial in the field

The cultivars of alfalfa were sown in four locations of the experiment field. The first experiment field was at the Vėžaičiai Branch of Lithuanian Research Centre for Agriculture and Forestry (in the western part of

Lithuania). The soil of the experimental site was *Bathygleyic Dystric Retisol* (WRB, 2022), with a texture of sandy light loam, high acid soil reaction, phosphorus and potassium rich soil, organic carbon $C_{org.}$ 1.23%, total nitrogen N_{total} 0.12–0.14% and mobile Al 1.78-23.41 mg kg^{-1} (Table 1).

Table 1
Sites' characteristics

Indices	***Experimental site***			
Pedological indices	***Vėžaičiai Branch***	***Institute of Agriculture***	***Utena PVTD***	***Pasvalys PVTD***
Soil type	*Retisol*	*Cambisol*	*Luvisol*	*Cambisol*
Soil texture	sandy light loam	light loam	sandy loam	clay loam
Sand, %	46.9	49.0	55.6	22.7
Silt, %	45.1	37.5	32.0	50.3
Clay, %	8.0	13.5	12.4	27.0
pH_{KCl}	4.4–4.7	6.9–7.3	6.4	6.4
Mobile Al, mg kg^{-1}	1.78–23.41	0.00	0.00	0.00
Mobile P_2O_5, mg kg^{-1}	177–335	201–270	127	234
Mobile K_2O, mg kg^{-1}	195–234	101–175	187	366
N_{total}, %	0.12–0.14	0.14–0.16	0.13–0.15	0.15–0.16
Organic C, %	1.23	1.47	1.06	1.35
Climatic indices	2021			
Total annual precipitation, mm	907.7	515.7	623.0	795.2
Annual mean temperature, °C	7.4	7.4	6.9	7.9
Growing season's total precipitation, mm	528.1	388.5	433.6	526.6
Growing season's mean air temperature, °C	13.3	13.7	13.2	13.6
	2022			
Total annual precipitation, mm	803.2	628.4	807.0	642.9
Annual mean temperature, °C	8.1	8.0	7.3	7.7
Growing season's total precipitation, mm	461.4	472.1	579.8	427.1
Growing season's mean air temperature, °C	13.2	13.3	12.6	13.0
	2023			
Total annual precipitation, mm	1045.6	504.7	754.5	578.6
Annual mean temperature, °C	8.6	8.8	8.2	8.4
Growing season's total precipitation, mm	487.7	323.3	466.6	398.7
Growing season's mean air temperature, °C	13.8	14.4	13.8	14.1

Notes: Growing seasons from 4 to 10 months. PVTD – Plant Variety Testing Division.

The second experiment field was at the Institute of Agriculture of Lithuanian Research Centre for Agriculture and Forestry (Dotnuva, in the central part of Lithuania). The soil of the experimental site was *Endocalcari Epigleyic Cambisol* (WRB, 2022). The physicochemical properties of investigated soil were: light loam texture, neutral soil reaction, phosphorus rich soil and low amount of potassium in soil, organic carbon C_{org} 1.47% and total nitrogen N_{total} 0.14–0.16%.
The soil of the experimental site in Utena (North-eastern part of Lithuania) was *Luvisol*, with a texture of sandy loam, neutral soil reaction, medium amount of phosphorus and potassium rich soil, organic carbon $C_{org.}$ 1.06%, total nitrogen N_{total} 0.13–0.15%.
The soil of the experimental site in Pasvalys (North part of Lithuania) was *Cambisol*, with a texture of clay loam, neutral soil reaction, phosphorus and potassium rich soil, organic carbon $C_{org.}$ 1.35%, total nitrogen N_{total} 0.15–0.16%.
In order to evaluate agro-biological traits, alfalfa cultivars were sown on neutral (*Cambisol*) and low-yielding acid soil (*Retisol*). The seeds of six cultivars were sown in 2020. During the period of 2021–2023, the agro-biological traits (overwintering, plant height before flowering, fresh and dry matter yields) were evaluated. The plants of alfalfa cultivars were cut three times in *Cambisol*; however, the plants were cut two times in *Retisol*, due to slow regrowth after cuts. In each location of the experiment, the seeds of alfalfa cultivar were sown in two rows of 3 m length in a randomized block design with three replications. Each alfalfa cultivar was sown in smaller experimental plots of 1.5 m^2 with a 1.0 m spacing between different genotypes. Weed control in alfalfa crops was managed using the herbicide Basagran 480 (active ingredient: bentazon 480 g L^{-1}) at a rate of 2 L ha^{-1}.

Cultivar testing and registration

In this experiment, Lithuanian alfalfa cultivars 'Antanė', 'Birutė', 'Malvina' and 'Žydrūnė', the cultivar 'Skriveru' from Latvia and a new Lithuanian cultivar 'Milda' (*Medicago varia* Martyn.) were used. In 2008, the cultivar 'Milda' has begun developed by hybridization method in the greenhouse conditions. Two cultivars ('Augūnė II' × 12991) were crossed between.

After the developing of the breeding population AI-3058 'Milda', this population was transferred to testing the value for cultivation and use (VCU) at the State Variety Testing Division in two locations of Lithuania – North-eastern (Utena State Plant Variety Testing Division) and North (Pasvalys State Plant Variety Testing Division). At the same time other testing of population AI 3058 'Milda' for DUS (Distinctness, Uniformity, Stability) was carried out in 2020–2023 at the Research Centre for Cultivar Testing (COBORU) in Poland. After the confirmation of positive DUS and VCU tests, in 2024, the cultivar 'Milda' was included to the Lithuanian National List of Plant Varieties as well as to EC Common catalogue of varieties of agricultural plant species.

Weather conditions of experiment locations

Lithuanian climate zone is semi-continental with moderately warm summers and moderately cold winters. The weather conditions of the experimental years in the central region of Lithuania (Dotnuva) were cold and wet in winter and very warm and humid in summer. Throughout the study period, the average air temperature was −1.1 °C in January and 19.5 °C in July, with an annual precipitation of 550 mm, varying from 505 mm in 2023 to 628.4 mm in 2022 (Table 1).

During the study period in the north-eastern region of Lithuania (Utena), the average air temperature was –1.7 °C in January and 18.9 °C in July. Annual precipitation was 728 mm and ranged between 623 mm in 2021 and 807 mm in 2022 (Table 1).

In the north-eastern region of Lithuania (Pasvalys), the average temperature during the study period was –0.6 °C in January and 19.1 °C in July. Annual precipitation was 672 mm and ranged between 579 mm in 2023 and 795 mm in 2021 (Table 1).

The western region of Lithuania (Vėžaičiai) distinguishes for the maritime climate and is characterized as moderately warm and humid. In comparison with the other regions, the amount of precipitation is the highest there. During the study period, the average air temperature was 0.6 °C in January and 18.3 °C in July. The average annual precipitation was 908 mm and ranged between 803 mm in 2022 and 907 mm in 2021 (Table 1).

Statistical analysis

The statistical analyses were performed using the statistical program SAS Enterprise Guide, version 7.13 (SAS Institute Inc., USA). The significance of the differences between experimental treatments was evaluated by one-factor analysis of variance (ANOVA). Tukey's HSD test was performed for multiple comparisons at the significant probability level $p < 0.05$.

Results and Discussion

Lithuanian National List of Plant Varieties contains 7 alfalfa (*Medicago sativa* L.) cultivars, 4 of them – Lithuanian. In 2024, a new sand alfalfa (*Medicago* × *varia* T. Martyn) cultivar 'Milda' was included. According to the studies of economic value in 2022–2023, it was determined to be resistant to overwintering, crop flattening (Table 3). In the beginning of flowering, the plants were 3.0 cm taller, compared to the standard Latvian cultivar 'Skriveru'. 'Milda' was more yielding (1.93 t ha^{-1}) for the dry matter yield than 'Skriveru'. The indicators of forage quality were similar to the standard cultivar: proteins – 20.0% 'Milda' and 21.1% 'Skriveru', fibre – 27.2% and 26.3%, leafiness – 45.8% and 45.2%, respectively.

The results of the study showed that the overwintering, plant height before flowering, fresh matter yield and dry matter yield were significantly influenced ($P < 0.0000$) by the soil pH_{KCl}, and the weather conditions of experimental year (Table 2). According to the results of 2022–2023, cultivar 'Milda' overwintered very well (9 points). The overwintering of cultivars 'Antanė', 'Birutė', 'Žydrūnė', 'Malvina' and 'Skriveru' was similar to 'Milda' (ranged from 8.6 to 8.9 points). Our study showed that all cultivars of alfalfa differed by the plant height before flowering under different environmental conditions during the growing season in 2022–2023. Plant height is related to the environmental conditions and the genetics of individual genotypes (Kavut et al., 2014; Djaman et al., 2020).

In the vegetation period of 2022, contrastive weather conditions – rainy and warm dominated. The period of spring-summer in 2023 was less rainy, hotter and drier. Therefore, the cultivars of alfalfa were 1.1 times taller before flowering in 2022 than in 2023. During the growing stage in 2022 that was mentioned above, the height of plants of cultivar 'Milda' was similar to 'Antanė', 'Malvina' and 'Skriveru', and slightly lower compared to alfalfa cultivars 'Birutė' and 'Žydrūnė' 1.05 times, respectively. In 2023, alfalfa cultivar 'Milda' was taller than Latvian cultivar 'Skriveru', but lower than cultivar 'Žydrūnė' 1.1 times each, respectively.

Environmental conditions play a significant role in the variation of fresh and dry matter yields among alfalfa cultivars (Veronesi et al., 2010). Fresh matter yield of alfalfa cultivars was 1.3 times higher in 2022 than in 2023. The fresh matter yield of cultivar 'Milda' (47.6 t ha^{-1}) was similar to 'Birutė' (47.7 t ha^{-1}). 'Milda' was more yielding compared to cultivars 'Antanė' and 'Skriveru' by 1.1 times and was more yielding compared to 'Žydrūnė' and 'Malvina' by 1.05 times. In 2023, the fresh matter yield of cultivars 'Milda', 'Antanė', 'Žydrūnė' and 'Malvina' was similar and ranged from 32.8 t ha^{-1} to 37.0 t ha^{-1}, while the most yielding cultivar was 'Birutė' (40.6 t ha^{-1}).

The dry matter yield of alfalfa was similar in 2022 and 2023- 8.8 t ha^{-1} and 9.6 t ha^{-1}, respectively. Dry matter yield of cultivars 'Milda' and 'Žydrūnė' was similar in 2022, and these cultivars were more yielding compared to 'Skriveru', by 1.1 times. The dry matter yield of cultivars 'Antanė' and 'Birutė' was the highest and these cultivars were by 1.4 times more yielding compared to 'Skriveru' and by 1.2 times more yielding compared to 'Milda'.

Table 2
The ANOVA results for the soil $pH_{KCl,}$ under field conditions effects on alfalfa wintering, height at before flowering, fresh and dry matter yields

Traits	***Source***		
	Cultivar	***Soil pH_{KCl}***	***Year***
Overwintering (score)	P<0.0000	P<0.0000	P<0.0000
Plant height before flowering (cm)	P<0.0000	P<0.0000	P<0.0000
Fresh matter yield (t ha^{-1})	P<0.0000	P<0.0000	P<0.0000
Dry matter yield (t ha^{-1})	P<0.0000	P<0.0000	P<0.0000

Table 3
The value for cultivation and use (VCU) of tested alfalfa cultivars in a high productivity soil in 2022-2023

Traits	***2022 (2021 sowing year)***		***2023 (2021 sowing year)***		***2023 (2022 sowing year)***	
	Pasvalys Plant Variety Testing Division					
	Milda	***Skriveru***	***Milda***	***Skriveru***	***Milda***	***Skriveru***
Overwintering (1–9 score)	9.0	9.0	9.0	9.0	9.0	9.0
Resistance to subsidence (1–9 score)	8.0	8.0	9.0	9.0	9.0	9.0
Plant height, cm	91.0	96.0	79.0	73.0	70.0	65.0
Leafiness, %	49.0	40.0	x	x	53.0	57.0
Crude protein, %	19.9	22.8	20.7	22.5	20.0	19.7
Crude fibre, %	30.6	28.7	26.4	26.0	26.3	26.6
Dry matter yield, t ha^{-1}	22.0	17.7	21.0	17.6	19.5	16.8
Vegetation period (days until the first cut)	168.0	168.0	157.0	157.0	157.0	157.0
	Utena Plant Variety Testing Division					
Overwintering, (1–9 score)	9.0	8.5	9.0	8.5	9.0	8.5
Resistance to subsidence (1–9 score)	7.3	7.6	9.0	9.0	8.5	8.5
Plant height, cm	72.0	68.0	63.0	59.0	64.0	60.0
Leafiness, %	33.3	32.1	x	x	47.9	51.5
Crude protein, %	18.7	20.7	18.9	20.7	21.8	20.0
Crude fibre, %	25.9	25.7	28.1	25.2	25.7	25.6
Dry matter yield, t ha^{-1}	10.99	9.77	8.51	9.14	8.2	7.64
Vegetation period days until the first cut	178.0	178.0	167.0	166.0	166.0	166.0

Notes: x – not determined. 1 score – very low value, 9 score – very high value.

The alfalfa cultivars ‘Milda’, ‘Antanė’, ‘Žydrūnė’ and ‘Malvina’ were similar for their dry matter yield in 2023, respectively: 9.5 t ha^{-1}, 9.7 t ha^{-1}, 9.7 t ha^{-1} and 9.8 t ha^{-1}. The dry matter yield of 4 cultivars mentioned above was 1.3 times higher than ‘Skriveru’ but 1.2 times less yielding compared to ‘Birutė’.

The fresh matter and dry matter yields of alfalfa depended on growing conditions in productive soils of different regions of Lithuania. According to the economic value studies of 2022 and 2023 in Pasvalys (North part of Lithuania), the dry matter yield of cultivar ‘Milda’ was by 1.2 higher than the standard cultivar ‘Skriveru’. Studies in Utena (North-eastern part of Lithuania) showed, that dry matter yield of alfalfa ‘Milda’ was by 1.1 times higher than ‘Skriveru’ in 2022, while the yield of standard cultivar was similar in 2023.

In 2022, the dry matter yield of alfalfa ‘Milda’ was by a long way higher (2.7 times) in Pasvalys, than in Dotnuva (central part of Lithuania). Cultivar ‘Skriveru’ was 2.4 times more yielding. In 2023, the dry matter yield of cultivar ‘Milda’ was 2.1 times higher in Pasvalys than in Dotnuva. In 2022, the dry matter yield of cultivars ‘Milda’ and ‘Skriveru’ was higher in Utena compared to Dotnuva, – by 1.3 times, respectively. Dry matter yield of cultivar ‘Milda’ in 2023 was higher in Dotnuva than in Utena – by 1.3 times.

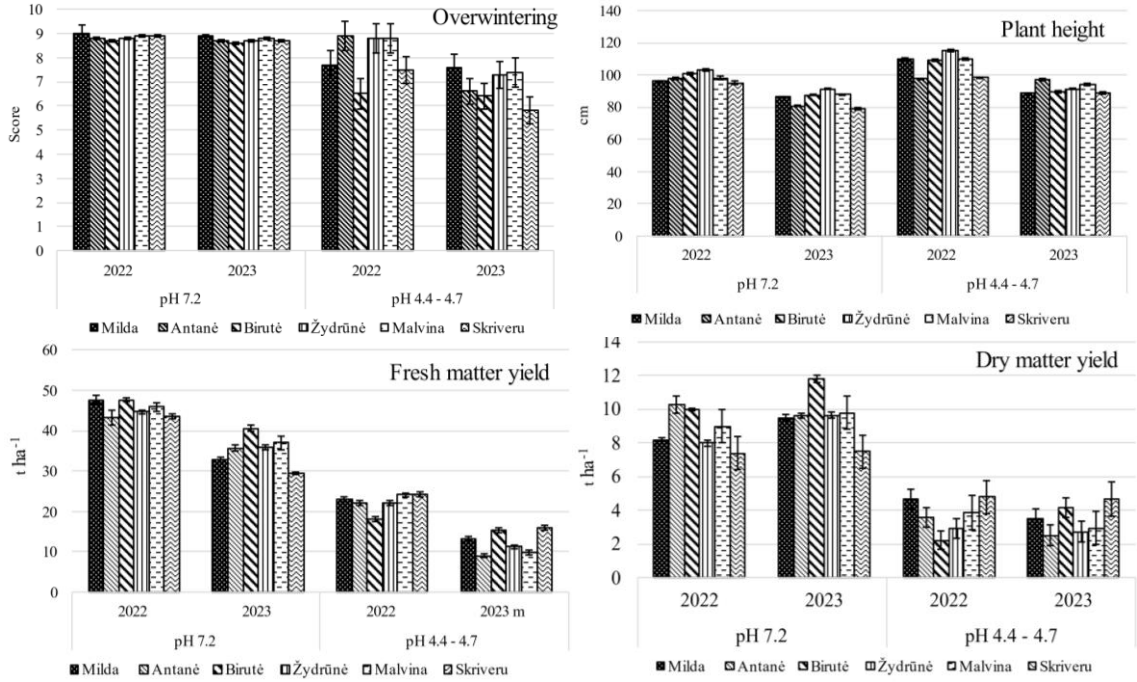
Acidic soils are mostly related to high aluminium ions concentration there (Ožeraitienė, 2000; Repšienė & Karčauskienė, 2016). Aluminium ions interfere with various physiological and cellular processes in the roots. High concentrations of mobile Al are toxic to plants and cause oxidative stress and may disrupt metabolic functions of plants (Langer et al., 2009; Bartoli et al., 2017). However, in acidic soil with small concentrations of mobile Al can sometimes increase plant growth or bring other desirable effects (Kisnerienė & Lepeikaite, 2015). Root function is

extremely dynamic and dependent on internal plant signals, root traits and morphology, and the physical, chemical and soil environment (Kuka et al., 2016). Our study showed that overwintering of alfalfa cultivars in acidic soil with mobile Al (13.6 mg kg^{-1}) concentration, was better (by 1.2 times) in the second winter than in the third winter. Overwintering of cultivars 'Milda' and 'Skriveru' was by 1.2 times worse in the second winter compared to cultivars 'Antanė', 'Žydrūnė' and 'Malvina'. In the third winter, cultivars 'Milda', 'Žydrūnė' and 'Malvina' persisted (overwintered) similarly, and they overwintered by 1.3 times better than 'Skriveru'.

The height before flowering of studied alfalfa cultivars was by 1.2 times higher in the second year of use than in the third year of use. The cultivars 'Milda', 'Birutė' and 'Malvina' were taller by the height before flowering in the second year of use than 'Antanė' and 'Skriveru', by 1.1 times. Alfalfa 'Birutė' distinguished for the plant height (115.3 cm). In the third year of use, 'Milda', 'Birutė' and 'Skriveru' were by 1.1 times taller at before flowering compared to 'Antanė' and 'Malvina'.

Figure 1

Comparison of agro-biological traits of alfalfa in productive and less productive soil



Notes: pH – soil acidity (pH_{KCl}) by the potentiometric method in the extraction of 1 M KCl. Vertical dashes indicate the mean of standard error.

The fresh matter yield of the alfalfa cultivars was 1.8 times higher in the second year of use than in the third year of use, because grasslands of alfalfa thinned. The fresh matter yield of the second year of use of cultivars 'Malvina' and 'Skriveru' was similar to 'Milda', while it was by 1.1 times higher than 'Antanė' and 'Žydrūnė' and by 1.3 times higher than 'Birutė'.

In the third year of use, the fresh matter yield of alfalfa 'Birutė' and 'Skriveru' was higher compared to cultivars 'Milda' – by 1.2, 'Žydrūnė' – by 1.4 and 'Malvina' – by 1.6 times. The highest dry matter yield of the alfalfa cultivars 'Milda' and 'Skriveru' (4.7 t ha^{-1} and 4.8 t ha^{-1} respectively) was in the second year of use. It was by 1.2 times higher than cultivars 'Antanė' and 'Malvina'. In the third year of use, the alfalfa cultivar 'Skriveru' distinguished for the highest dry matter yield (4.7 t ha^{-1}). This cultivar was more yielding than 'Milda' – by 1.3 times, 'Žydrūnė' – by 1.7 times and 'Antanė' – by 1.9 times.

In summary of the average data, in less productive soils the amount of overwintered alfalfa plants in the second winter was lower by 10.1%, and in the third winter it was lower by 20.7% than in productive soils ʻFigure 1'. Analysed alfalfa plants of the second year of use in the beginning of flowering were by 8.2% taller in less productive soils, and in the third year of use – taller by 7.1% compared to alfalfa that was growing in productive soils ʻFigure 1'. The fresh matter and dry matter yields of examined alfalfa of the second year of use in less productive soils were 2.0 and 2.4 times lower, and in the third year of use – 2.8 and 2.8 times lower than in productive soils ʻFigure 1'. Alfalfa spread is limited by the soil acidity and the abundance of moisture in the soil (Daugėlienė, 2010).

Conclusions

1. New alfalfa cultivar ʻMilda', similarly as the other examined cultivars distinguished for the high and

stable fresh matter and dry matter yields and are adapted to the conditions of Lithuanian climate.
2. The fresh matter and dry matter yield of the examined alfalfa cultivars on average in three years were 40.4 and 9.2 t ha^{-1} in productive soils and 17.4 and 3.6 t ha^{-1} in less productive soils. In the beginning of flowering, plants grown in productive soils were by 7.6 lower compared to those grown in less productive soils.
3. Lithuanian cultivars could be grown in more acid soil if pH_{KCl} is not lower than 4.5 and the amount of mobile aluminium is not higher than 25.0 mg kg^{-1}.

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EFFICACY OF DIFFERENT FUNGICIDE DOSES AND APPLICATION TIMES IN WINTER WHEAT AGAINST LEAF BLOTCHES

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Abstract
Leaf blotches, caused by *Pyrenophora tritici-repentis* and *Zymoseptoria tritici* are among the most devasting and widespread diseases in Latvia and other regions where wheat is extensively grown. Two field experiments were conducted over three years (2022-2024) in farmer's fields situated in the Central region of Latvia. The aim of research was to evaluate various fungicide and biological product application schemes, with wheat sown following preceding crops of either wheat or oilseed rape. Application schemes included fungicide application in different wheat growth stages and doses, as well as one biological product. Obtained data indicates that tan spot, caused by *Pyrenophora tritici-repentis*, was the predominant disease with severity ranging from 3 to 32% depending on a year and pre-crop. Level of tan spot was notably higher in repeated wheat sowings. The severity of Septoria leaf blotch ranged from 0% to 7%, and was not influenced by pre-crop. Fungicide application reduced the severity of leaf blotches; however, effectiveness varied significantly both across and within treatments. On average, more effective results were observed when a single fungicide treatment was applied at the end of heading and the beginning of flowering. The efficacy of the lowest fungicide dose was inconsistent, exhibiting greater variability compared to higher doses. Additionally, split spraying did not provide remarkable results compared to a single application. Application of biological product did not provide control of diseases. Strong, positive correlation was observed between the reduction in leaf blotches severity and the additional yield obtained.
Keywords: *Pyrenophora tritici-repentis*, *Zymoseptoria tritici*, severity, yield, plant protection.

Introduction

Wheat is one of the most widely cultivated and economically important crops in Latvia and globally. However, the spread of various diseases, particularly leaf diseases, poses one of the most significant risk to crop production. Leaf blotches, caused by *Pyrenophora tritici-repentis* and *Zymoseptoria tritici* are among the most devasting and widespread diseases in Latvia and other regions where wheat is extensively grown (Savary et al., 2019; Švarta et al., 2023).

The severity of leaf blotches and the associated yield losses are well documented, but results vary depending on region and others factors. Comprehensive review of the significance of these diseases has been conducted in the Nordic and Baltic countries. The severity fluctuated between 2% to 77% for tan spot and from 3% to 46% for Septoria leaf blotch respectively, depending on the year and agronomic practises (Jalli et al., 2020). According to the research by Jalli et al. (2020), yield losses reached between 529 and 1208 kg ha^{-1} due to these diseases.

Effective control of leaf blotch requires complex approach, in which agronomic practises and application of fungicides play principal role. Crop rotation and soil tillage may reduce level of leaf blotches, particularly tan spot. However, importance of agronomic practise in controlling of Septoria leaf blotch remains unclear, as the results of trials are inconsistent (Švarta et al., 2023). The life cycles of tan spot and Septoria leaf blotch differ under conditions of Latvia (Bankina et al., 2021). The causal agent of tan spot, *Pyrenophora tritici-repentis*, primarily survives in crop debris. Pseudothecia form in the straw at the end of vegetation season and continue to develop into the following spring. Consequently, the amount of residues determines level of tan spot. In contrast, *Zymoseptoria tritici* overwinters in living wheat as pycnidia. The intensity of disease is influenced by the potential for conidia to be transferred to the upper leaves, which is dependent on meteorological conditions.

Numerous experiments worldwide have been conducted to determine the best strategies for fungicide application against wheat leaf blotches. However, the results have been contradictory. Various doses of fungicides, timings of application and their interactions have been evaluated. Effectiveness of control depends on multiple factors, including the resistance level of cultivars, weather conditions, agronomic practices and the pressure of diseases (Cruppe et al., 2021; Breunig et al., 2022).

Recent research focuses on the potential to reduce fungicide applications and develop alternative methods for wheat leaf blotches control. Although some promising results have emerged, the effectiveness of control and convenience of application remain insufficient for practical use.

The aim of presented research is to evaluate efficacy of fungicide schemes and biological product for controlling wheat leaf blotches.

Materials and Methods

Field studies were conducted over three years (2022-2024) in farmer's fields situated in the Central region of Latvia, specifically at coordinates 56.318117° N, 24.03363° E and 56.330209° N., 24.032006° E. This region is characterized by its highly fertile soils and significant proportion of wheat in the sowing structure.

The variety 'Skagen' was selected for the study due to its extensive cultivation in Latvia, good winter hardiness, and moderate resistance to leaf diseases.

Two field experiments were established to evaluate various fungicide and biological product application schemes, with wheat sown following preceding crops of either wheat or oilseed rape.

Crop management practices mirrored those used on the specific farm and were typical of commercial fields with an intensive growing system characteristic of this region. Reduced soil tillage was implemented through disk harrowing to a depth of 18 cm. Nitrogen fertilization rates ranged from 139 to 160 kg ha^{-1}.

The seed was treated with fungicide at a rate of 1 L t^{-1}, containing fludioxonil (50 g L^{-1}) and tebuconazole (10 g L^{-1}). Growth retardants were applied twice during season of vegetation, with no insecticides used.

One-factor trials were designed with nine variants and four replicates, arranged in a randomized design. Experimental plots, each measuring 2.5 × 10 m, were established within production fields. Various doses of fungicides and application timings were evaluated, and one biological product (the product is not yet registered; therefore, the composition of the microorganisms has not been disclosed) was included as a treatment (Table 1).

The severity of diseases was assessed visually at the milk ripeness stage (GS 73 to 77 according to BBCH scale), by evaluating severity (%) on the two upper leaves.

The relative increase in yield (%) depending on treatment and relative decrease in leaf blotches severity (%) were calculated.

Significance of differences in disease severity was evaluated using the nonparametric Kruskal–Wallis test followed by Dunn's post-hoc test with the rstatix package (Kassambara, 2023). Pearson correlation coefficients were generated using the ggpairs function from the GGally package (Schloerke et al., 2025) and visualised with the ggplot2 package (Wickham, 2016).

Table 1

Fungicide and biological product application scheme

No.	***Designation***	***Product***	****Dose, L ha^{-1}***	***Growth stages according BBCH***
1.	A	Control (fungicide was not used)		
2.	B	Bixafen 65 g L^{-1}; prothioconazole 130 g L^{-1}; fluopyram 65 g L^{-1}	1.50	59-61
3.	C	Bixafen 65 g L^{-1}; prothioconazole 130 g L^{-1}; fluopyram 65 g L^{-1}	1.15	59-61
4.	D	Bixafen 65 g L^{-1}; prothioconazole 130 g L^{-1}; fluopyram 65 g L^{-1}	0.75	59-61
5.	E	Bixafen 65 g L^{-1}; prothioconazole 130 g L^{-1}; fluopyram 65 g L^{-1}	1.50	51-53
6.	F	Bixafen 65 g L^{-1}; prothioconazole 130 g L^{-1}; fluopyram 65 g L^{-1}	1.15	51-53
7.	G	Bixafen 65 g L^{-1}; prothioconazole 130 g L^{-1}; fluopyram 65 g L^{-1}	0.75	51-53
8.	H	Prothioconazole 160 65 g L^{-1}; spiroxamine 200 65 g L^{-1}; proquinazid 40 65 g L^{-1}	0.75	32-33
		Bixafen 65 g L^{-1}; prothioconazole 130 g L^{-1}; fluopyram 65 g L^{-1}	0.75	59-61
9.	I	**BIF-BEAUB	15.00	32-33
		BIF-BEAUB	15.00	51-53

*Fungicide doses based on main active ingredient (prothioconazole).

**Code of biological product developed by commercial company Bioefekts Ltd.

Results and Discussion

Meteorological conditions varied throughout the experimental period 'Figure 1'. Spring of 2023 was notably dry, with higher temperature compared to other years, which significantly influenced the development of leaf blotches.

Obtained data indicates that tan spot, caused by *Pyrenophora tritici-repentis*, was the predominant disease affecting wheat from 2022 to 2024, with the severity ranging from 3 to 32% depending on the year and pre-crop 'Figure 2'. Level of tan spot was notably higher in repeated wheat sowings ($p<0.001$).

Figure 1
Meteorological conditions during the period of vegetation in the years 2022-2024

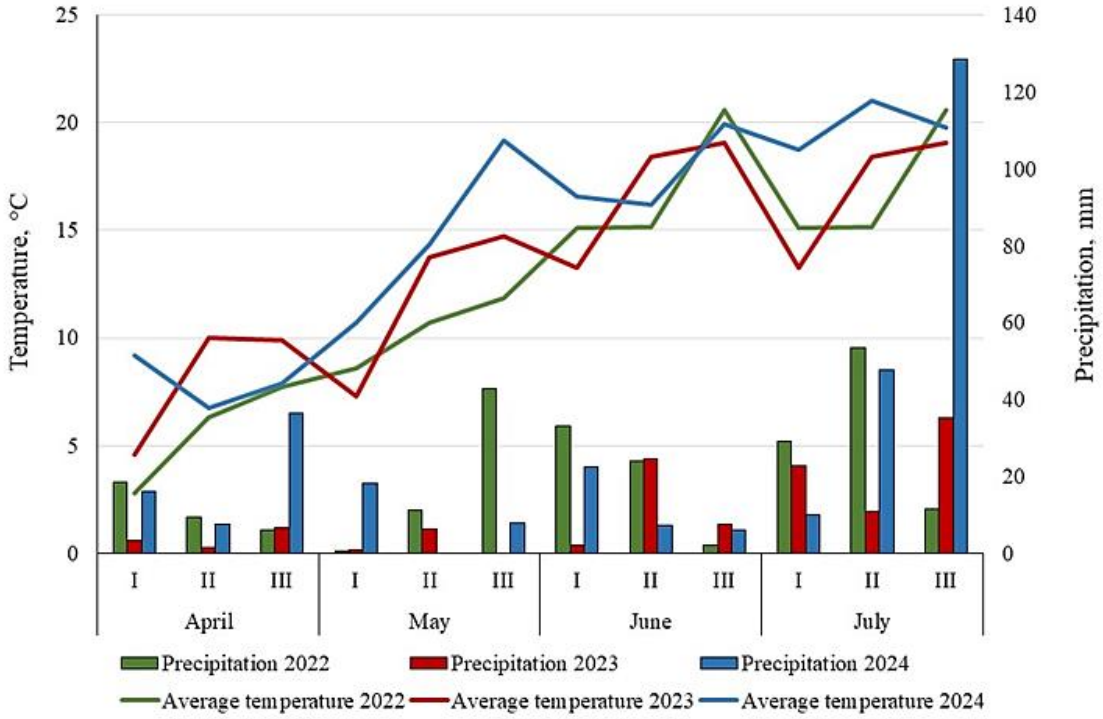
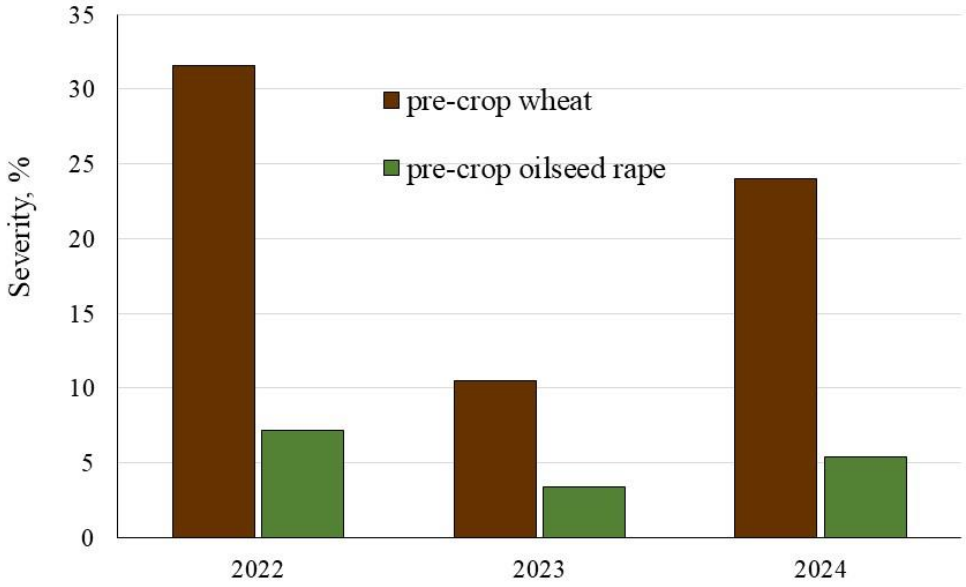
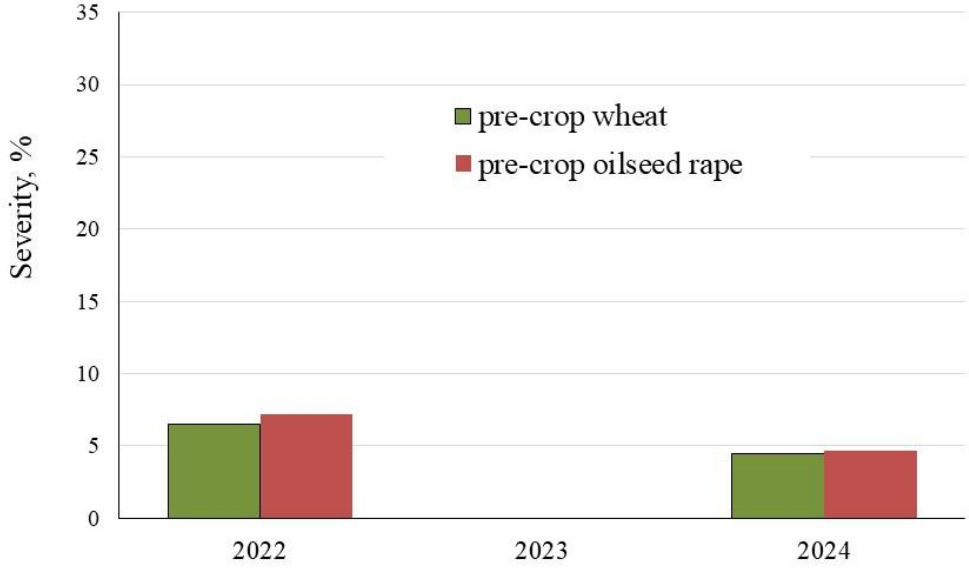


Figure 2
The severity of tan spot, caused by Pyrenophora tritici-repentis at the milk stage of ripening depending on year and pre-crop



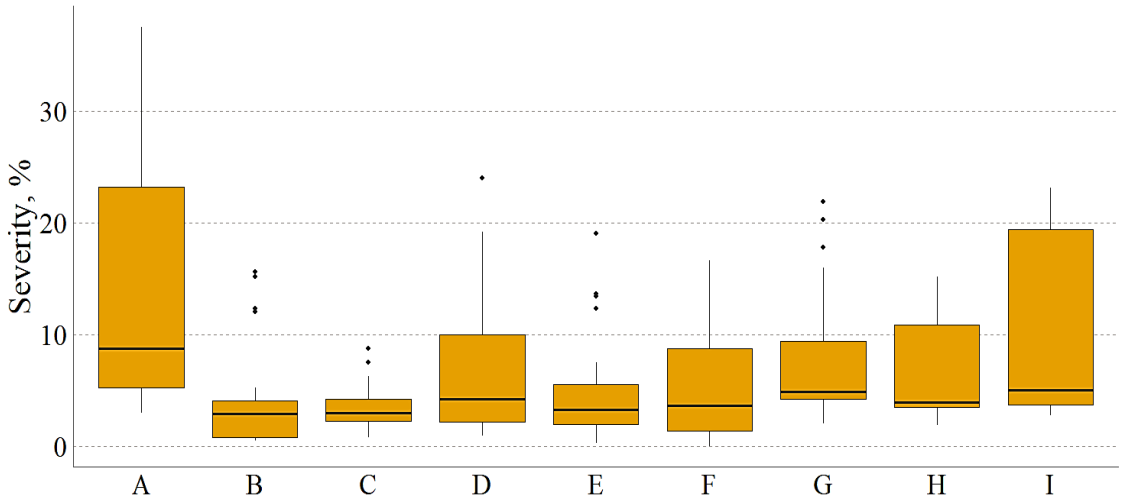
In contrast, Septoria leaf blotch, caused by *Zymoseptoria tritici*, was recorded on the upper two leaves only in 2022 and 2024. Its severity ranged from 0% to 7%, significantly lower comparing with tan spot 'Figure 3'. Level of Septoria leaf blotch was not influenced by pre-crop used.

Figure 3
The severity of Septoria leaf blotch, caused by Zymoseptoria tritici at the milk stage of ripening depending on year and pre-crop



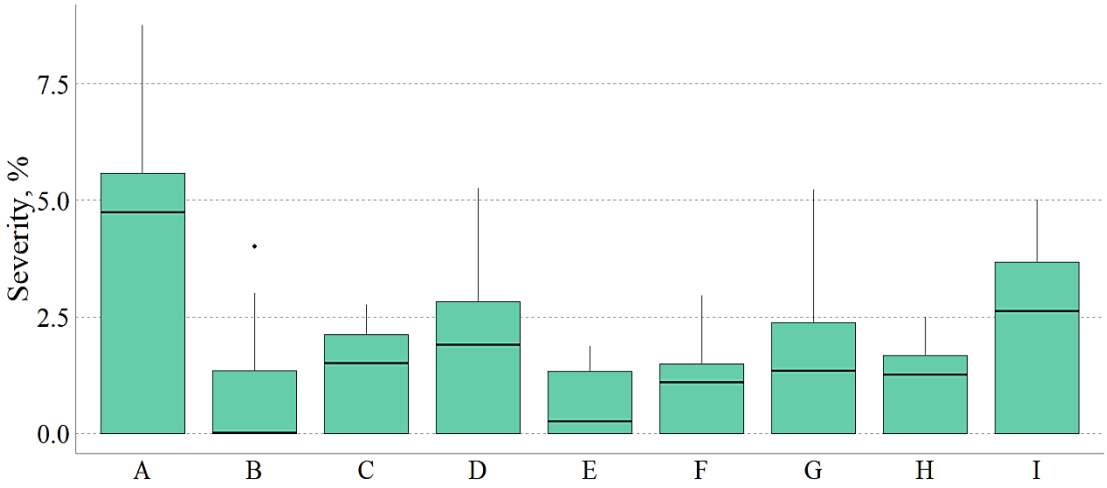
Fungicide application reduced the severity of tan spot; however, its effectiveness varied significantly both across and within treatments 'Figure 4'. Neither the year of cultivation nor the pre-crop had a significant impact on the effectiveness of fungicides.

Figure 4
The severity of tan spot, caused by Pyrenophora tritici-repentis, depending on treatment scheme: A – without fungicide; B – fungicide at the BBCH 59–61, dose 1.5 L ha^{-1}; C – fungicide at the BBCH 59–61, dose 1.15 L ha^{-1}; D – fungicide at the BBCH 59–61, dose 0.75 L ha^{-1}; E – fungicide at the BBCH 53-55, dose 1.5 L ha^{-1}; F – fungicide at the BBCH 53-55, dose 1.15 L ha^{-1}; G – fungicide at the BBCH 53-55, dose 0.75 L ha^{-1}; H – fungicide at the BBCH 32.-33. and 59.-61., doses 0.75 L ha^{-1} and 0.75 L ha^{-1}, I – BIF-BEAUB at the BBCH 32.-33. and 51.-63., doses 15 L ha^{-1} and 15 L ha^{-1}



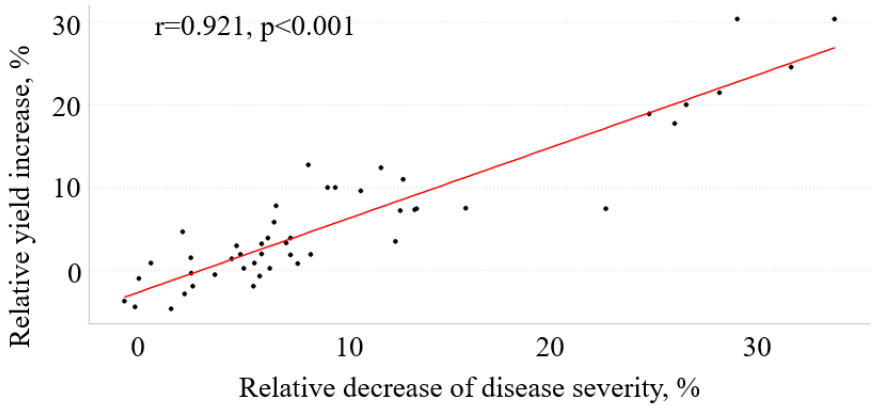
Applying a single fungicide application at the end of heading and the start of flowering generally produced better results. The efficacy of the lowest fungicide dose was inconsistent, exhibiting greater variability compared to higher doses. Additionally, split spraying did not provide superior results compared to a single application. Efficacy of Septoria leaf blotch control is difficult to evaluate, because level of disease was low. In general, level of disease was reduced in all schema of fungicide application, but the best variant was not clear 'Figure 5'.

Figure 5
The severity of Septoria leaf blotch, caused by Zymoseptoria tritici, depending on treatment scheme: A – without *fungicide; B – fungicide at the BBCH 59–61, dose 1.5 L ha^{-1}; C – fungicide at the BBCH 59–61, dose 1.15 L ha^{-1}; D – fungicide at the BBCH 59–61, dose 0.75 L ha^{-1}; E – fungicide at the BBCH 53-55, dose 1.5 L ha^{-1}; F – fungicide at the BBCH 53-55, dose 1.15 L ha^{-1}; G – fungicide at the BBCH 53-55, dose 0.75 L ha^{-1}; H – fungicide at the BBCH 32.-33. and 59.-61., doses 0.75 L ha^{-1} and 0.75 L ha^{-1}; I – BIF-BEAUB at the BBCH 32.-33. and 51.-63., doses 15 L ha^{-1} and 15 L ha^{-1}*



The biological product proved mostly ineffective, resulting in notably higher both leaf blotches severity compared to chemical treatments.
The yield of winter wheat varied significantly. In untreated variants, where wheat followed wheat, yields ranged from 5.0 to 9.2 t ha^{-1}, in contrast, when wheat was grown after oilseed rape, yields were higher, ranging from 7.9 to 9.4 t ha^{-1}. On average, fungicide application enhanced yields, achieving values between 5.9 to 9.9 t ha^{-1} after wheat, and 7.7 to 9.9 t ha^{-1} after oilseed rape, depending on year and specific treatment. The harmfulness of diseases was calculated by considering the relative reduction in disease severity and the corresponding relative increase in yield. Strong, positive correlation was observed between the reduction in leaf blotches severity and the additional yield obtained ‘Figure 6’.

Figure 6
The correlation between relative decrease in leaf blotches severity at the milk ripening and relative increase in winter wheat yield



Leaf blotches, caused by *Pyrenophora tritici-repentis* and *Zymoseptoria tritici* were identified as the most significant diseases over the three years. This outcome was expected, as similar results have been reported in others experiments conducted worldwide.
The severity of diseases fluctuated depending on various factors, including meteorological conditions, characteristics of varieties and agronomic practises.

Repeated wheat sowings and reduced soil tillage essentially increase level of tan spot (Jalli et al., 2021); however, the effects on Septoria leaf blotch results are contradictory (Bankina et al., 2021).

The obtained results regarding the dominance of tan spot align with previous findings in Latvia, especially in repeated wheat sowings (Bankina et al., 2021; Švarta et al., 2023). However, these data differ from the situation in most European countries, where tan spot is considered a minor disease. In contrast, Septoria leaf blotch is identified as the most devasting disease of winter wheat, including North Europe, excluding Norway and Sweden (Willocquet et al., 2021).

The number of rainy days and high relative air humidity are the most important factors that influence level of Septoria leaf blotch (Andersson et al., 2022). This disease was not observed in 2023 due to insufficient precipitation during May and first decade of June 'Figure 1', which prevented the release *Zymoseptoria tritici* conidia from pycnidia on the leaves. These conidia, mainly formed in previous autumn, typically spread to the upper leaves under favourable conditions.

The high amount of precipitation promotes the development of tan spot, as noted by Cook et al. (2024). This finding was confirmed in our trials: the highest pressure of tan spot was observed in 2022, when the first half of summer was more humid compared to other years.

Different fungicides are widely used to protect wheat and increase yield; however, prothioconazole (14α-demethylase inhibitor) is recognized as one of the most effective against tan spot (Kaņeps et al., 2024) and Septoria leaf blotch (Jorgensen et al., 2018); therefore, this fungicide has been chosen. Despite a significant number of field trials, the optimal timing and dosage of fungicide remain unclear. The results of presented study are also controversial. Although most of researchers have recognized heading as the best time for fungicide spraying (Peterson et al., 2023), the latest application produced better results according to the current study. This discrepancy can possibly be explained by variations in the spectrum of diseases. Tan spot develops quickly only after flowering, making the later treatment more suitable under specific conditions in Latvia.

Despite variations in the effectiveness of fungicide applications, treatment increased yield by an average of 0.29 ha^{-1}. Although two applications of fungicides are commonly recommended (Wang et al., 2024), the findings of this study did not support it, as Septoria leaf blotch was only a minor disease. Similarly, Wegulo et al. (2011) and Breunig et al. (2022) noted that two fungicide sprayings are necessary only during humid seasons with high pressure of diseases.

The amount of additional yield depended on various factors, including disease pressure (Cruppe et al., 2021), with the level of protection positively associated with yield (Willocquet et al., 2021). Similar conclusion was drawn in the presented study – the greatest suppression of leaf blotch severity resulted in the higher additional yield.

Conclusions

1. Fungicide treatment is essential to protect winter wheat and ensure high yields; however, the timing and dosage of application depend on the specific conditions of the year and the individual field.
2. Unfortunately, the biological product tested in this study was not effective.

Fluctuations in the results indicate that standardised treatment schemes are ineffective under changing meteorological conditions and other influencing factors.

3. Monitoring disease development and evaluating risk factors are crucial for effective and environmentally friendly disease control in winter wheat.

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THE MOST IMPORTANT POTATO DISEASES AND MICROBIOLOGICAL AGENTS FOR THEIR CONTROL: A REVIEW

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Abstract
Following the regulations of the European Union 'Farm to Fork Strategy' encourages a significant reduction in the use of plant protection products and mineral fertilizers by 2030. Potatoes are grown widely because they are a valuable source of nutrition. However, achieving high levels of yield and quality remains a challenge, particularly due to the risk of diseases. The causal agents of diseases belong to various kingdoms – fungi, bacteria, and viruses. The potato late blight (caused by *Phytophthora infestans*), early blight (caused by *Alternaria* spp.), black scurf (caused by *Rhizoctonia solani*), silver scurf (caused by *Helminthosporium solani*), black dot (caused by *Colletotrichum coccodes*), fusarium dry root (caused by *Fusarium* spp.) and common scab (caused by *Streptomyces* spp.) are the most important potato leaf and tuber diseases. The market offers a wide variety of microbiological products, which contain microorganisms for the control of potato diseases. The active ingredients in these products are primarily microorganisms from the fungal and bacterial kingdoms, such as *Bacillus* spp., *Trichoderma* spp., *Pseudomonas* spp., or their combinations. However, they differ in effectiveness against pathogens, as well as in the timing of application, the number of applications, the form of the products, and the most favorable meteorological conditions during and after treatment. It has a future and potential to be a good alternative to chemical plant protection. The aim of this study was to summarize information from researches about the popular microbiological products, their component biology and effectiveness to control potato diseases.
Keywords: *Solanum tuberosum* L., potato diseases, *Bacillus* spp., *Trichoderma* spp., *Pseudomonas* spp.

Introduction

Potato (*Solanum tuberosum* L.) is the most widely cultivated and one of the major tuber crops in the world. It is ranking third to fourth place among the most cultivated crops, following wheat (*Triticum aestivum*), rice (*Oryza sativa*) and sharing place with maize (*Zea mays*) (Simko, 2004; Kumar & Chandra, 2018; Campos & Ortiz, 2020). One of the main challenges in growing potatoes is the impact of diseases and pests, which can significantly affect plant development.

Another major issue is the low availability of nutrients during the early stages of growth (Finckh et al., 2006). Potato yields worldwide show a significant difference between conventional and biological growing systems, with yield gaps typically ranging from 9% to 25%, and in some cases reaching as high as 70% (Ierna & Parisi, 2014; Wilbois & Schmidt, 2019; Zarzyńska et al., 2023). This variation is strongly influenced by factors such as diseases and pests and the timing of disease development. Other factors that may influence the yield difference include the growing conditions of the year, lack of irrigation, and other cultivation technologies (De Ponti et al., 2012).

Due to the increasing spread of plant diseases and pests, farmers are using chemical plant protection products with greater frequency.

However, the European Union's 'Farm to Fork' strategy encourages a major reduction in the use of plant protection products and mineral fertilizers by 2030 (European Union, 2020). Over the past 20 years, global demand for pesticide-free food has grown, driven not only by concerns for human health but also by the desire to reduce environmental risks (Basu, 2009).

Microorganisms play a crucial role in reducing the use of chemical pesticides in agriculture. These organisms can promote plant growth and development, increase crop yield and quality, decompose organic matter, fix atmospheric nitrogen, and convert it into a form that is easily absorbed by plants and reduce or limit the spread of plant pathogens through various mechanisms (Marjanović et al., 2024).

The aims of this study were to summarize information from researches about the beneficial microbiological agents, their biology and effectiveness, as well as how it can be used in sustainable agricultural practices to control the development of common pathogens of potato diseases.

Materials and Methods

This review paper draws on scientific literature concerning microbiological plant protection products (bioagents), their suitability for use, and their impact on potato leaf and tuber diseases. The study examines the experience of various countries with registered microbiological agents and analyzes most common potato diseases, their pathogens, and control options.

Results and Discussion

The most significant and potentially damaging potato leaf diseases are late blight (caused by *Phytophthora infestans*) and early blight (caused by *Alternaria* spp.). From tuber diseases the major ones are potato black scurf (caused by *Rhizoctonia solani*), silver scurf (caused by *Helminthosporium solani*), black dot (caused by *Colletotrichum coccodes*), common scab (caused by *Streptomyces* spp.) and bacterial blackleg (caused by *Pectobacterium* spp.), as well as many *Virus* kingdom microorganisms, such potato X, Y, M, S, mop-top viruses etc. (Finckh et al., 2006; Fiers et al., 2012; Campos & Ortiz, 2020).

Potato leaf diseases

Potato late blight caused by *Phytophthora infestans* from the *Chromista* kingdom, *Oomycota* phylum, *Peronosporales* order. It is one of the most significant and destructive potato diseases in the world (Subhani, 2016). It reproduces sexually through oospores and asexually through conidia and zoospores. This allows for a wider and faster development of the infection (Nowicki et al., 2012). The pathogen survives in potato tubers, plant debris in the form of mycelium and in the soil as oospores (Andrivon, 1995). Asexual spores are transmitted by wind and water. The optimal development temperature is moderately warm, the range of 10–25 °C, with a relative humidity 90–100% (Nowicki et al., 2012; Subhani, 2016).

Potato early blight caused by *Alternaria* spp. from the *Fungi* kingdom, *Ascomycota* phylum, *Pleosporales* order. Sexual reproduction is not observed, but the high species diversity indicates extensive pathogen recombination (Schmey et al., 2024). The pathogens reproduce asexually through conidia. The fungus *Alternaria* survive and overwinter in the form of mycelium or conidia in plant debris, the soil, and potato tubers. The spores can be dispersed by wind and water, sometimes with the help of insects (Tsedaley, 2014; Yuldashova et al., 2023). The optimal weather conditions for the pathogen development are hot and humid. The quick development of conidia occurs at temperatures between 20–30 °C, with relative air humidity under 70% (Tsedaley, 2014; Escuredo et al., 2019).

Potato tuber disease

Black scurf, stem canker and root rot caused by *Rhizoctonia solani* from the *Fungi* kingdom, *Basidiomycota* phylum, *Cantharellales* order. *R. solani* survives in the form of mycelium in plant debris or as sclerotia in the soil, and spreads through infected seed material (Aydin, 2022; Nasimi et al., 2024). The optimal growth temperature for the pathogen is moderate, the range of 15–25 °C (Orozco-Avitia et al., 2013). Increased soil moisture, about 20%, is beneficial (Kiptoo et al., 2021).

Silver scurf caused by *Helminthosporium solani* from the *Fungi* kingdom, *Ascomycota* phylum, *Pleosporales* order. Initially, the fungus produces mycelium, followed by the production of conidia. The pathogen survives in infected tubers and in the soil (Avis et al., 2010; Tiwari et al., 2020). The spread of the disease starts in the soil, with the first symptoms appearing during harvest, but the pathogen continues to develop even in storage. Optimal conditions are above +3 °C with a relative humidity of 90% (Abbas et al., 2013; Tiwari et al., 2020). Maximum sporulation and the highest number of conidia are observed at +24°C and humidity 90–95% (Tiwari et al., 2021). However, the fungus can develop over a wide temperature range of 2–30 °C (Abbas et al., 2013).

Black dot caused by *Colletotrichum coccodes* from the *Fungi* kingdom, *Ascomycota* phylum, *Glomerellales* order. The pathogen survives in infected seed material and soil (Lees & Hilton, 2003; Cannon et al., 2012; Mattupalli et al., 2013; Johnson et al., 2018). Infection occurs early in the season, but visible symptoms and sclerotia begin to appear closer to harvest time (Mattupalli et al., 2013; Johnson et al., 2018). The optimal temperature for conidia growth is +22 °C, while mycelium grows best in the temperature range from 25 to 31 °C, and moist soil conditions (Lees & Hilton, 2003).

Potato common scab caused by *Streptomyces* spp. from the *Monera* kingdom, *Actinobacteria* class and *Actinomycetales* order. *Streptomyces* spp. infects tuber crops worldwide (Lerat et al., 2009; Hamedo & Makhlouf, 2013). Bacteria form structures that are morphologically similar to hyphae and spores. The mycelium is made up of hyphae, and spores being released from their ends (Braun et al., 2017). The pathogen survives in the soil, plant debris, and infected seed material. The pathogen spores can penetrate through damaged areas or lenticels (Dees & Wanner, 2012; Braun et al., 2017). The optimal soil pH for the bacterium development is slightly acidic to neutral, between 5.5 and 7.5. It infects young tubers most intensively when the temperature is above +20 °C and the soil moisture is between 65–70% or lower (Braun et al., 2017).

Microbiological agents

To achieve a high quality potato harvest, it is essential to follow a set of agrotechnical practices, primarily focused on prophylactic measures. This includes selecting the appropriate variety, implementing various cultivation technologies during the growing season, and ensuring proper storage conditions in warehouses (Tresnik, 2007). Some bacteria and fungi also have beneficial properties that can be applied in biological farming and sustainable agricultural practices. Products containing bacteria or their metabolites, enzymes, or antibiotics are frequently mentioned in the literature, such as *Bacillus* spp., *Pseudomonas* spp., *Azospirillum* spp., and *Azotobacter* spp. The most popular fungi are *Trichoderma* spp. and *Aspergillus* spp., which produce secondary metabolites.

Bacteria from genera ***Bacillus*** is gram-positive, aerobic, rod-shaped, and motile bacteria (Maughan & Van der Auwera, 2011). The most well- known species is *B. subtilis*, which produce metabolites, such as enzymes, antibiotics, and enhance the plants resistance to pathogens and pests. Other species, for example, *B. velezensis*, *B. macerans*, *B. azotofixans* etc., are known as *Plant Growth-Promoting Bacteria* (PGPB). Bacteria found in the rhizosphere can protect plants in several ways: 1) they produce volatile organic compounds that increase root exudation; 2) produce secondary metabolites that have antibiotic compounds; 3) form biofilms, colonize the roots and protect them from harmful effects of pathogens (Choudhary & Johri, 2009; Khan et al., 2022).

Bacillus spp. increase yield and improve disease resistance in most cereal grains, legumes, as well as cucumbers, tomatoes, and potatoes (Miljaković et al.,

2020). There are several ways to use *Bacillus* based treatments:

1. Seed tuber treatment with a bioagent requires soaking potato seed tubers in a *Bacillus* containing solution for 20–30 minutes, and this treatment improves both yield and biomass growth (Kumar et al., 2013). Additionally, it helps reduce the development of late blight during storage after harvest (Lastochkina et al., 2022), as well as reduces the incidence and severity of black scurf under greenhouse conditions (Saber et al., 2015).
2. Seed tuber and foliar treatment. A bioagent based on talc, which is later prepared as a solution, is used. The seed tubers are treated as mentioned above, and 40 days after planting (DAP), the same solution is used for foliar spraying (Wei et al., 2024).
3. Soil and foliar treatment. *Bacillus* through soil treatment or drenching before planting potatoes is applied. Later, during the growing season, foliar spraying with the bioagent is carried out. These measures reduce the spread of late blight and improve various physiological parameters of potato plants compared to the control (Kumbar et al., 2019).

Global research is exploring various bacterial species and their interactions with pathogens, particularly focusing on the *Pseudomonas* spp., *Azospirillum* spp., and *Azotobacter* spp., which are classified as PGPB. *Pseudomonas* spp. can form biofilms, release metabolites with potent antifungal properties, synthesize phytohormones, fix atmospheric nitrogen, and facilitate nutrient decomposition and absorption (Sah et al., 2021).

In a field trial, treating potato tubers with ***Pseudomonas*** based bioagents before planting helped limit *R. solani* growth. A talc-based formulation was more effective than a *Pseudomonas* suspension, significantly reducing stem cancer and black scurf while increasing yield (Lal et al., 2022). In another study, three genera of microbiological agents (*Pseudomonas* spp., *Trichoderma* spp. and *Bacillus* spp.) showed high efficacy against *Alternaria* spp. in *in vitro* and under greenhouse conditions (Aldiba & Escov, 2019). *P. putida* shows effectiveness against *H. solani*, but the experiment was conducted only on plates (Elson et al., 1997).

For foliar disease control, multiple bioagent spray applications were necessary. A multi-year study found that applying *P. putida*, *B. subtilis*, and *T. erinaceum* eight times effectively controlled *P. infestans* for 60 days, reducing disease severity by nearly half (Islam et al., 2022).

***Azospirillum* spp.** promotes plant growth by fixing atmospheric nitrogen and producing phytohormones (Cassán & Diaz-Zorita, 2016; Fukami et al., 2018). *A. lipoferum* effectively controls potato early blight (caused by *Alternaria* spp.) in both greenhouse and field conditions. In field trials, spraying the bioagent at BBCH 15–17 reduced disease incidence by 40–50% compared to the control (Mehmood et al., 2021).

***Azotobacter* spp.** are widely known for their nitrogen fixing properties; however, they are also capable of producing antifungal substances that limit the activity of fungal pathogens near the root system (Jiménez et al., 2011; Wani et al., 2016; Sumbul et al., 2020; Al-Baldawy et al., 2023).

Microbiological products containing combinations of different microorganisms, such as *Pseudomonas* spp., *Bacillus* spp. and *Azotobacter* spp., showed the lowest development compared to the control. These bioagents, in various combinations, were applied once to the seed tuber material at the planting (Aguk et al., 2018). Seed tuber treatment with *Azotobacter* spp. may reduce the incidence of *R. solani* (Meshram, 1984).

***Trichoderma* spp**. produces secondary metabolites that enhance plant growth and development and is referred to as a plant growth promoting agent (PGPA) (Yao et al., 2023). *Trichoderma* spp. is the most widely used fungal genus in biological plant protection, accounting for about 90% of cases (Błaszczyk et al., 2014). This fungus is most commonly used as a soil disease controller, which can colonize plant roots, but it can also limit pathogens on the aerial parts of the plant – leaves, stems and spikes. *Trichoderma* interact with other pathogenic fungi: 1) by suppressing, entering the cells of other organisms, such as *Phytophthora* sp., *Pythium* sp., *R. solani*, *Colletotrichum* spp., *Sclerotinia sclerotiorum*, *Botrytis cinerea* and secreting various enzymes; 2) by competing for nutrients, such as with *B. cinerea*; 3) by producing compounds similar to antibiotics that act against pathogens, such as *B. cinerea*, *R. solani*, and *F. oxysporum* (Błaszczyk et al., 2014; Yao et al., 2023); 4) *Trichoderma* is also capable of induced systemic resistance (ISR), activate plant self defense mechanisms (Dutta et al., 2023; Yao et al., 2023).

The most common products on the market contain *Trichoderma* species such as *T. viride*, *T. virens*, and *T. harzianum* and the less commonly used species, *T. asperellum*, *T. longibrachiatum*, *T. koningii*, *T. polysporum*. These products are often available in the form of granules or powder, which are used to treat seed tuber material before sowing (Zin & Badaluddin, 2020; Yao et al., 2023). A spore solution containing bioagent was applied twice to the plants on the 15 and 45 DAP (Rakibuzzaman et al., 2021). Recent studies also examine the impact of *Trichoderma* spp. on potato early blight (caused by *Alternaria* spp.) (Metz & Hausladen, 2022).

The combination of fungus *T. harzianum* and bacteria *B. subtilis* different strains has shown high effectiveness against the potato common scab (caused by *Streptomyces* spp.). Different concentrations of bioagents were used, which were added once to the seed potatoes in the furrows (Wang et al., 2019). In another experiment against potato black scurf, bioagent *T. harzianum* showed higher effectiveness than *B. subtilis*. In this case as well, the seed tuber material was treated once before planting by soaking the seeds in the isolate solution (Khalil et al., 2019).

***Aspergillus* spp.** and ***Penicillium* spp.** both genera include beneficial and harmful microorganisms (Houbraken et al., 2020). Certain species of both genera limited the growth of *R. solani*, *P. infestans*, and *Fusarium* spp. on the plate (Lal et al., 2016; Trabelsi et al., 2016). *P. viridicatum* and *T. viride* showed high effectiveness against late blight when applied as a bioagent suspension spray 40 DAP (Gupta et al., 2004). *P. chrysogenum* is effective against early blight reducing pathogen growth in both *in vitro* and *in vivo* conditions when potato leaves were treated with the bioagent solution (Hatem et al., 2022).

Table 1 illustrates the interaction of various microbiological agents and potato disease pathogens, as well as the different methods of their application. In the table, a cross indicates which specific pathogens are affected by the bioagent.

Based on the information available in scientific publications, it is evident that various microbiological agents are used to control plant disease pathogens, with varying degrees of effectiveness. A large number of studies have been conducted under controlled laboratory conditions; however, there are relatively few field conditions studies.

Table 1

The interaction of beneficial microorganisms with pathogens and application of microbiological products

Beneficial microorganisms in microbiological products	***Pathogens***						***Notes***
	P. infestans	**Alternaria spp.**	**R. solani**	**H. solani**	**C. coccodes**	**Streptomyces spp.**	
***Trichoderma* spp.** (Aldiba & Escov, 2019; Blaszczyk et al., 2014; Islam et al., 2022; Khalil et al., 2019; Metz & Hausladen, 2022; Wang et al., 2019; Yao et al., 2023; Zin & Badaluddin, 2020)	×	×	×		×	×	A wide range of applications. Seed tuber material treatment before sowing (in-furrow treatment, soaking, spraying, etc.). Soil and leaf spraying under greenhouse conditions. Foliar spraying on 34, 41, 48, 53, 57, 62, 69 un 75 DAP*.
***Bacillus* spp.** (Aldiba & Escov, 2019; Islam et al., 2022; Kumbar et al., 2019; Lastochkina et al., 2022; Saber et al., 2015; Wang et al., 2019; Wei et al., 2024)	×	×	×			×	Seed tuber material is treated with agent shortly before planting. Leaf spraying starts from the 34 DAP.
***Pseudomonas* spp.** (Aldiba & Escov, 2019; Elson et al., 1997; Islam et al., 2022; Lal et al., 2022)	×	×	×	×			Soil and leaf spraying under greenhouse conditions. Seed tuber material treatment before planting. Leaf spraying starts from the 34 DAP *in vitro* conditions.
***Azospirillum* spp.** (Mehmood et al., 2021)		×					In field trials, leaf spraying at BBCH 15–17.
***Azotobacter* spp.** (Meshram, 1984; Sumbul et al., 2020)			×	×			Seed tuber material treatment before planting.
***Aspergillus* spp., *Penicillium* spp.** (Gupta et al., 2004; Hatem et al., 2022; Lal et al., 2016; Trabelsi et al., 2016)	×	×	×				Reduce pathogen growth on the plate. Foliar spraying at 40 DAP.

*****DAP – days after planting.

Conclusions

1. The most significant potato pathogens are *Phytophthora infestans*, *Alternaria* spp., *Rhizoctonia solani*, *Helminthosporium solani*, *Colletotrichum coccodes* and *Streptomyces* spp.

2. The most common and extensively studied microbiological agents come from the kingdoms of bacteria and fungi – *Bacillus* spp., *Trichoderma* spp.; less studied genera include *Pseudomonas* spp., *Azotobacter* spp., *Aspergillus* spp. and *Penicillium* spp.

3. The use of microbiological agents in the formulation of various products is increasing. These microbiological agents also have potential in low-input

agriculture, as they provide a good alternative to chemical plant protection products.

4. Most microbiological agents show effectiveness against potato tuber diseases; however, some microorganisms, when applied to the leaves, also demonstrate effectiveness against potato early blight and late blight. Further research is necessary, as fewer studies have been conducted under field conditions compared to *in vitro* studies, and different strains of biological agents exhibit varying levels of effectiveness against diseases.

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REVIEW OF APPLE TREE ARCHITECTURE PARAMETERS AND THEIR POTENTIAL APPLICATIONS IN BREEDING THROUGH HIGH-THROUGHPUT PHENOTYPING

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Abstract
This review paper examines the importance of apple tree architecture parameters in breeding programmes, focussing on the roles of canopy volume, tree shape, and fruit-bearing habits in optimising orchard management and breeding efficiency. Canopy volume is a critical indicator of tree growth and productivity, often measured using advanced methods such as LiDAR and UAVs, which provide high-resolution 3D data, especially useful in dense orchards. Tree shape, including branching patterns, angles, and overall structure, plays a key role in optimizing light capture, airflow, space utilization, and tree vigour, which can be efficiently assessed through remote sensing technologies. Early selection of desirable branching traits, such as internode length and branch angle, enables optimisation of tree architecture and improved fruit production in high-density orchards. Fruit-bearing habits, including the timing and position of flowering and fruiting, significantly influence yield regularity and fruit quality and can be analysed using technologies such as photogrammetry, multispectral imaging, and RGB cameras. These tools enable automated identification of key tree characteristics, allowing for better management of tree health, pruning, and fruit-bearing zones. Despite advances in these technologies, further research is needed to better understand the relationship between tree shape, productivity, and longevity, to refine orchard management strategies and improve the efficiency of breeding programmes. This article emphasises the growing role of smart technologies in improving phenotyping and accelerating apple tree breeding processes.
Keywords: *Malus domestica*, phenotyping, tree architecture traits, smart breeding.

Introduction

Apple trees are the most widely cultivated fruit crop species in Europe. In 2017, they comprised 36.6% of the total fruit tree area in the European Union, covering 473,550 hectares (Eurostat, 2017). Similarly, apple trees are the main fruit tree species in Latvia, with an area of 3,508 hectares in 2023 (CSBRL, 2023).

The most significant challenge facing agriculture today is climate change; therefore, specific solutions for various geographic regions are required to reduce environmental impacts while improving crop yield. Breeding innovative, resilient, and robust cultivars offer the ability to reduce environmental impact while promoting sustainable agriculture (Chawade et al., 2019; Naqvi et al., 2022).

More than 100 apple tree breeding programmes are currently underway worldwide, aiming to develop promising apple cultivars (Letschka et al., 2021). For example, the University of Minnesota, one of the most prominent and extensive apple breeding institutions in the United States, currently has 20,000 to 25,000 apple seedlings in different stages of evaluation (Clark & Bedford, 2022). The Latvian apple breeding programme involves more than 5,000 apple seedlings handled and more than 40 unique characteristics phenotyped at various stages by the Institute of Horticulture (Ikase et al., 2022).

Apple breeding is time-consuming and resource-intensive, necessitating ongoing efforts to shorten the breeding cycle and reduce resource investment in trait phenotyping. The goal is to obtain faster and more accurate data to select the most promising hybrids. Consequently, there is a growing interest in the development and implementation of high-throughput field phenotyping tools to improve the efficiency of the breeding process (Chawade et al., 2019; Huang et al., 2020).

Machine learning has advanced rapidly and is now widely used in plant genotyping and phenotyping globally. High-throughput tools enable the collection of large amounts of data on plant genotypes and phenotypes, thus optimising resource investment. Machine learning encompasses a range of computer-based modelling techniques that identify data patterns and facilitate automated decision-making. These machine-learning algorithms are sufficiently robust to process even large-scale datasets (Naqvi et al., 2022).

Advances in DNA sequencing have significantly enhanced genotyping efficiency; however, phenotyping has not progressed at the same pace. Automated phenotyping, in particular, has developed gradually over the past three decades, limiting breeders' ability to accurately assess the genetics of quantitative traits, such as crown architecture parameters. Most breeders still rely on traditional phenotyping methods, which involve visual evaluation of traits, often influenced by the breeder's personal experience. This process is labour-intensive, time-consuming, and requires considerable human resources to select the best hybrids from large populations. As a result, the adoption of high-throughput phenotyping techniques is urgently needed. These methods not only accelerate the breeding process, but also conserve resources, provide more objective results, and are applicable year-round, including during winter (Reynolds et al., 2020; Yang et al., 2020). This review article provides a comprehensive summary of research on the potential application of smart technologies in apple tree breeding, with a particular focus on apple tree

architecture parameters. This paper aims to review the latest research achievements on the current state of the art in the application of smart technologies to apple tree breeding, with an emphasis on the exploration of potential phenotyping parameters that are associated with apple tree architecture.

Materials and Methods

This study used a monographic approach to analyse the architectural traits of apple trees and their possible utility in breeding, with numerous phenotyping techniques used for precise identification. The analysis was based on scientific literature from a range of journals and monographs, drawing from studies conducted in the United States, China, the United Kingdom, Germany, France, the Netherlands, Japan, Australia, Canada, Italy, Spain, and other countries with advanced agricultural research programmes.

Results and Discussion

The architecture of the apple tree is the spatial configuration and structural desing of the components of the tree, including the trunk, branches, canopy, and root system. A comprehensive understanding of these architectural characteristics is necessary not only for effective tree management and yield forecasting but also for breeding programmes aimed at optimising the tree's morphological qualities and functional performance (Jiang et al., 2025). The evaluation of architectural traits of apple trees, such as trunk height, branch number, and branch length, is crucial in breeding programmes because these characteristics influence the structure, light capture, and overall biomass of the tree, which in turn affect its growth and fruit production (Béland & Baldocchi, 2021).

The branching topology of apple trees is a direct reflection of their gene expression and optimal adaptation to environmental factors. Consequently, a detailed and accurate characterisation of apple tree architecture facilitates a deeper understanding of how structural organisation governs functional performance and ecological adaptability (Lau et al., 2018).

Assessment technologies for tree parameters

Unmanned aerial vehicles (UAVs) equipped with cameras and sensors capture high-resolution images and 3D data, which provide detailed insights into tree architecture, height, canopy volume, and vigour (Wu et al., 2020). UAVs are particularly useful for collecting data on tree height, canopy volume, branching patterns, and fruit-bearing zones, thus improving the precision and efficiency of apple breeding programmes (Huang et al., 2020). While UAVs offer high spatial resolution and are capable of covering large areas quickly, they are limited by weather conditions and can be costly (Sangjan & Sankaran, 2021). Furthermore, the data processing involved can be time-consuming, which can pose a challenge in large-scale, real-time breeding applications (Wu et al., 2020).

LiDAR technology (light detection and ranging) is utilised to measure tree height, canopy structure, and volume by emitting laser pulses and analysing their return time (Sinha et al., 2022). This method is particularly advantageous in dense orchards where precise measurements are required, allowing for detailed 3D modelling of tree structures (Sinha et al., 2022). LiDAR is highly accurate and provides valuable data to assess tree height, canopy volume, and overall structure (Huang et al., 2020). However, it is often associated with high costs and requires advanced equipment and software for data processing (Madec et al., 2017).

Satellites are used to capture images that assess large-scale tree health, canopy size, and other architectural parameters in vast areas (Huang et al., 2020). Although they offer global coverage and continuous monitoring, the resolution of satellite imagery is lower compared to UAVs or LiDAR, which can make them less precise for individual tree analysis (Huang et al., 2020). Additionally, the temporal resolution can be limited, meaning that detailed real-time monitoring may not be achievable (Sangjan & Sankaran, 2021). Despite these limitations, satellite technology provides valuable insights for monitoring overall orchard growth trends and offers a broader view of potential changes in tree performance over time (Huang et al., 2020).

Multispectral and hyperspectral imaging capture data at multiple wavelengths to assess vigour, leaf area, tree canopy characteristics, and tree health (Tsoulias et al., 2023). Multispectral and hyperspectral imaging are powerful tools for detecting early signs of stress or disease and for evaluating the tree's overall vigour (Best et al., 2008). However, they tend to be expensive and require specialised equipment, and their data interpretation is often complex. Despite these challenges, these methods are invaluable in selecting traits such as optimal tree vigour and disease resistance in apple breeding programmes (Tsoulias et al., 2023).

Automated ground-based systems, such as autonomous vehicles and robotic platforms, are increasingly used to capture measurements such as tree height, trunk diameter, and leaf area index (Sangjan & Sankaran, 2021). These systems offer high-throughput phenotyping and are cost-effective, particularly when applied to large-scale orchards (Sangjan & Sankaran, 2021). Automated systems are less affected by weather conditions and can provide consistent, high-efficiency phenotyping (Best et al., 2008). However, their effectiveness can be limited by the complexity of the orchard terrain and plant arrangement, which may hinder their application in certain orchard environments. Despite these limitations, automated ground-based systems are valuable for evaluating traits such as tree vigour and structural attributes across many trees (Sangjan & Sankaran, 2021).

Assessment of key tree parameters and traits

Tree height is a significant selection criterion in apple breeding programmes, especially in field settings

(Moles et al., 2009), because a plant's ecological strategy is significantly affected by its height. It has a major impact on a species' ability to compete for light resources and is closely related to factors like lifespan and time to maturity. Furthermore, plant height is related to important ecosystem functions, including carbon sequestration capacity (Moles et al., 2009).

Tree height is significantly influenced by both genetic and environmental factors, such as rootstock type, growing conditions (e.g., soil fertility, water availability, temperature), and orchard management practices (Hooijdonk et al., 2011; Xu & Ediger, 2021; Jiang et al., 2025).

The height of trees can serve as an important selection criterion in breeding programmes to evaluate overall tree health (Chang et al., 2020), tree viability (Sestras R. E. & Sestras A. F., 2023), biomass (Gennaro et al., 2020) and yield (Sarron et al., 2018). Breeding programmes for modern intensive orchards aim to develop compact apple trees that reach a height of 2.5 to 3.5 metres within 3 to 4 years (Mukhanin et al., 2006; Zemisov et al., 2021).

Tree height is traditionally measured manually using a long stick or ruler from the ground to the top, which is time-consuming and error-prone, especially when analysing numerous trees (Qiu et al., 2024; Sestras R. E. & Sestras A. F., 2023; Sangjan & Sankaran, 2021). A laser rangefinder can also estimate tree height more accurately. Usually used in forestry, it also works for apple trees. This method is faster and less difficult than using a tape measure, but it needs a clear view of the tree's apex (Larjavaara & Muller-Landau, 2013). As a result, tree height is rarely monitored directly in breeding programmes, but rather as part of overall growth vigour.

Tree height, an important trait in apple breeding, can be accurately measured using high-throughput technologies such as UAVs, satellites, and LiDAR, with methods such as LiDAR-based systems showing strong correlations to manual measurements (Madec et al., 2017; Huang et al., 2020).

Tree vigour is a genetically regulated trait influenced also by environmental conditions, rootstock, scion genotype, and orchard management practices. It refers to the ability of the tree to absorb, store and use carbohydrates for growth, leading to rapid shoot development and large canopies (Rebolledo et al., 2015). Vigour is a complex characterized by shoot elongation, leaf size, tree height, and trunk diameter, and it affects the overall growth capacity of the tree, the development of the root system, and fruit production (Hooijdonk et al., 2011; Hugalde et al., 2019). High vigour is associated with fast growth and large canopies, while lower vigour may lead to more controlled growth (Rebolledo et al., 2015).

The primary objective of modern breeding is to achieve balanced and indeterminate tree vigour, preventing excessive and uncontrolled vegetative growth (Blažek & Kelinová, 2013). According to the ECPGR (Lateur et al., 2022), it can be assessed and classified into five categories: extremely weak, weak, indeterminate, vigorous, and extremely vigorous. Vigour can be evaluated within a single year by examining the height and spread of trees older than five years, with accurate comparisons requiring the use of reference cultivars planted in the same location and grafted onto the same rootstock (Lateur et al., 2022). Tree vigour can also be assessed by measuring both height and trunk diameter, with trunk diameters recorded at 20 cm above the graft union. The trunk cross-sectional area (TCSA) is then calculated to assess the tree's growth vigour (Milošević et al., 2023). Vigour can also be classified into three categories weak, medium, and strong (Sestras R. E. & Sestras A. F., 2023). Although this method is less time-consuming and requires less effort, it is less accurate. Therefore, the use of remote sensing technologies would be a more reliable approach (Best et al., 2008).

Growth vigour, a key trait in apple tree breeding, can be assessed using multispectral, hyperspectral imaging, LiDAR, and UAVs to monitor variations in tree growth, although further research is needed to optimise these technologies for large-scale breeding programmes and commercial orchards (Scalisi et al., 2021; Tsoulias et al., 2023; Jiang et al., 2025).

Canopy volume refers to the three-dimensional space occupied by the branches and leaves of an apple tree, including the entire live canopy from the base of the crown to the highest point and from the centre of the crown to the furthest tips while excluding dead branches. It is a key parameter for evaluating the growth, structure, and overall health of the tree (Usha & Singh, 2013). A larger, well-formed canopy typically reflects a healthy and vigorous tree capable of efficiently capturing energy and allocating nutrients (Wright et al., 2006).

In breeding programmes, canopy volume is an important metric used to assess tree growth and productivity, as it provides insights into how efficiently a tree captures sunlight for photosynthesis (Usha & Singh, 2013). Canopy volume can be measured manually, but accurate determination of canopy size can be challenging and labour-intensive due to complex growth patterns and irregular tree shapes. Traditionally, canopy volume is estimated by measuring a crown diameter and canopy height, assuming a simplified 3D crown shape. However, because the crown shape and branch positioning vary, calculating the precise volume can be difficult. One such method, proposed by (Wright et al., 2004), calculates the canopy volume (V) using the formula $V = (1/3)\ \pi r^2 h$, where h represents the canopy height and r is the average radius of the base, assuming that the surrounding trees are straight. These methods are commonly used to evaluate crown compactness and overall tree vigour in apple tree breeding (Dubrasich et al., 1997; Best et al., 2008; Zemisov et al., 2021).

The volume of the canopy can be accurately measured using LiDAR and UAV technologies to create 3D models although more research is needed to explore its impact on long-term fruit yield, quality, and tree longevity (Huang et al., 2020; Sinha et al., 2022; Paudel et al., 2023).

The global shape of the tree refers to the overall form or outline of the entire tree, encompassing not only the crown but also the trunk and branches. It represents the tree's growth pattern and is influenced by factors such as genetics, pruning practices, and environmental conditions (Othman et al., 2015; Zhang et al., 2016). In addition to the overall shape of the tree, branch patterns and angles are crucial structural features that affect the canopy architecture of trees (Johansen et al., 2018). A well-structured shape influences the volume, compactness, and symmetry of the tree canopy, improving light penetration and air circulation within the canopy while reducing the risk of diseases by preventing overcrowding of the branches (Zhang et al., 2016; Lordan et al., 2018; Wang et al., 2023). The vigour of a tree's growth can also influence its shape. Trees with excessive vigour may develop irregular or overly dense shapes, which can be corrected through pruning (Sestras R. E. & Sestras A. F., 2023).

The length of the internodes and the angle of the layer relative to the shoot are heritable traits closely linked to the future canopy architecture of apple seedlings. These traits can be effectively assessed in the first year of growth in apple hybrids. An obtuse angle relative to the shoot is characteristic of weeping apple trees, while short internodes are indicative of columnar forms or compact trees. By evaluating these traits, it is possible to select up to 90% of hybrids with the desired canopy architecture from hybrid families already in the first year of seedling growth (Bendokas et al., 2012).

The trunk provides support for branch growth while transporting water and nutrients absorbed by the roots, as well as organic matter made by the leaves to ensure normal growth of fruit trees (Jurjević et al., 2020). The diameter of the trunks of individual trees is an important indicator to help describe the growth status and the development trend of apple trees (Krause et al., 2019).

In breeding programmes, tree shape is a key trait to improve orchard efficiency and maximise production. By selecting parent trees with desirable shapes, such as compact, symmetrical, or pyramidal forms, breeders can develop new cultivars that are easier to manage and harvest (Zhang et al., 2016; Lordan et al., 2018). Furthermore, selecting optimal tree shapes can reduce the need for excessive pruning, contributing to more efficient orchard management (Wang et al., 2023).

The shape of the tree is a critical consideration in the development of new apple cultivars for high-density or modern orchards, where uniformity, compactness, and productivity are essential (Lordan et al., 2018). The shape of the tree before production may differ from its form at harvest time, making it difficult to accurately assess it using traditional methods. However, this variation can be more precisely evaluated using remote sensing technologies, as individually assessing each tree in breeding programmes is often difficult and time-consuming (Sestras R. E. & Sestras A. F., 2023).

The shape of the tree can be classified into two main groups: columnar, characterised by a narrow, upright form with minimal lateral branching, and ramified, which features more extensive branching and a broader, spread-out canopy. Only varieties with a ramified tree type can be more specifically classified and described based on their shape, including upright, upright to spreading, spreading, drooping, and weeping forms (UPOV, 2023). The desired tree shape in apple breeding programmes typically emphasises compact, symmetrical forms for high-density orchards to optimise space, light capture, and fruit production, while also facilitating ease of management and harvesting (Chaploutskyi et al., 2023).

Branching patterns are typically measured early in plant development, often during the first year of hybrid apple tree growth, as these early traits are indicative of the plant's future canopy architecture. By analysing branching patterns and angles, it is possible to make early selections of desirable genotypes for further breeding or more efficient orchard management. In breeding programmes, the desired branching angles for apple trees are selected based on the form of the tree, with narrow angles (closer to vertical) favoured for columnar shapes, wide angles for weeping forms, and moderate angles (typically 45°–60°) for balanced growth and optimal fruit production (Bendokas et al., 2012).

The global shape of the tree, including parameters such as crown width, perimeter and branching patterns, can be precisely measured using UAVs with deep learning algorithms and LiDAR although further research is needed to optimise algorithms and explore the relationship between tree shape and productivity (Johansen et al., 2018; Hadas et al., 2019; Wu et al., 2020; Zhang et al., 2020).

Fruit-bearing habits refer to the pattern of flower and fruit production of the tree over time. This includes the number of flowers or fruits per tree, the distribution of spurs or branches bearing fruit, the timing of fruiting (annual or biennial), and the location of fruiting (in new or older wood). The fruit-bearing habit influences the yield and quality of the fruit and is the key factor in the orchard productivity.

In fruit trees, the relationship between vegetative growth and flowering, and fruiting processes is key to achieving regular fruit production. For apple trees, this relationship is also determined by the specific variety and how fruits are positioned on long shoots, either in lateral or terminal locations, known as the fruiting type (Lauri et al., 1997). Fruit tree cultivars are typically categorised as 'annually bearing' or 'biennially bearing' (Evans, 2017).

Flowering is mainly influenced by physiological factors, especially carbohydrates and hormones. The quality of flower buds depends on their position; terminal buds in fruiting branches are larger and of higher quality due to better nutrient supply and more developed vascular tissues. In contrast, flower buds at the ends of long vegetative growths tend to be of lower quality (Obrucheva, 2014).

The primary objective of breeding programmes is to develop apple varieties that exhibit consistent and reliable bearing, ensuring fruit production every season (Laurens et al., 2000). This includes optimising fruit bearing on spurs to maximise fruit production per unit of tree size, while also focussing on cultivars with predictable and high yields, and minimising excessive vegetative growth that could negatively impact fruit production (Sedov, 2014).

Fruit-bearing habits can be evaluated in a single year, ideally on trees that have not been excessively pruned Béland be classified into five types: columnar branches produce fruit only on spurs with few branches. Type I features short, long-lived spurs with a fruit zone close to the trunk and sparse, upright branching. Type II also bears fruit on spurs, but the fruit zone moves slightly outward and the tree spreads with age due to more frequent branching. Type III branches fruit in both spurs and 1 to 3-year-old shoots, spreading outward with frequent branching. Type IV branches primarily fruit at the ends of 1-year-old shoots, with a drooping tendency and fruit mostly at the extremities (Watkins & Smith, 1982; Lateur et al., 2022).

Fruit-bearing habits can be analysed and optimised using high-throughput technologies such as UAVs equipped with multispectral sensors, RGB cameras, and LiDAR to model tree structures, assess canopy density, and identify fruiting zones, improve orchard management (Straub et al., 2022; Mao et al., 2024).

Conclusions

1. Canopy volume, tree shape, and fruit-bearing habits are key traits in apple tree breeding programmes, directly influencing productivity, fruit quality, and orchard management efficiency.
2. Early identification of heritable traits related to branching patterns and canopy structure allows for faster and more accurate selection of desirable hybrids in apple tree breeding programmes.
3. The integration of advanced technologies such as LiDAR, UAVs, and multispectral imaging significantly enhances the precision of phenotyping, improving the accuracy and efficiency of breeding programmes.
4. Automated phenotyping systems and remote sensing technologies streamline the breeding process by reducing manual labour and providing high-resolution real-time data on tree architecture.
5. While high-throughput phenotyping has advanced, challenges such as cost, data complexity, and standardisation remain. More research is needed to enhance these technologies for better breeding applications.

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HOW AGRICULTURAL CROP CLASSES RELATE TO SOIL TAXONOMIC DIVERSITY: AN EXAMPLE OF TWO CONTRASTING LANDSCAPES IN LATVIA

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Abstract
The spatial composition of different soil types has traditionally been evaluated through soil mapping and broad-scale regional assessments of soil properties. However, mathematical quantification of soil taxonomic diversity in agricultural landscapes with varying management intensities remains largely unexplored. To address this gap, we applied Shannon Diversity Index at landscape level and potential pedodiversity index (PD_H) at a 30 × 30 m cell resolution in two distinct agricultural landscapes in Latvia – Taurene and Platone municipalities – characterized by different soil formation conditions, topography, heterogeneity of soil cover, land-use structure and farming practices. Soil mapping data based on the World Reference Base for Soil Resources (WRB) system was used. Soil taxonomic diversity at the municipality level was assessed using a single Shannon Diversity Index for each area, calculated separately for first-level reference soil groups without qualifiers and second-level classification with qualifiers. Cropping classes were determined using dominant crop types over a 9-year period (2015–2023) and grouping crop types into classes. At the broad soil classification level, the upland landscape of Taurene showed higher soil taxonomic diversity than Platone, aligning with its more complex soil formation factors and processes. However, at a more detailed classification level, Platone exhibited slightly higher diversity, contradicting established theoretical expectations for such landscapes. Study results of both agricultural landscapes show that the highest soil taxonomic diversity values were observed in areas of temporary grasslands sown in arable land.
Keywords: taxonomy, pedodiversity, Shannon index, land use, moving window.

Introduction

In Europe, soils are subjected to various threats, including water and wind erosion, the reduction of organic matter in both mineral and organic soils, as well as soil compaction (Stolte et al., 2016). Within the framework of the European Union Soil Strategy for 2030, the importance of soil research is emphasized not only as a means to improve soil conditions but also to mitigate the climate impact of soil management practices (Panagos et al., 2022). Rasmussen (2022) identifies the study of soil spatial distribution, its properties, and the processes occurring within it as one of the key priorities in contemporary soil science research.

There are numerous studies worldwide on the patterns of soil spatial distribution (McBratney, 1998), highlighting the significance of various environmental factors in shaping soil processes, morphology, and properties. Furthermore, soil processes and their interactions under different environmental conditions vary considerably, contributing to the diversity of soils (Targulian & Krasilnikov, 2007).

Measuring soil diversity (*syn*. pedodiversity) is inherently complex and lacks a universal approach (Usher, 1983). As a result, multiple research methodologies and classification systems have been developed. Ibáñez et al. (1995) proposed a framework based on the prevailing biological diversity classification, categorizing soil diversity into four hierarchical levels depending on the spatial scale of analysis: micro-scale diversity at the polypedon level, α-scale diversity representing soil associations at a medium scale, γ-scale diversity at the landscape or watershed level, and ϵ-scale diversity referring to soil diversity at a geographical regional level. In contrast, Mikhailova et al. (2021) provided an example of dividing soil diversity into four distinct types: taxonomic diversity, which encompasses variation in soil groups, types, and subtypes; genetic diversity, referring to the diversity of soil genetic horizons; parametric diversity, which accounts for differences in soil physical and chemical properties; and functional diversity, which describes variability in soil characteristics under different land use conditions. This soil diversity classification aligns more closely with contemporary trends in soil research.

Significant uncertainties persist regarding the application of specific soil classification systems in determining spatial distribution patterns. As a result, soil scientists often disagree on the extent to which environmental factors influence soil distribution at regional and local scales (Gray et al., 2009). Incomplete knowledge of environmental conditions can sometimes lead to an overestimation or underestimation of soil formation processes, complicating the use and comparison of different classification systems (Reintam, 2002; McBratney et al., 2003).

Previous research has made significant contributions to the statistical assessment of STD, particularly in forest ecosystems. For example, Samec et al. (2018) study conducted in the Czech Republic has provided valuable insights into the diversity of forest soils, offering a methodological framework for similar investigations. An innovative methodology for evaluating STD was introduced in the studies by Vacek et al. (2020) and Vašát et al. (2023). These works propose a new method of analysis – the potential pedodiversity index (PD_H). This approach is based on the widely used Shannon diversity (entropy) index (Shannon, 1948), which is extensively applied in

ecology and landscape research. The index is calculated within raster cells using the moving window method, which uses a fixed geometric shape to repeatedly scan the area, calculating local values within each window as it moves across the territory, allowing for a spatially explicit assessment of STD. PDH is defined as a pressure of the surroundings on the soil unit change at a particular soil point location (Vacek et al., 2020).

Based on these foundations, our study aims to further explore STD the context of agricultural land use in Latvia. Agricultural practices influence soil properties, biodiversity, and ecosystem functions, thereby shaping soil diversity at both local and regional scales (Trivedi et al., 2016, Briones & Schmidt, 2017). Intensive land use can lead to soil homogenization, loss of taxonomic diversity, and degradation of soil functions, whereas low-intensity or diversified land use may enhance soil heterogeneity and resilience (Burton et al., 2023). Studies on soil diversity in relation to agricultural intensity help to assess the impact of land management practices on soil sustainability, inform precision agriculture strategies, and support policy-making for sustainable land use planning. Therefore, our aim was to assess the soil taxonomic diversity and its possible relationship with different agricultural crop classes in two contrasting landscapes in Latvia.

Materials and Methods

For the geospatial analysis of STD, publicly available soil mapping data from the 'E2SOILAGRI' project were used, based on the WRB system (IUSS Working Group WRB, 2022). The data cover the Taurene and Platone municipalities (Figure 1) at a 1:10,000 scale. Data are available on the national geospatial information portal (www.geolatvija.lv) under a CC 4.0 license and on the Latvian open data portal (www.data.gov.lv) under a CC 1.0 license State Plant Protection Service, 2024 (Valsts augu aizsardzības dienests, 2024). Soil mapping was conducted by the University of Latvia, Faculty of Geography and Earth Sciences, during 2021–2023 (Nikodemus et al., 2023). Platone and Taurene represent contrasting pedological environments. Platone is located in Zemgale lowland plain into transition zone between the Baltic Ice lake sands (in northern part) and clay sediments of the meltwater basins in glacial lowland (in southern part); furthermore, alluvial sandy sediments are distributed in certain areas (Geological map of Latvia, 1981; Zelčs & Markots, 2004; Zelčs et al., 2011) and represent low topographic variation, ranging in elevation from just 0.7 to 24 meters above sea level. This flat terrain fosters relatively homogeneous soil formation processes.

In contrast, Taurene features a glacigenic deposits and undulated topography (Geological map of Latvia, 1981; Zelčs & Markots, 2004; Zelčs et al., 2011), with elevations between 175 and 256 meters above sea level. Its pronounced relative elevation changes, combined with diverse microclimatic and geological conditions, drive spatially heterogeneous pedogenesis, resulting in more complex soil properties and distributions.

STD at municipality level was analysed by calculating a single Shannon's diversity index for each study area for the first level classification for unique reference soil groups without qualifiers and separately for the second level classification with qualifiers. The soil mapping process did not encompass all potential qualifiers for the relevant soil groups (Nikodemus et al., 2023), which may lead to a simplified representation of actual STD. For spatial data visualization, ArcGIS desktop software was used (ESRI, 2020).

To examine the relationship between STD and agricultural land-use, the Potential Pedodiversity Index (PD_H) was calculated at a fine-scale 30 × 30 m cell resolution, but only using the first-level classification (Reference Soil Groups without qualifiers). PD_H was the main method of assessing STD in this article. Since municipality-level soil mapping was conducted at a 1:10,000 scale, with a minimum elementary soil contour size of 0.3 ha the initial vector data were rasterized at a 30-meter resolution. A 300-meter radius was selected for the moving window analysis. The analysis was conducted using R programming language in R Studio version 4.4.2. Following packages were used: 'sf' for spatial data operations (Pebesma, 2018; Pebesma & Bivand, 2023), 'dplyr' for data manipulation, 'terra' (Hijmans, 2024a) and 'raster' (Hijmans, 2024b) for raster file management, 'ggplot2' for visualization (Wickham, 2016), 'doParallel' for multi-core processing (R Core Team, 2024), 'FSA' for post-hoc testing (Ogle et al., 2025), 'agricolae' for reference diversity index calculations (De Mendiburu, 2021), and 'nortest' for performing normality tests on large datasets (Gross & Ligges, 2015).

The mathematical foundation of the PD_H index is based on the Shannon diversity index (Shannon, 1948), adapted for soil data (Vacek et al., 2020). The PD_H index was calculated initially by determining the proportion (Pa) of cells occupied by each soil type relative to the total number of soil cells (Pat) within the defined search window. Results were then log-transformed, and the product of Pa and Pat was multiplied by this transformed value. Finally, these individual contributions were summed and multiplied by -1 to yield the PD_H index (Equation 1). PD_H calculation codelines can be found in associated master's thesis annex section (Župerka, 2025).

$$PD_H = -\sum_{i=1}^{S} \frac{Pa}{Pat} ln \frac{Pa}{Pat} \quad (1)$$

where:

PD_H – potential pedodiversity index,

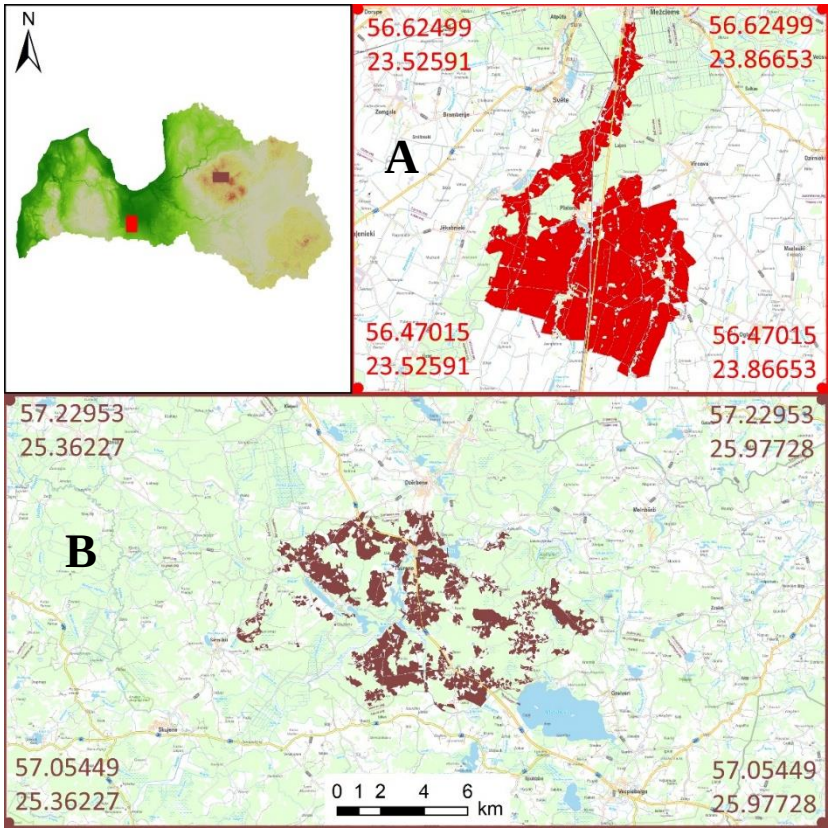
Pa_i – number of cells occupied by a given soil type within the search window;

Pat_i – total number of cells occupied by all soil types within the search window.

The classification of cropping classes was based on dominant crop types observed over a 9-year period (2015–2023), which we use as a proxy for recent land-use practices. Spatial data were sourced from the Field Register of the Rural Support Service (RSS, Lauku atbalsta dienests, 2025), comprising land parcels and their associated crop types from 2015 to 2023. Crop types are encoded using a standardized three-digit, three-level hierarchical classification based on crop characteristics and usage (LR Ministru Kabinets, 2023). For analysis, second-level groups were used for grasslands and first-level groups for other crops. Crop types were then grouped into classes and used in further analysis (Table 1).

Figure 1

Study areas and reference bounding box coordinates (decimal degrees): A – Platone Municipality, B – Taurene Municipality



The Anderson-Darling normality test confirmed that the distribution of PD_H values in both territories deviated significantly from normality. Consequently, the non-parametric Wilcoxon rank-sum test was employed to assess whether the median PD_H values differed significantly between the two territories. The Kruskal-Wallis rank-sum test was used to evaluate differences across all crop groups. To further investigate specific pairwise differences between groups, a post-hoc Dunn's test with Bonferroni correction for multiple comparisons was conducted. Welch's ANOVA was used to assess differences between diversity values variances of two territories.

Table 1

Classification of agricultural land into agricultural crop classes

CC*	***Crop type***	***Crop names and codes after Cabinet of Ministers of the Republic of Latvia (Latvijas Republikas Ministru Kabinets, 2023)***
1	Fallow	Green manure fallow (612)
2	Vegetables	Starch potatoes (825), Potatoes not elsewhere specified (820), Other unspecified cabbages (870), Table beets, chard / leaf beets (844), Onions, shallots, chives, Welsh onions and Japanese bunching onions (846), Garlic (847)
3	Fabaceae fields Legumes	Red clover (723), White clover (724), Alfalfa (726), Field beans (410), Peas (420), Soybean (443)
4	Permanent grasslands**	Permanent grasslands (710)

*CC**	*Crop type*	*Crop names and codes after Cabinet of Ministers of the Republic of Latvia (Latvijas Republikas Ministru Kabinets, 2023)*
5	Permanent crops (orchards, short-rotation coppice, energy crops)	Apple trees (911), Pear trees (912), Sweet and sour cherries (932), Plum trees (914), Aronia (918), Sea buckthorn (919), Blackcurrants (922), Quince bushes (928), Fruit trees and berry bushes (except strawberries), each occupying less than 0.1 ha in a continuous area (950), Woody plant nurseries on agricultural land (640)
6	Others (not specifically classified)	Other crops sown pure in arable land (872), Mustard, including white mustard (215), Various crops in small arable areas or multiple crops grown in a continuous field, each occupying less than 0.1 ha, or areas used for flower cultivation (811)
7	Temporary grasslands sown in arable land***	Mixture of grasses or forage herbs (including protein crops) sown in arable land (720), Mixture of grasses and legumes sown in arable land, with legumes >50% (760)
8	Grain crops	Oats (140), Oats with grass or legume undersowing (141), Spring wheat (111), Winter wheat (112), Spring barley (131), Spring barley with grass or legume undersowing (133), Winter barley (132), Rye (121), Cereal and pea mixture with peas >50% (445), Other unspecified maize (741)
9	Oil and fibre crops	Winter rapeseed (212)
10	Single-species grass swards	Red oat grass for seed production (735)

*CC – agricultural land crop class; ** - Permanent grasslands are grassland areas that until 2014 were declared as permanent meadows and pastures. Areas declared as permanent grasslands include those that for five consecutive years have been declared as arable land sown with mixtures of grasses and/or fodder herbs (such as timothy, alfalfa, vetch, sainfoin, eastern galega, rough hawkbit) or as pure grass sown fields, or as pure fodder herb fields. In addition to permanent grasslands, areas recognized as biologically valuable grasslands or grasslands important for biodiversity — such as protected grassland habitats or bird habitats resulting from the cessation of agricultural activities — are also declared as permanent grasslands (Latvijas Republikas Ministru Kabinets, 2023). ***Temporary grasslands sown in arable land are grassland areas that have been declared for less than five consecutive years as mixtures of grasses or forage herbs (including protein crops) sown in arable land (code 720), or as mixtures of grasses and legumes sown in arable land with legumes comprising more than 50% (code 760).

Results and Discussion

Shannon's diversity index at municipality level

The number of unique Reference Soil Groups (RSG) was consistent across both territories, with 12 groups present in each. Similarly, the number of unique soil and principal qualifier combinations showed only a slight difference between the two territories: Platone had 223 unique combinations, while Taurene had 208. The Shannon's Diversity Index for broad RSGs without qualifiers was 1.90 for Taurene and 1.35 for Platone. Thus, at broad soil classification level Taurene area was assessed as more diverse than Platone area. This is in line with previous studies showing much higher diversity of soil formation processes and their driving factors in heterogeneous upland areas (Kasparinskis & Nikodemus, 2012; Nikodemus et al., 2024) where small-scale topographic variability can significantly influence soil formation and heterogeneity (Groß et al., 2023). In Platone, the largest soil areas were dominated by Luvisols and Planosols, which covered 62% and 12% of the total mapped area, respectively, while other RSGs each constituted less than 10%. In contrast, dominant RSGs distribution in Taurene exhibited greater diversity, with the three most prevalent RSGs being Luvisols (33%), Retisols (19%), and Phaeozems (14%).

The Shannon's Diversity Index for RSGs with qualifiers was 3.72 for Taurene and 3.92 for Platone. These results contrast with our results based on RSGs without qualifiers.

These findings are in line with recent literature on local scale, e.g. Nikodemus et al. (2024), which underscores the challenges of mapping regions with complex topography, e.g. Taurene, where high STD complicates spatial capture. At broader mapping scales, small-scale soil variations – and consequently specific qualifiers – may not be adequately captured, potentially contributing to the lack of distinct patterns observed at the municipal level. The higher overall STD recorded in Taurene without considering qualifiers, contrasted with greater soil group diversity observed in Platone when qualifiers are included, suggests a need for more detailed soil mapping. This would ensure that ecologically relevant soil variations, particularly in geomorphologically complex and heterogeneous areas such as Taurene, are accurately represented. Previous research has demonstrated that small-scale topographic variability can significantly influence soil formation and heterogeneity (Groß et al., 2023).

However, studies on STD in our region remain scarce, and no well-established reference values exist for agricultural lands. For the Boreal biogeographical region, the reported Shannon index is 3.27 for the second-level WRB groups and 2.49 for the first-level WRB groups (Ibáñez et al., 2013). However, this coarse-scale values cannot be compared to landscape-level results. Thus, we could not compare our results to draw more detailed conclusions.

Potential pedodiversity index at cell level

The absolute differences between PD_H in the two territories were minimal as well, with Taurene showing a slightly higher overall index values compared to Platone. Statistically significant differences between the medians of the two territories ($W > 8 \cdot 10^8$, $p < 0.001$) were observed. The median

PD_H value for Taurene was 0.93, while for Platone, it was 0.86. Welch's ANOVA also indicated significant differences in group variances ($F_{(84,889)} = 328.1$, $p < 0.001$), a finding supported by the histograms. The spatial distribution of the index displayed a more distinct pattern in Platone, with the highest PD_H values located in the northern part of the municipality. In contrast, Taurene exhibited no clear spatial patterns (Figure 2). Higher STD in northern part of Platone area could be explained by soil genesis and geological formation of area, e.g. varying soil texture of the soil parent material (Kasparinskis & Nikodemus, 2012). According to geological map of Latvia (1981) – area of Platone municipality is located in Zemgale lowland into transition zone between the Baltic Ice lake sands (in northern part) and clay sediments of the meltwater basins in glacial lowland (in southern part); furthermore, alluvial sandy sediments are distributed in certain areas (Zelčs & Markots, 2004). The contact zone of diverse or double-sided soil parent material (clay in subsoil and sand in topsoil) is characterized by heterogeneity conditions, e.g. higher variety of soil formation processes (e.g., accumulation of organic matter, podzolization, increase of soil moisture conditions, gleying, etc.) instead of homogeneous clay sediments (in southern part of Platone municipality area).

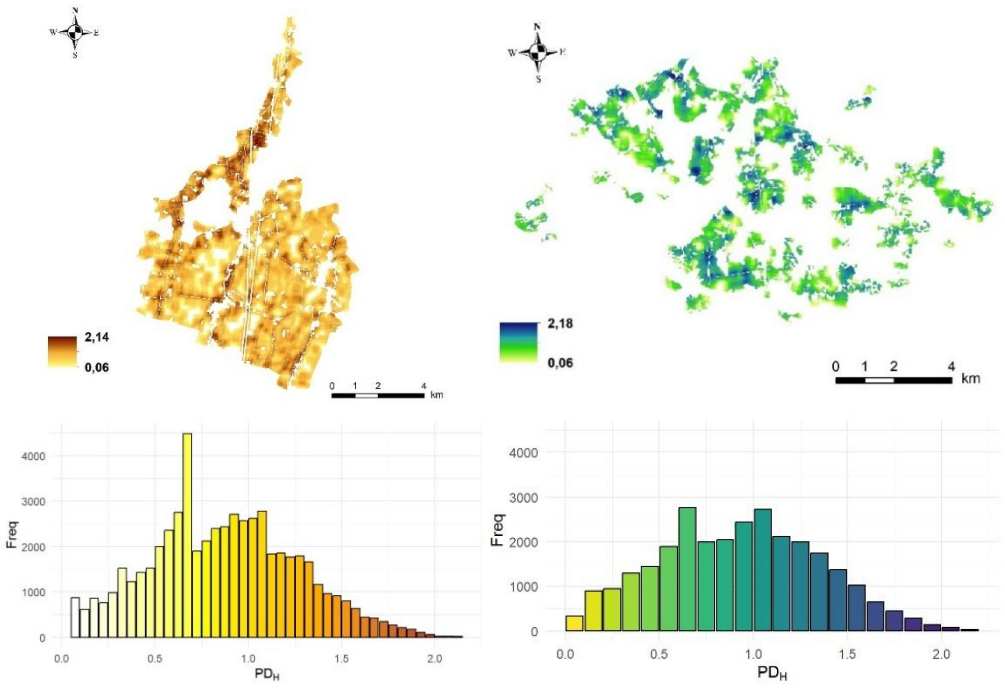
In Taurene area such relationships are not visible. However, soil diversity is being provided mainly by undulated topography and glacigenic deposits (Geological map of Latvia, 1981; Zelčs & Markots, 2004; Zelčs et al., 2011).

Relationship between soil taxonomic diversity and agricultural crop classes

It is well established that the local soil biodiversity decreases with increasing agricultural land use intensity (Tsiafouli et al., 2015). In addition, intensive agriculture drives profound changes in soil properties to the degree that the soil can no longer be considered representative of its undisturbed counterpart (Amundson et al., 2003).

Figure 2

Potential soil diversity index in Platone (left) and Taurene (right) and value distribution histograms (Freq on y axis indicates number of 30x30m cells)



Our two study regions differed considerably in agricultural crop class composition (Figure 3). Only 28% of the Taurene Municipality area was used for agriculture, and almost 82% of this area corresponded to the 4th class – permanent grasslands. On the contrary, 45% of the Platone Municipality was covered by agricultural lands, and 86% of them were intensively used and corresponded to the 8th class – grain crops.

Statistical tests confirmed significant differences between group medians ($\chi_{(9)} = 3{,}118.9$, $p < 0.001$). Post-hoc testing revealed several significant differences between the cropping groups, with group 10 (single-species grass swards) exhibiting the lowest PD_H values compared to the others, while group 7 (temporary grasslands sown in arable land) showed the highest values in the range (Figure 4). Furthermore, no significant differences in soil groups were found across cropping classes. Permanent grasslands in Taurene had much higher PD_H values than those in Platone, even though they belong to the same land-use class. This unexpected difference suggests that STD hardly explains land use patterns. Therefore, other

factors related to land use – such as historical land management, crop rotation, fertilization, or farmer decisions - should be considered in future analyses to gain a deeper understanding of the relationship between STD and crop choices.

Current research trends show that major land use intensity studies have not even listed STD as a factor (Marcos-Martinez et al., 2017; Van Vliet et al., 2015), yet the assessment and conservation of soil diversity as an important part of the European natural heritage is gaining increasing recognition (Ibáñez et al., 2013). Thus, we call for greater integration of different aspects of soil diversity including STD into land use research, policy frameworks, and sustainable agricultural practices to ensure its protection and long-term ecological resilience.

Figure 3
Agricultural crop classes in Platone (left) and Taurene (right)

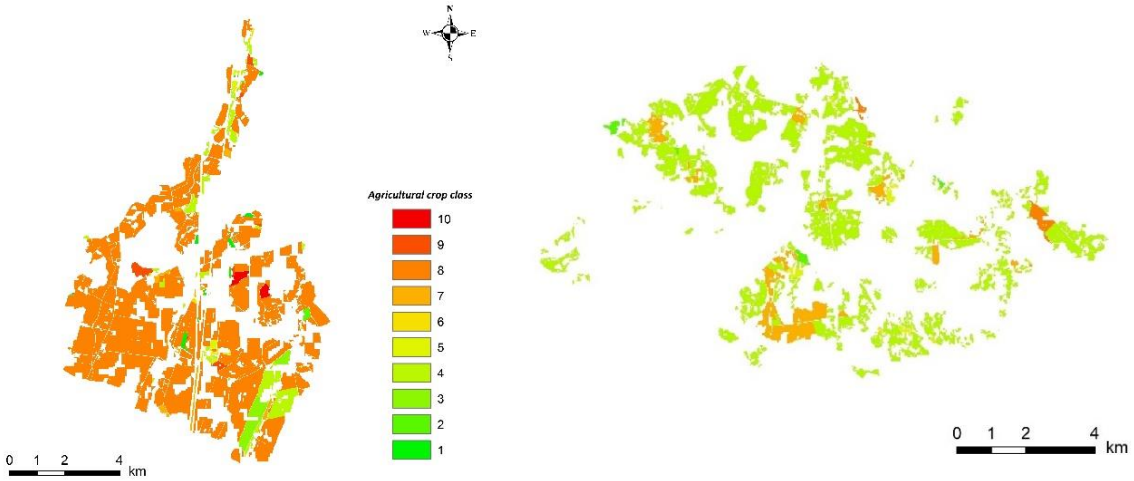
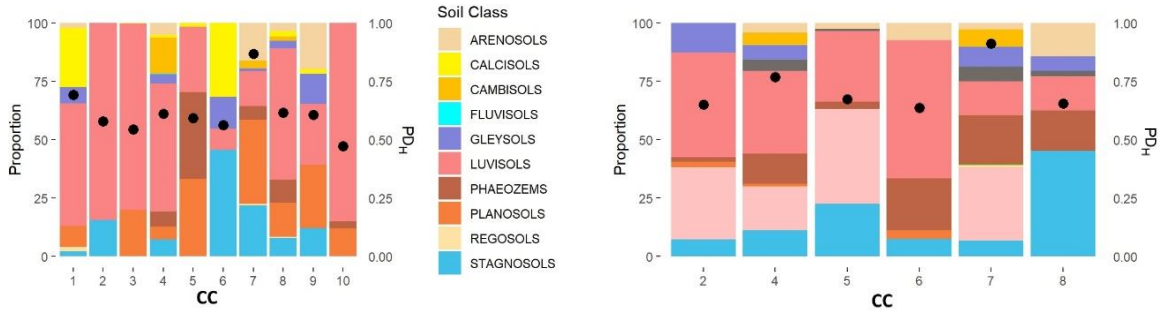


Figure 4
Soil taxonomic composition and median PD_H index (black points) in different cropping classes in Platone (left) and Taurene (right). The codes for cropping classes are the same as in Table 1



It is important to note that PD_H index cannot be used in the same way as Shannon Diversity, because it does not directly measure diversity in a given area but rather shows a tendency for diversity to change in relation to nearby areas (Vacek et al., 2020). Therefore, high PD_H values should not be interpreted in the same manner as a regular diversity index, as demonstrated in our study through a comparison of the absolute index calculated at the municipality scale versus the PD_H calculated at each raster cell, which yielded substantially different results between the two territories. PD_H allows for high-resolution mapping of soil taxonomic diversity by assigning a diversity index value to individual map units, potentially making it useful for inclusion in detailed spatial models.

Conclusions

1. Minor absolute differences were observed in STD between the two municipalities, with PD_H values generally being slightly higher in Taurene, a less intensively managed area, compared to Platone, which has relatively higher cropping intensity.
2. To enhance the accuracy of STD assessment in topographically complex terrains, higher-resolution soil mapping should be conducted to improve the representation of small-scale soil formations that are not detectable at larger mapping scales.
3. Temporary grasslands sown in arable land were related to high soil diversity areas while single-species grass swards fields were confined to areas with low soil diversity.

4. In both agricultural landscapes, the highest STD values were observed in areas of temporary grasslands sown in arable land. Other factors related to land use should be considered in future analyses to gain a deeper understanding of relationship between STD and cropping classes.
5. At municipal level, Taurene exhibited higher soil taxonomic diversity than Platone, consistent with its more heterogeneous upland landscape and previously documented complexity of soil formation processes. Platone showed a slightly higher Shannon Diversity Index values per cell than Taurene, which contradicts theoretical assumptions about soil taxonomic diversity in such landscapes.
6. Further research should focus on high-resolution modelling of the PD_H index, incorporating other environmental factors available at a detailed scale, such as topographic indicators or soil parent material. Additionally, other diversity metrics, such as Simpson's Diversity Index or Patch Richness and Evenness, should be calculated using a similar approach to determine whether other indexes could reveal relationship between STD and cropping classes better.

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EVALUATION OF BIOMASS PRODUCTION IN DIFFERENT POTATO GENOTYPES UNDER VARIOUS NITROGEN LEVELS IN VITRO

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Abstract
Different potato genotypes vary in nitrogen uptake and biomass production at different available nitrogen levels. In vitro experiments offer a controlled environment to further explore these variations. The study aimed to evaluate the morphological traits of various potato genotypes in a two-factorial experiment, analysing microplant responses depending on nitrogen availability in the growth medium in vitro. The study, conducted in 2022 in Priekuli, Latvia, tested 19 potato genotypes under varying nitrogen levels in an in vitro medium. The experiment was carried out in three time-shifted series each with four replications. The Murashige and Skoog basal medium used for the experiments included N concentrations of 60 mmol L^{-1} (N60), 20 mmol L^{-1} (N20), and 7.5 mmol L^{-1} (N7.5). The morphological traits analyzed in the potato microplants included plant height, fresh weight (FW) and dry weight (DW) of the total plant, as well as FW and DW of the shoots and roots. Additionally, calculated traits included the root % share, root-to-shoot ratio and the nitrogen stress tolerance coefficient (NstC) of the genotypes. Results showed significant differences in biomass production between different N levels ($p<0.05$) as well as significant differences between genotypes grown under the same N level were identified. NstC differed between genotypes.
Keywords: potato microplants, nitrogen stress tolerance, nitrogen availability.

Introduction

Potato (*Solanum tuberosum* L.) is an important crop for global food and nutritional security. As a crop it requires a large amount of nitrogen (N) (Haverkort et al., 2003; Vos, 2009; Hirel et al., 2007; Lammerts van Bueren et al., 2014; Tiwari et al., 2018). To comply with environmentally friendly and sustainable agricultural practices, the fundamental goal of crop production is to optimise high nutrient efficiency in crops, thereby ensuring that economic benefits increase and environmental pollution due to nitrate loss is reduced (Getahun et al., 2020; Stefaniak et al., 2021). One approach is the development of enhanced-efficiency fertilizer and optimised nutrient management (Hopkins et al., 2008), but the second approach is the breeding of cultivars with improved nitrogen use efficiency (NUE) (Schum & Jansen, 2014).

Although field trials are crucial, pre-screening of genotypes under controlled environmental conditions can be helpful in the breeding and selection process (Schum & Jansen, 2014). *In vitro* trials for NUE evaluation are rare, only a few of them are described by Hajari et al. (2014, 2015), Shum & Jansen (2014) and Schum et al. (2017). *In vitro* trials allow us to investigate many plants under controlled conditions in a short period; nevertheless, this also allows us to observe root development, which is usually impossible in field trials (Rabante-Hane et al., 2022).

Knowledge about the key traits affecting NUE is essential to investigate plant growth. NUE is connected with N metabolism in potato plants, affecting N uptake, assimilation, utilization and remobilization in different parts of the plant (roots, stems, leaves, stolons/tubers) (Foulkes et al., 2009). High N supply can ensure more shoot growth, resulting in higher plant (Tiwari et al., 2018).

Roots are an important part of plants and provide uptake of water and nutrients (White et al., 2013). Potato has a relatively shallow root system, which results in a deficient acquisition of nutrients (Wishart et al., 2013). According to Ospina et al. (2014) physiological and molecular mechanisms are involved in N uptake, transport, assimilation, and utilization in potato plants. Various genotypes have different responses to nitrogen levels (Dimante et al., 2024). Many physiological and molecular mechanisms among different potato cultivars influence N uptake, transport, assimilation and utilization (Zebarth et al., 2004; Ospina et al., 2014). Potato genotypes may perform better under reduced N availability and different meteorological conditions (Skrabule et al., 2023).

The objective of this study was to assess the biomass production, root-to-shoot ratio, and nitrogen stress tolerance in 19 potato genotypes grown *in vitro* under three nitrogen levels.

Materials and Methods

Plant material

A set of 19 potato (*Solanum tuberosum* L.) genotypes was used for *in vitro* trials, including ten Latvian cultivars from various maturity groups: 'Agrie Dzeltenie', 'Madara', 'Monta', 'Rigonda' (early) 'Prelma' and 'Lenora' (medium early), 'Magdalena', 'Brasla', 'Imanta', 'Jogla' (medium late), as well as, five breeding clones with high potential from AREI: S 03067-33 and S 01085-21, S 11161-85, S 11152-7. Additionally, four popular cultivars from external breeding companies were included: German varieties 'Vineta', 'Jelly', 'Verdi' and 'Kuras'; the latter is widely known in starch production and was bred in the Netherlands.

Stock cultures of virus-tested *in vitro* microplants were kept in glass test tubes on agar-solidified Murashige & Skoog basal medium (MS medium) (Murashige & Skoog, 1962) supplemented with 30 g L^{-1} sucrose and no growing regulators. Cultures were incubated at 22±1 °C, photoperiod 16/8 h; light intensity 15.5±2.5 W m^{-2} and subcultured every four to six weeks until the necessary number of microplants was obtained.

Shoot tips of approximately 1.5 – 2.0 cm in length were excised from newly developed microplants and used for *in vitro* trials in different nitrogen levels.

In vitro testing

For *in vitro* testing, ten shoot tips were placed in perforated polypropylene plates within Magenta™ vessels (575 mL), each containing 50 mL of liquid MS medium supplemented with 30 g L^{-1} sucrose and 1.5 mL L^{-1} PPM™. The pH (measured in KCl) of the medium was adjusted to 5.7 ± 0.1. The experiments included a standard N level of 60 mmol L^{-1} (N60) and two reduced N levels of 20 mmol L^{-1} (N20), and 7.5 mmol L^{-1} (N7.5). Media was adjusted with respective concentrations of NH_4NO_3, KNO_3 and KCl. Cultures were incubated for 24 days according to the environmental conditions of the stock culture.

The *in vitro* trial was repeated in three independent time-shifted trials, each series comprised four replications per N level. Overall, the experiment included two factors: genotype and nitrogen concentration in the MS medium. A total of 19 genotypes and 3 nitrogen levels were tested, resulting in 57 treatment combinations. Each replicate included 10 plants, which meant 40 plants per treatment per series. With 3 series, that totals 120 plants for each treatment, according to genotype and nitrogen level. In total, 360 microplants per genotype were used in the study.

Morphological traits and measurements

Morphological traits of microplants were measured for each unit of 10 plantlets, and data were averaged across replications and experimental series. To compare and analyse differences between the N levels, the morphological traits assessed in the potato microplants were plant fresh weight (FW) and dry weight (DW), and FW and DW of the shoots and roots. To compare the differences between the root and shoot systems development, the root percentage share of total FW was determined as well as the root-to-shoot ratio (R:S ratio) was calculated using the formula developed by Wilson (1988), Equation (1):

$$R{:}S\ ratio = \frac{DWroots}{DWshoots} \quad (1)$$

DW roots – the dry weight of roots;
DW shoots – the dry weight of shoots.

Nitrogen stress tolerance coefficient (NstC) of the genotypes

$$NstC = \frac{(1 - Ps \div Pc)}{(1 - meanPs \div meanPc)} \quad (2)$$

Ps – Total DW under stress conditions (N7.5);
Pc – Total DW under control conditions (N60);
meanPs – mean of all genotypes under N7.5;
meanPc – mean of all genotypes under N60.

Potato genotypes were evaluated based on their stress susceptibility index (NstC) (2), calculated using total plant dry weight according with the formula established by Fisher and Maurer (1978), Equation (2).

Statistical analysis

To analyse the impact of factors, a factor analysis of variance (ANOVA) was conducted. Tukey's post hoc test, with a significance level set at $\alpha = 0.05$, was used to identify groups with significant differences. The statistical analysis was carried out using Jamovi software (version 2.6.23) (Jamovi The Jamovi), which operates in conjunction with R version 4.4.

Results and Discussion

Biomass production

Nitrogen reduction in medium affected morphological traits of potato genotypes. The two-factor analysis showed that there was significant effect of Genotype and N level on dependent variables such as total FW, FW of shoots and roots, shoot length and total DW ($p<0.005$), and that there was an interaction between genotype and N level concerning the dependent variables, ($p<0.005$) (Table 1).

The total FW per replication (10 microplants) was determined for each treatment, and average values across four replications are presented. These ranged from 2.21 g to 19.01 g at N60, 3.55 g to 14.09 g at N20, and 2.05 g to 8.04 g at N7.5 (Table 1). Cultivars 'Rigonda', 'Monta', 'Agrie Dzeltenie', and breeding line S 01085-21 showed the highest total FW under N60 (Figure 1). Additionally, these genotypes demonstrated a significant reduction in biomass as nitrogen availability decreased in the media. However, genotypes such as S 03067-33, S04065-2, S 11161-85, 'Jogla', and 'Kuras' did not show significant differences between the N60 and N20 treatments. The 'Madara' cultivar showed higher total FW with N20 compared to N60. The difference between N20 and N7.5 resulted in a total FW of 2.89 g.

The average shoot FW per 10 microplants ranged from 2.11 g to 11.99 g at N60, 0.7 g to 12.05 gat N20, and 1.36 g to 7.39 g at N7.5 (Table 1). The shoot FW of most genotypes decreased with reduced nitrogen supply (Figure 2). However, in three genotypes (S 03067-33, 'Magdalena', 'Madara'), we observed that shoot FW was higher at N20 compared to N60, but only for 'Madara' difference between N20 and N60 was significantly higher. These tendencies were not sustained at N7.5.

The average root FW per 10 microplants ranged from 0 g to 8.91 g in N60, 0.27 g to 5.07 g at N20, and 0 g to 1.62 g at N7.5 (Table 1). Root FW decreased under lower nitrogen supply in all genotypes except 'Prelma', which showed higher root FW at N20 compared to N60.

Root percentages of the total plant fresh mass

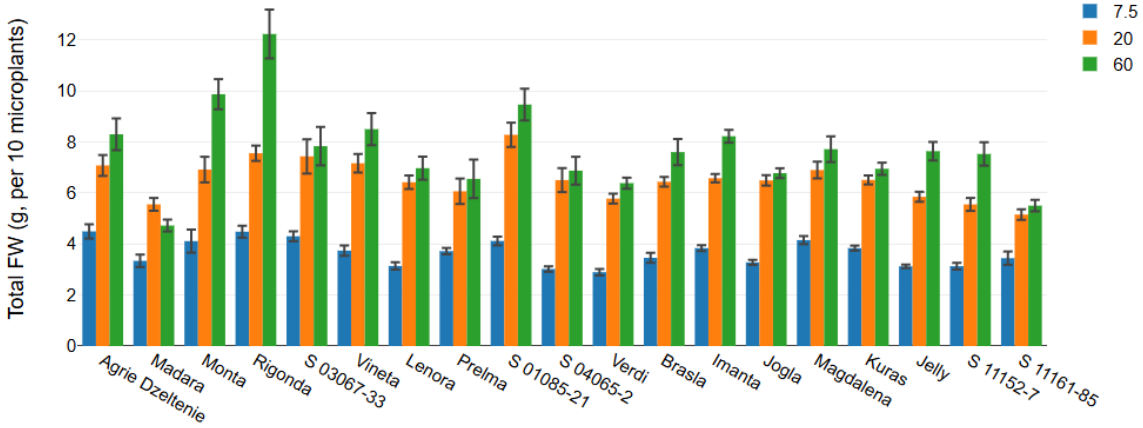
The root percentage share of total FW ranged from 0.00% (S 11152-7) to 46.87% ('Rigonda') at N60 (Table 1). In the reduction of available nitrogen, two different responses were observed among genotypes after 24 days in the media. Most genotypes showed a constant decrease in root FW percentage with

increasing nitrogen deficiency stress, while some genotypes showed improved root development under N20 and N7.5 conditions. For example, 'Prelma' showed a 6.93% FW root percentage at N20 compared to N60, but 'Magdalena' showed by a 3.98% better root percentage at N7.5, than observed at N20.

Table 1
Overview of plant performance across all genotypes at different N levels

Trait	*N60*		*N20*		*N7.5*		*F statistics*		
	Mean	*Min/Max*	*Mean*	*Min/Max*	*Mean*	*Min/Max*	*N level (N)*	*Genotype (G)*	*N x G*
Fresh weight Total (g/10 plants)	7.70	2.21/19.01	6.56	3.55/14.09	3.67	2.05/8.04	547.06***	15.68***	3.91***
Fresh weight Shoots (g/10 plants)	5.35	2.11/11.99	4.95	0.70/12.05	2.96	1.36/7.39	321.44***	12.14***	1.75*
Fresh weight Roots (g/10 plants)	2.35	0.00/8.91	1.62	0.27/5.07	0.71	0.00/1.62	482.97***	15.59***	7.38***
Shoot length (cm)	8.66	2.90/13.20	4.46	1.10/9.80	3.11	1.20/9.00	1215.27***	15.07***	5.04***
Dry weight Total (g/10 plants)	0.59	0.23/1.10	0.63	0.28/1.05	0.46	0.23/0.83	111.86***	11.35***	2.02***
Dry weight Shoots (g/10 plants)	0.47	0.14/0.86	0.53	0.17/0.95	0.40	0.21/0.80	66.86***	10.40***	1.81***
Dry weight Roots (g/10 plants)	0.12	0.00/0.40	0.10	0.01/0.21	0.06	0.00/0.15	280.31***	18.31***	4.82***
R:S ratio	0.44	0.00/0.88	0.36	0.07/7.24	0.25	0.00/0.55	25.54***	1.48ns	1.52**
Root percentage (%)	29.94	0.00/46.87	24.47	6.31/87.87	19.13	0.00/35.33	155.51***	14.24***	3.7***
*Significantly different at the 0.05 probability level p<0.05; ** p<0.01; ***p<0.001; ns – not significant									

Figure 1
Total fresh weight (g, per 10 microplants) of genotypes under different N levels



The average R:S ratio per 10 microplants ranged from 0 to 0.88 in N60, 0.07 to 7.24 in N20, and 0 to 0.55 in N7.5 (Table 1) ANOVA revealed a significant effect of nitrogen levels on the root-to-shoot (R:S) ratio Tukey's post-hoc test showed the pairwise comparisons between N60 - N20, N60 - N7.5, and N20 - N7.5 that resulted in $p<0.05$. The highest R:S was observed for 'Prelma' in N20 (7.24) (Figure 3). Statistical analysis showed that the effect of genotype was not significant in relation to the R:S ratio within each N treatment, but there was a significant interaction between the genotype and N level ($p<0.005$) in relation to the R:S ratio. Most of the genotype R:S ratio reduced as the N level reduced.

However, for some genotypes - such as 'Agrie Dzeltenie', 'Monta', S 03067-33, and S 11161-85 - the R:S ratio did not differ significantly between N20 and N7.5. For 'Magdalena', which previously showed a higher root percentage at N7.5 than at N20, the difference in R:S ratio was minimal (0.07). Interesting results showed 'Prelma', whose R:S ratio didn't significantly differ between N60 (0.14) and N7.5 (0.16), but was significantly higher at N20 (0.76).

Stress susceptibility index (NstC)

Further analysis of biomass production depending on N concentration in the medium was conducted using the ranking method, where genotypes were ranked according to the stress susceptibility based on total DW of microplants. The NstC reflects the rate of change for

each genotype and the stability of a specific parameter under stress conditions, with higher values indicating lower tolerance (Figure 4). The NstC was calculated between the N60 (standard) and N7.5 (N stress) treatments. The average NstC across genotypes was 1.02 with eight genotypes falling below average value, indicating greater tolerance to nitrogen reduction. The lowest values were detected for S 01085-21 (-0.92), 'Agrie Dzeltenie' (0.52), 'Madara' (0.53) and S 11161-85 (0.53), while genotypes S 04065-2 (1.66), 'Lenora' (1.67) and 'Verdi' (1.71) demonstrated lower tolerance to N availability changes.

Figure 2
Shoot fresh weight (g, per 10 microplants) of genotypes under different N levels

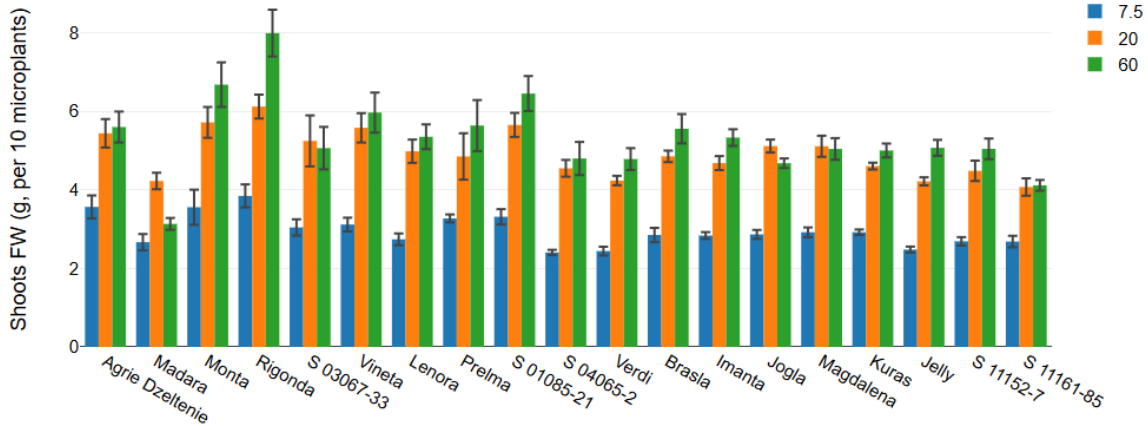
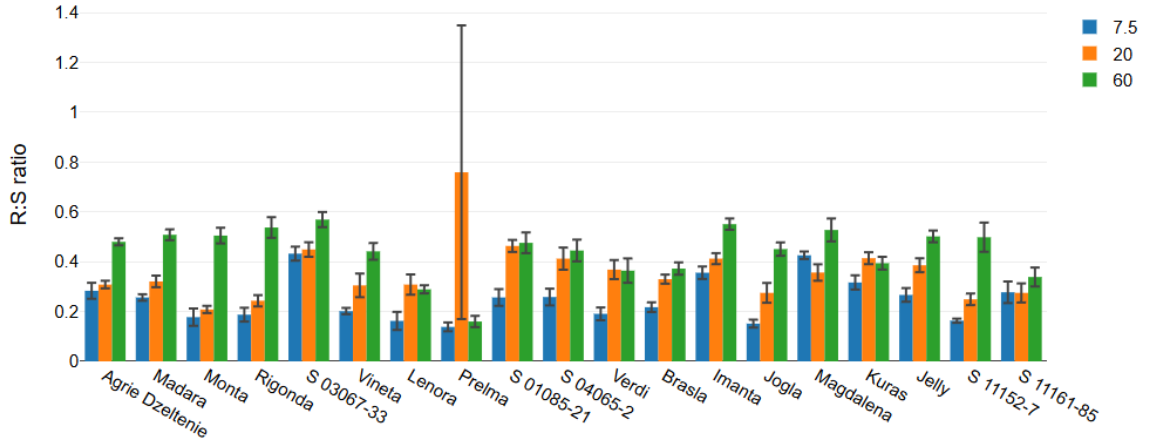


Figure 3
R:S ratio of genotypes under different N levels



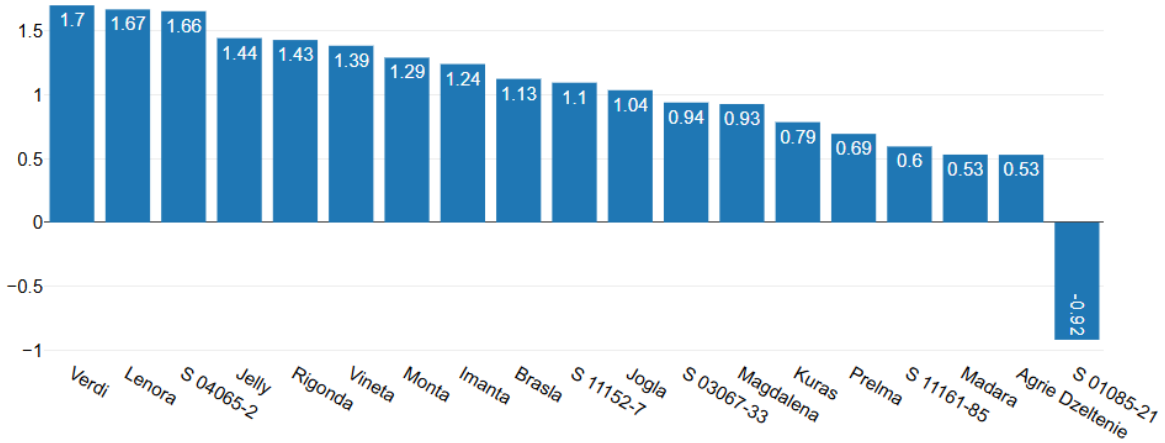
The observed significant differences between genotypes and N treatments ($p<0.005$) indicate that both genetic factors and nitrogen availability are essential for plant development and biomass production, showing that the response of a genotype under various levels of nitrogen may differ as described by Dimante et al. (2024).

In our study genotypes 'Rigonda', 'Monta', 'Agrie Dzeltenie' and breeding line S 01085-21 showed increased total FW at N60, demonstrating the significance of selecting genotypes that can improve biomass production under optimal conditions. The results align with the findings of Shum & Jansen (2014), Schum et al. (2017), and Tiwari et al. (2018), which indicate that increased nitrogen supply improves shoot growth and total plant biomass accumulation. The observed reduction in biomass related to lower nitrogen availability supports the hypothesis that decreased nitrogen levels may prevent growth and affect nutrient transport and assimilation (Tiwari et al., 2018). Still, we detected that some genotypes (S 03067-33, S04065-2, S 11161-85, 'Jogla' and 'Kuras') did not show significant differences between the N60 and N20 treatments. The 'Madara' cultivar showed higher total FW at N20 compared to N60. The analysis of shoot and root FW indicated that shoots typically formed the largest part of biomass in most genotypes. The individual response of the 'Madara', 'Magdalena' and S 03067-33, which showed higher shoot FW under N20 compared to N60, suggests that a stronger nitrogen level reduction may not negatively affect shoot FW in some genotypes.

This is consistent with findings by Skrabule et al. (2023), who reported that certain genotypes may perform better under reduced nitrogen conditions. This observation may also suggest adaptive mechanisms for nutrient uptake across different potato genotypes, aligning with the findings of White et al. (2013), which indicate the essential role of roots in providing nutrient acquisition.

Figure 4

Stress susceptibility index (NstC) of genotypes under different N levels



Observations of the development of roots under *in vitro* conditions are significant due to the potato's relatively shallow root system, which often limits nutrient acquisition (Wishart et al., 2013). The R:S ratio determines the growth relationship between the plant's roots and its upward structures, such as stems and leaves. This ratio provides insights into a plant's health, resource distribution, and overall growth strategy.

Under reduced nitrogen availability, two different responses were observed among genotypes. In some genotypes, the R:S ratio between N20 and N7.5 didn't significantly differ, like 'Agrie Dzeltenie', 'Monta', S 03067-33 and S 11161-85. We observed an indication that the highest R:S ratio was at N20, suggesting a change in growth strategy in response to lower nitrogen levels. Interaction between genotype and nitrogen supply under *in vitro* conditions is best described by Schum & Jansen (2014) and Schum et al. (2017), who suggest that certain genotypes may demonstrate distinct adaptive traits. Still, no significant differences in R:S ratios among genotypes ($p>0.05$) within N treatments were observed in our experiment, suggesting that although all genotypes react to nitrogen availability, their overall growth patterns are similar.

Most genotypes demonstrated a decrease in root FW under conditions of reduced nitrogen availability. However, 'Prelma' demonstrated a 6.93% increase in root weight at N20 compared to N60. This indicates a possible adaptive strategy for improving nutrient intake under unfavourable conditions, which may be essential to plant survival (Foulkes et al., 2009; Schum et al., 2017). The R:S ratio for 'Prelma' showed no significant difference between N60 and N7.5, suggesting that this cultivar may function well under nitrogen-limited conditions. In case of 'Magdalena' higher root percentage at N7.5, did not result in higher R:S ratio. The notable increase in root percentage share of total FW for specific genotypes under reduced nitrogen conditions suggests a strategic adaptation to improve nutrient absorption during stress, as previously documented (Ospina et al., 2014). Adaptive traits may improve breeding programs aimed at improving NUE in potatoes.

The NstC offers a quantitative measure of genotypic stability under stress conditions. High NstC values indicate lower tolerance to nitrogen deficiency, while lower values suggest better adaptability (Schum & Jansen, 2014). Eight genotypes (S 01085-21, 'Agrie Dzeltenie', 'Madara', S 11161-85, 'Prelma', 'Kuras', 'Magdalena' and S 03067-33) were below average values indicating that these genotypes have a higher tolerance to nitrogen reduction. When comparing NstC tendencies with additional traits, we can find some similarities that genotypes 'Prelma', 'Magdalena', 'Kuras' and 'Agrie Dzeltenie' showed good results regarding to root development under different N levels while 'Madara' had positive response in shoot FW. Still, the variations in response to nitrogen availability among genotypes, support the concept that genetic differences significantly influence nitrogen uptake and utilization (Zebarth et al., 2004; Skrabule et al., 2023).

Conclusions

1. Reduced nitrogen availability negatively impacts potato growth, as shown by the overall decrease in shoot and root FW among the majority of genotypes.
2. Certain genotypes have adaptive mechanisms for enhanced nutrient uptake, supporting the theory that specific genetic traits give advantages in nitrogen-limited environments.
3. R:S ratio presents insight into growth strategies in connection with the availability of nitrogen. The highest R:S ratio in limiting N levels shows a change in growth patterns, demonstrating adaptive responses to nutrient limitation.

4. The NstC provides valuable insights into the genotypic stability of various plant genotypes under nitrogen deficiency.
5. Genotypes with lower tolerance to nitrogen reduction are not always expressed by morphological traits that indicate complex interactions between genetic traits and nitrogen utilization.

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SEED INOCULATION WITH RIZOLINE-R AND FOLIAR APPLICATION OF KALNINI ENHANCE ORGANIC SOYBEAN GROWTH AND YIELD

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Abstract
The study investigates the effects of seed inoculation with *Rizoline-r* and foliar application of *KALNINI* on the growth, physiological parameters, and yield of soybean (*Glycine max* L.) grown under organic-mimicking conditions. The objective was to enhance nitrogen fixation, photosynthetic efficiency, and yield performance in sustainable farming systems without synthetic inputs. A full-factorial randomized pot experiment was conducted using three soybean varieties (*Laulema*, *Paradis*, *Tiguan*), seed inoculation (3 L t^{-1} *Rizoline-r*), and foliar application of 1% *KALNINI* at the third trifoliate and full flowering stages. The experiment simulated organic production by excluding synthetic fertilisers and pesticides. Results showed that seed inoculation increased plant height by 6.1% and biomass accumulation by 11.0%, while foliar treatment significantly enhanced leaf area index by 28.6% and chlorophyll content by 14.5%. The combined application of both treatments demonstrated a synergistic effect, resulting in the greatest improvements in all traits assessed. Notably, pod formation increased by 34.3%, and seed yield rose by 15.9% compared to the untreated control. These physiological and agronomic enhancements suggest improved plant metabolism, nitrogen uptake, and stress tolerance. The findings underline the potential of integrating microbial inoculants and foliar biostimulants into organic-compatible cropping systems. Such strategies can reduce dependency on synthetic agrochemicals while improving productivity and sustainability. Further research under diverse environmental and soil conditions is recommended to confirm the consistency and adaptability of these results and to develop region-specific treatment protocols suitable for wide adoption in low-input agriculture.
Keywords: organic soybean, seed inoculation, foliar fertilization, nitrogen fixation, yields improvement.

Introduction

Soybean (*Glycine max* L.) is a vital crop with significant economic and nutritional value due to its high protein and oil content. In sustainable agriculture, particularly under organic-compatible systems, improving soybean productivity without synthetic inputs remains a major challenge. One promising approach involves the application of biological seed inoculants and natural foliar formulations to stimulate plant development and enhance yield potential.

Seed inoculation with microbial preparations, such as Rizoline-r, plays an important role in improving nitrogen fixation, root architecture, and overall plant vigour. These preparations contain beneficial strains that establish symbiotic interactions in the rhizosphere, increasing nutrient availability and promoting sustainable crop performance (Gadzovskiy et al., 2020). Additionally, foliar applications supply nutrients directly to the foliage during critical developmental stages, potentially enhancing chlorophyll content, photosynthetic activity, and reproductive success (Di Mauro et al., 2023).

Research confirms that the combination of seed inoculation and foliar fertilisation can positively affect plant biomass, pod development, and seed quality (Negrea et al., 2022; Suciu et al., 2022). Several studies support the role of foliar fertilisation with micronutrients—such as molybdenum, phosphorus, calcium, and boron—in increasing nodulation, leaf area index, and protein content (Jarecki, 2023; Domingos et al., 2019; Muminova et al., 2022).

Additional research demonstrates that inoculation with *Bradyrhizobium japonicum* combined with foliar feeding significantly enhances grain quality and yield (Bărdaș et al., 2023; Delfim et al., 2022). While Machado et al. (2021) showed that foliar treatments influenced thousand-grain weight, Muminova et al. (2022) emphasised the role of genotype and environment in determining treatment efficacy. Korobko (2023) further underlined the synergistic effect of inoculants and foliar nutrients in organic soybean cultivation systems.

The effectiveness of these inputs depends on multiple agrotechnical factors. For instance, localised rhizosphere loosening has been shown to improve soybean root development and pod formation (Pashchenko et al., 2019). Moreover, recent field studies highlight the importance of adapting agronomic practices and sowing time to seasonal variability in order to stabilise yields under low-input conditions (Syromyatnikov et al., 2023).

The present study evaluates the combined impact of Rizoline-r seed inoculation and KALNINI foliar application on soybean growth, physiological traits, and yield performance under organic-mimicking conditions. The objective is to determine the extent of treatment synergy and its practical implications for sustainable soybean production.

Materials and Methods

The study was carried out in a controlled greenhouse environment at the Institute of Plant Protection

Research 'Agrihorts' of Latvia University of Life Sciences and Technologies. The aim of the experiment was to evaluate the individual and combined effects of seed inoculation with *Rizoline-r* and foliar application of *KALNINI* on the growth, physiological development, and yield of soybean (*Glycine max* L.) cultivated under organic-mimicking conditions (Regulation (EU) 2018/848). A full-factorial randomised experimental design was used, consisting of two independent factors: seed inoculation and foliar fertilisation. Seed inoculation included two levels: untreated control and seeds treated with *Rizoline-r*, a microbial bioinoculant based on *Bradyrhizobium japonicum* (applied at a dose of 3 litres per tonne of seed). Foliar fertilisation also included two levels: no treatment and spraying with *KALNINI* at a concentration of 1% during the V3 (third trifoliate leaf) and R2 (full flowering) stages. Each treatment combination was replicated three times, resulting in a total of 12 experimental units. Each unit consisted of one soybean plant grown in a 10-litre plastic pot filled with a peat-based organic substrate. The substrate had the following characteristics: pH 6.1, electrical conductivity 1.8 dS m^{-1}, organic matter content 78%, and a loose structure suitable for root development under low-input conditions.

Environmental conditions in the greenhouse were maintained close to optimal for soybean growth: the air temperature was kept at 24 ± 2 °C, relative humidity at 60–70%, and a 16-hour photoperiod was provided using natural light supplemented by LED lamps. Air temperature and humidity were monitored using digital sensors, and substrate moisture was maintained at approximately 70% of field capacity through regular manual irrigation.

Although three soybean varieties (*Laulema*, *Paradis*, and *Tiguan*) were used in the experiment to reflect different maturity groups (early-, mid-, and late-season types), no statistical comparison between varieties was conducted; therefore, variety was not considered a research factor in this study. Seeds were sown directly into pots after surface disinfection and drying.

Rizoline-r, the seed inoculant used in this experiment, is a liquid microbial preparation produced by BTU-Center GmbH (Germany). It contains strains of *Bradyrhizobium japonicum*, which are known to promote nitrogen fixation and early root development. The foliar product *KALNINI* is an experimental, non-commercial fertiliser developed by ZS *Kalninkalni* (Latvia), intended for application in organic and low-input systems. According to the manufacturer, it consists of trace elements suspended in a humate-based carrier. The formulation was tested under research-only conditions and applied using a handheld sprayer with fine mist nozzles to ensure uniform leaf coverage.

Growth stages were monitored according to the BBCH scale, including VE (emergence), V3 (third trifoliate), R1 (beginning of flowering), R2 (full flowering), R5 (pod development), and R7 (physiological maturity). The following parameters were measured to evaluate the treatment effects: Plant height and stem diameter were measured at the R5 stage using a calibrated ruler and digital caliper. Leaf Area Index (LAI) was determined using a portable leaf area meter to assess canopy development. Relative chlorophyll content (SPAD values) was measured at R2 using the LEAF CHL STD meter (FT GREEN LLC, USA). Biomass accumulation was assessed at physiological maturity (R7) by drying and weighing the above-ground part of each plant and expressing the result as g m^{-2}. Number of pods per plant was counted manually at harvest. Seed yield was measured after threshing and adjusted to standard moisture content, then extrapolated from per-plant data to tonnes per hectare (t ha^{-1}).

All measurements were recorded using standardised protocols. Statistical analysis of the results was carried out using the software packages SPSS 27.0 and R. Two-way ANOVA (Analysis of Variance) was applied to assess the significance of the main effects (seed inoculation and foliar treatment) and their interaction. Tukey's HSD test was performed for post-hoc comparisons between means where significance was observed ($p < 0.05$). Additionally, regression analysis was used to assess relationships between physiological traits (SPAD, LAI) and yield components (biomass, seed yield), while Pearson correlation coefficients were calculated to evaluate interdependencies among measured variables. The statistical approach provided a comprehensive understanding of how *Rizoline-r* and *KALNINI* influence soybean performance under organic-compatible conditions. For regression analysis, treatment groups were numerically coded under a variable named X (Treatment Level), reflecting increasing input intensity: 0 = CTRL – untreated control; 1 = RZL – seed inoculation with Rizoline-r; 2 = KLN – foliar application of KALNINI; 3 = RZL+KLN – combined application of both treatments.

This coding was used in linear regression models to quantify trends across treatments. Each regression equation shows the expected change in the outcome variable (e.g., plant height, yield) per unit increase in TreatmentLevel. The coefficient reflects treatment effect strength, and the R^2 value indicates how well the model explains variability.

While boxplots show group medians and variability, regression highlights the average linear trend across treatment intensity. All regressions were statistically significant and consistent with the descriptive data.

Results and Discussion

Seed inoculation with Rizoline-r significantly increased soybean plant height across growth stages.

During the pod-filling phase, inoculated plants averaged 117.6 cm, 13% taller than the control (104.1 cm), indicating enhanced vegetative growth due to improved nitrogen fixation.

Figure 1
Effect of Seed Inoculation and Foliar Application on Soybean Plant Height

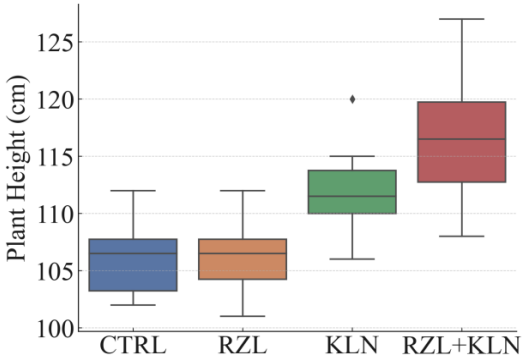


Figure 1 presents plant height distribution across treatments: Control (CTRL), Rizoline-r (RZL), KALNINI (KLN), and Rizoline-r + KALNINI (RZL+KLN). Compared to the control, Rizoline-r increased height by 6.1% (110.5 cm), KALNINI by 8.4% (112.8 cm), and their combined application by 13% (117.6 cm). The boxplot highlights the highest variability in the RZL+KLN group, with median values showing an increasing trend with treatment. Statistical analysis confirmed significant differences ($p < 0.05$), with the RZL+KLN treatment having the strongest impact.

Figure 2
Regression Analysis of Plant Height Across Treatment Groups. Regression equation: y = 104.1 + 4.5x (R^2 = 0.75, p = 0.044)

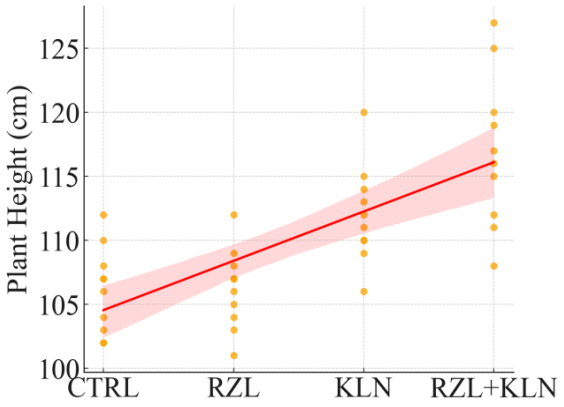


Figure 2 illustrates the regression analysis of plant height across treatment groups, demonstrating a significant positive correlation between treatment application and soybean growth. The combined application of Rizoline-r and KALNINI resulted in the highest plant height (117.6 cm). The regression analysis supports that the effect of combined treatment is statistically significant.

KALNINI foliar application significantly enhanced the Leaf Area Index (LAI), which was 18% higher during the flowering stage compared to untreated plants, suggesting improved canopy development and photosynthetic potential.

Figure 3
Effect of Seed Inoculation and Foliar Application on Leaf Area Index (LAI)

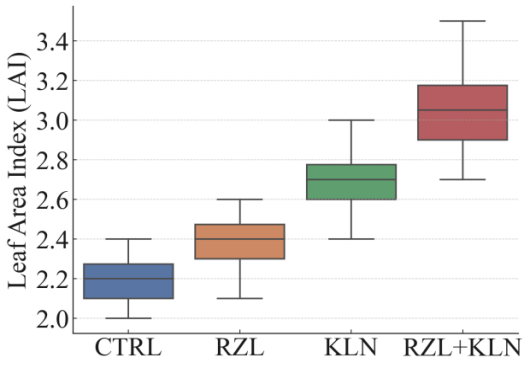
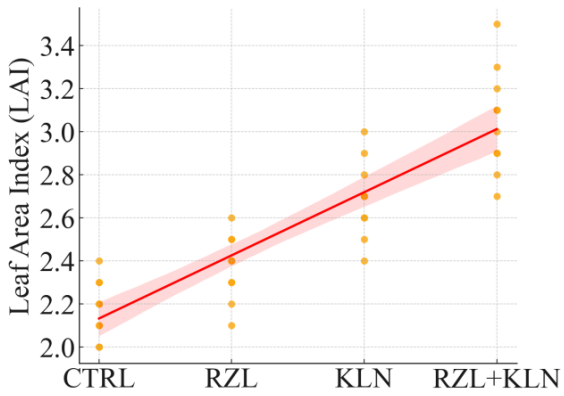


Figure 3 illustrates the impact of seed inoculation and foliar application on LAI: Control (2.1), Rizoline-r (2.5), KALNINI (2.7), RZL+KLN (3.1). Tukey's HSD test confirmed significant differences ($p < 0.001$), with the combined treatment showing the strongest effect.

Figure 4
Regression Analysis of Leaf Area Index Across Treatment Groups. Regression equation: y = 2.1 + 0.35x (R^2 = 0.84, p = 0.043)



The regression Figure 4 indicates a strong linear correlation between treatment intensity and LAI, confirming the physiological benefit of integrated application.

Foliar application of KALNINI at the V3 and R2 stages improved SPAD values, indicating higher chlorophyll content and nitrogen assimilation.

Figure 5 shows SPAD values: Control (35.2), RZL (38.5), KLN (40.3), RZL+KLN (43.2). Tukey's HSD

test indicated significance for all treatments ($p < 0.001$).

Figure 5
Effect of Seed Inoculation and Foliar Application on Chlorophyll Content (SPAD)

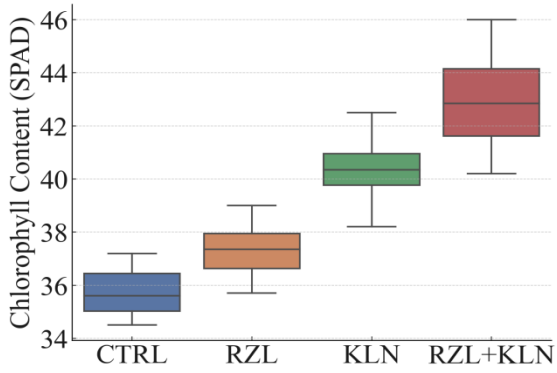
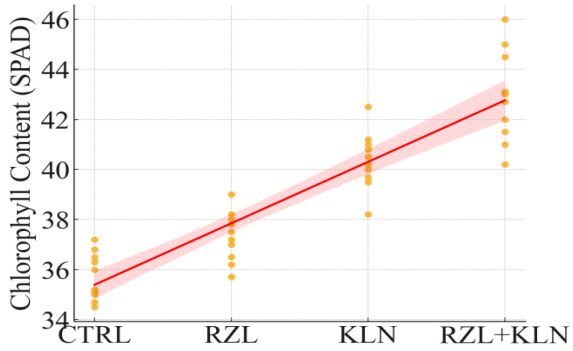


Figure 6
Regression Analysis of Chlorophyll Content (SPAD) Across Treatment Groups. Regression equation: y = 35.2 + 2.7x ($R^2 = 0.80$, $p = 0.018$)



The fitted regression Figure 6 line supports the observation that foliar application combined with inoculation substantially improves photosynthetic efficiency.
Reproductive development was also influenced.

Figure 7
Effect of Seed Inoculation and Foliar Application on Pod Formation

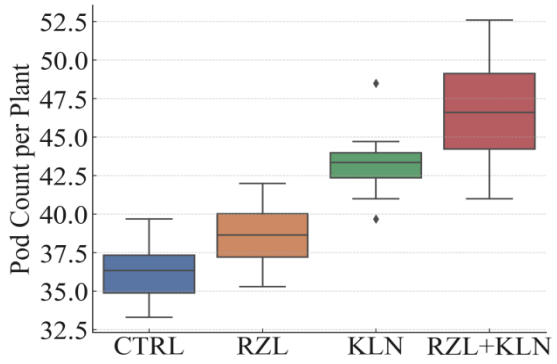
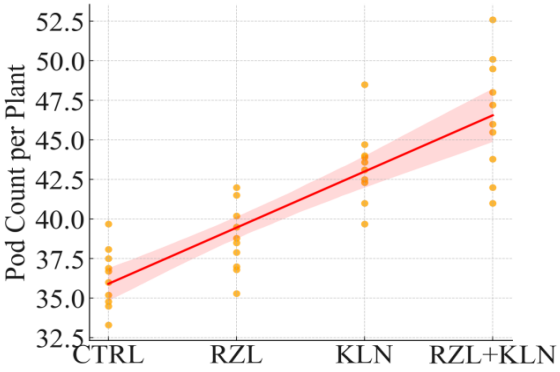


Figure 7 shows that pod number increased from 35 pods plant^{-1} (CTRL) to 47 pods plant^{-1} in the RZL+KLN group (+34.3%). Rizoline-r increased pod count by 17.1%, and KALNINI by 25.7%, both statistically significant ($p < 0.001$).

Figure 8
Regression Analysis of Pod Formation Across Treatment Groups. Regression equation: y = 35 + 4.1x ($R^2 = 0.84$, $p = 0.005$)



The regression Figure 8 confirms a direct positive trend between pod number and treatment intensity.

Figure 9
Effect of Seed Inoculation and Foliar Application on Seed Yield

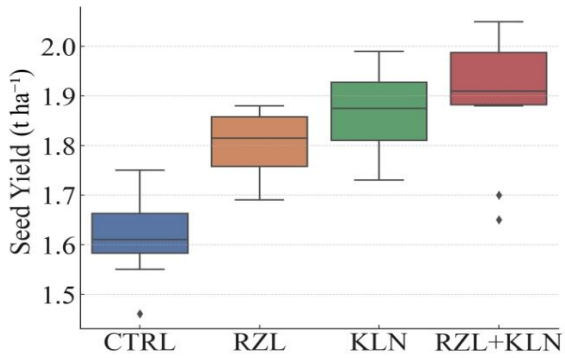
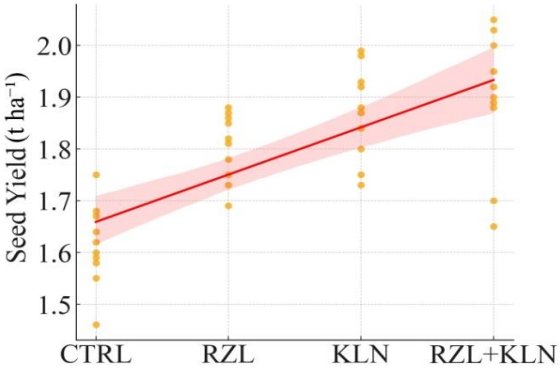


Figure 9 illustrates the effect of seed inoculation with Rizoline-r and foliar application of KALNINI on seed yield in soybean plants. The Control (CTRL) group had the lowest yield at 1.64 t ha^{-1}. Rizoline-r (RZL) increased yield by 8.5% to 1.78 t ha^{-1}, while KALNINI (KLN) enhanced it by 12.8% to 1.85 t ha^{-1}. The highest yield was observed in the combined treatment group (RZL+KLN), reaching 1.90 t ha^{-1}, a 15.9% improvement over the control. The boxplot demonstrates the greatest variability and improvement in the RZL+KLN group, confirming the synergistic effect of microbial inoculation and foliar fertilization on crop productivity.
Tukey's HSD test confirmed statistically significant differences among all treatment groups. The increase

in seed yield in the RZL+KLN group compared to the control was highly significant ($p < 0.001$). KALNINI alone improved yield significantly ($p < 0.01$), and Rizoline-r also contributed a measurable increase ($p < 0.05$). The difference between KALNINI and Rizoline-r alone was significant ($p < 0.05$), indicating that foliar fertilization has a more pronounced effect when used independently. Nonetheless, the combined treatment significantly outperformed KALNINI alone with an additional 5.4% yield increase ($p < 0.05$), confirming its superior effectiveness in enhancing organic soybean productivity.

Figure 10
Regression Analysis of Seed Yield Across Treatment Groups. Regression equation: $y = 1.64 + 0.09x$ ($R^2 = 0.92$, $p = 0.033$)



The regression Figure 10 line confirms that seed yield increased linearly with treatment intensity, and validates the practical effectiveness of combining Rizoline-r and KALNINI.

Figure 11
Effect of Seed Inoculation and Foliar Application on Biomass Accumulation

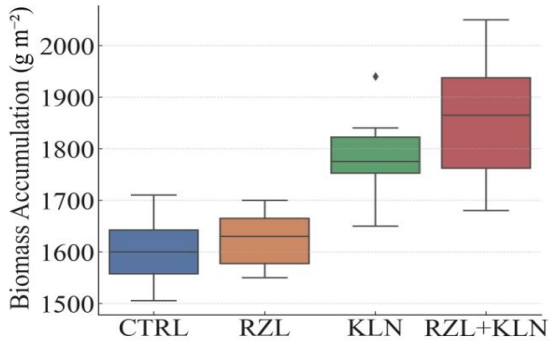
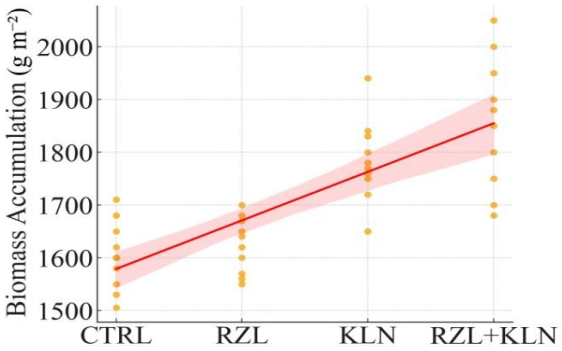


Figure 11 illustrates the impact of seed inoculation with Rizoline-r and foliar application of KALNINI on above-ground biomass accumulation in soybean plants. The Control (CTRL) group exhibited the lowest biomass at 1,550.0 g m^{-2}. Seed inoculation with Rizoline-r (RZL) increased biomass by 11.0% to 1,720.0 g m^{-2}, while foliar treatment with KALNINI (KLN) led to a 15.8% increase, reaching 1,795.0 g m^{-2}. The highest biomass was recorded in the combined treatment (RZL+KLN), where plants accumulated 1,881.7 g m^{-2}, representing a 21.4% increase over the control.

Tukey's HSD test confirmed that all treatments significantly enhanced biomass accumulation compared to the control ($p < 0.001$). KALNINI alone was significantly more effective than Rizoline-r ($p < 0.05$), and the combined application significantly outperformed both individual treatments. The synergistic interaction between the microbial inoculant and the foliar fertilizer resulted in an additional 4.8% biomass gain over KALNINI alone ($p < 0.05$), highlighting the practical benefits of integrating both technologies in organic crop management.

Figure 12
Regression Analysis of Biomass Accumulation Across Treatment Groups. Regression equation: $y = 1550 + 110x$ ($R^2 = 0.85$, $p = 0.004$)



This regression Figure 12 line indicates a strong, statistically significant relationship between biomass and treatment level. These data reinforce that the combined application of microbial inoculants and foliar fertilizers significantly enhances total productivity under organic conditions.

Table 1 summarizes the quantified effects of seed inoculation with Rizoline-r and foliar fertilization with KALNINI on soybean growth, physiological parameters, and productivity under organic conditions. The table presents key experimental outcomes, their agronomic relevance, and supporting statistical evidence based on ANOVA, Tukey's HSD tests, and regression analysis.

The results show that seed inoculation with Rizoline-r notably improved early-stage vegetative growth, including a 6.1% increase in plant height (110.5 cm vs. 104.1 cm; $p < 0.05$). Foliar application of KALNINI significantly enhanced photosynthetic function, resulting in a 14.5% increase in chlorophyll content (SPAD) and a 28.6% rise in LAI, indicating better nitrogen uptake and canopy development ($p < 0.01$).

The combined treatment (RZL+KLN) consistently produced the highest performance across all indicators, including a 15.9% increase in seed yield (1.90 vs. 1.64 t ha^{-1}), a 21.4% improvement in total biomass

accumulation (1,881.7 vs. 1,550.0 g m^{-2}), and a 34.3% increase in pod formation (47 vs. 35 pods $plant^{-1}$), all statistically highly significant ($p < 0.001$). Additionally, physiological enhancements such as a 22.7% improvement in SPAD values and a 47.6% increase in LAI reflect better stress tolerance and adaptability.

These outcomes confirm the synergistic benefit of integrating microbial inoculants and foliar nutrients in organic soybean cultivation. The statistical significance of treatment effects (with regression R^2 ranging from 0.75 to 0.92) validates the reproducibility and agronomic relevance of the findings for sustainable agricultural systems.

The combined application of biological seed inoculants and foliar biostimulants significantly enhanced soybean performance under organic-mimicking greenhouse conditions. The observed increases in chlorophyll content, leaf area index, and biomass accumulation confirm the physiological benefits of such treatments and are consistent with findings from previous studies.

Foliar fertilisation has been shown to improve nutrient assimilation and photosynthetic efficiency, especially when applied during critical growth stages. For instance, Jarecki (2023) and Domingos et al. (2019) reported similar improvements in leaf area and grain protein concentration following foliar applications of molybdenum, phosphorus, and calcium. The current study's results also support the synergistic interaction between seed inoculation and foliar feeding, which was highlighted by Bărdaș et al. (2023), who found improved physiological parameters and seed yield when both treatments were combined.

Table 1

Summary of the Effects of Seed Inoculation with Rizoline-r and Foliar Application of KALNINI on Soybean Growth and Productivity

Aspect	***Key Findings***	***Practical Implications***	***Supporting Data and Significance***
Seed Inoculation Effectiveness	Stimulated early plant growth, particularly stem elongation and vigor	Recommended for organic systems to improve initial nitrogen fixation and vegetative development	+6.1% plant height (110.5 cm vs. 104.1 cm), $p < 0.05$
Foliar Fertilization Impact	Enhanced chlorophyll synthesis and photosynthetic activity	Apply KALNINI during V3 and R2 stages for optimal chlorophyll and nutrient assimilation	+14.5% SPAD (40.3 vs. 35.2), $p < 0.01$
Combined Treatment Performance	Highest values in all measured traits due to synergistic effect	Use both technologies jointly to maximize productivity and resource efficiency in organic soybean farming	+15.9% yield (1.90 vs. 1.64 t ha^{-1}), +21.4% biomass (1,881.7 vs. 1,550.0 g m^{-2}), $p < 0.001$
Physiological Improvements	Increased LAI and chlorophyll content, contributing to better stress tolerance	Improves crop resilience, canopy coverage, and photosynthetic surface	+47.6% LAI (3.1 vs. 2.1), +22.7% SPAD (43.2 vs. 35.2), $p < 0.001$
Reproductive Performance	Increased pod number and seed set	Enhances reproductive efficiency and final yield potential	+34.3% pods $plant^{-1}$ (47 vs. 35), $p < 0.001$
Statistical Significance	Differences confirmed by ANOVA, Tukey's HSD, and regression ($R^2 > 0.75$)	Results are statistically validated and reproducible under controlled organic conditions	All indicators significant at $p < 0.05$, regression R^2: 0.75–0.92

The extrapolated grain yield values, although derived from a controlled setting, align with outcomes from comparable pot and small-plot trials (Di Mauro et al., 2023; Delfim et al., 2022), suggesting that the observed trends may translate under field conditions. Moreover, the responsiveness of yield components such as pod number and thousand seed weight reinforces the role of foliar inputs in enhancing reproductive success, as also reported by Machado et al. (2021).

Genotype and environmental interactions remain critical in determining treatment efficacy, particularly in organic systems where variability is high (Muminova et al., 2022; Korobko, 2023). However, the relatively uniform response observed in this study suggests that the combined approach of microbial and foliar application can serve as a stable yield-improving strategy even under variable growth conditions.

In summary, our results support existing evidence that biologically-based inputs can enhance key physiological and yield traits in soybean. Further field-based validation is recommended to confirm scalability and reproducibility under practical farming conditions.

Conclusions

The study demonstrated that both seed inoculation with Rizoline-r and foliar fertilization with KALNINI significantly improved the growth, physiological parameters, and yield of soybean (*Glycine max* L.) cultivated under organic-mimicking conditions. Their combined application produced a consistent synergistic effect, leading to superior performance across all measured traits.

1. Vegetative Growth Enhancement: Inoculation with Rizoline-r and foliar application of KALNINI increased plant height by 13% and total above-ground biomass by 21.4% compared to the untreated control. These improvements reflect better nitrogen fixation and more efficient nutrient assimilation, especially in early growth stages.

2. Physiological and Photosynthetic Improvements: The treatments improved photosynthetic capacity, with SPAD values rising by 22.7% and leaf area index (LAI) by 47.6% in the combined treatment group. These physiological changes are indicative of improved chlorophyll synthesis, canopy development, and stress resilience.

3. Reproductive Development and Yield Performance: Pod number per plant increased by 34.3%, and seed yield rose by 15.9% (from 1.64 to 1.90 t ha^{-1}) in the combined treatment. These results confirm the substantial impact of integrated biostimulant strategies on reproductive efficiency and yield formation under organic-compatible cultivation.

Statistical validation through two-way ANOVA, Tukey's HSD, and regression analyses (with R^2 values ranging from 0.75 to 0.92) confirms that the treatment effects are highly significant and consistent. These findings support the adoption of microbial seed inoculants and natural foliar fertilizers as practical tools to improve crop productivity in sustainable and low-input farming systems.

Future research should focus on validating these results across diverse soil types, climatic conditions, and on-farm scales to develop adaptable protocols for broader use in certified organic agriculture.

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EFFECTIVENESS OF BIOPREPARATIONS FOR GROWING SWEET POTATO AND JERUSALEM ARTICHOKE IN SUSTAINABLE AGRICULTURE

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Abstract
Biopreparations, including microbial inoculants and organo-mineral fertilisers, offer a sustainable approach to improving crop yield and quality. This study examined their effects on the sweet potato (*Ipomoea batatas*) and Jerusalem artichoke (*Helianthus tuberosus*) under agroecological conditions in Ukraine. The highest sweet potato yield (17.4 t ha^{-1} average over three years) was achieved through foliar application of Humifriend (1.5 L ha^{-1}) and Help-Rost (2 L ha^{-1}). For Jerusalem artichoke, the best result (32.6 t ha^{-1}) followed fertigation with Mykofriend (1 L ha^{-1}) and two foliar applications of Help-Rost (2 L ha^{-1}). Key quality traits assessed included dry matter, starch, total sugar, and vitamin C content. Significant increases in dry matter, total sugar, and vitamin C were recorded for both crops, with the strongest effects observed in total sugar for sweet potato and dry matter for Jerusalem artichoke. In contrast, starch content in Jerusalem artichoke showed no significant response. These results highlight the potential of Mykofriend and Help-Rost to enhance root crop productivity and nutritional value while reducing environmental impact. The findings support broader use of biopreparations in sustainable agriculture and emphasise the importance of optimising treatment strategies to maximise agronomic performance.
Keywords: microbial inoculants, organo-mineral fertilizers, tuber crops, sustainable fertilization, biofertilizers.

Introduction

The increasing demand for ecologically sound, resource-efficient, and climate-resilient agricultural systems has catalyzed a paradigm shift toward the use of biopreparations such as microbial inoculants, biofertilizers, and organo-mineral amendments as viable and sustainable alternatives to synthetic agrochemicals. These biologically active inputs enhance nutrient cycling, improve soil structure, increase plant resilience to abiotic stress, and support ecosystem services that are often degraded under intensive conventional practices (Bolokhovskyi et al., 2025). Their integration into agroecological systems is becoming a cornerstone of regenerative agriculture and long-term soil fertility strategies (Sofo et al., 2022).

Biopreparations function through complex biochemical and ecological interactions within the soil and plant continuum. Consortia of beneficial microorganisms including *Azotobacter*, *Bacillus* spp., mycorrhizal fungi, and *Pseudomonas fluorescens* can boost nutrient availability, suppress phytopathogens, and stimulate plant hormone pathways that enhance root growth and stress tolerance (Nakielska et al., 2024). When combined with organic amendments such as humic substances, amino acid complexes, or composted biomass, these inputs not only enrich microbial diversity but also restructure the soil matrix to improve aeration, moisture retention, and cation exchange capacity (Breza-Boruta & Bauza-Kaszewska, 2023). Furthermore, such biologically driven systems reduce the need for chemical fertilisers, which lowers environmental contamination risks and contributes to cleaner food production (Vasylovych, 2024; Romanowska-Duda et al., 2020).

These benefits are particularly significant for tuber crops such as Jerusalem artichoke (*Helianthus tuberosus*) and sweet potato (*Ipomoea batatas*), which serve as important sources of carbohydrates, fiber, antioxidants, and bioactive compounds. They are widely used not only in food systems but also in feed, energy, and pharmaceutical industries. Prior studies have demonstrated that bio-based inputs can substantially increase tuber yield and nutritional value, particularly in terms of dry matter, total sugars, starch, and vitamin C content, through enhanced nutrient uptake and plant metabolic efficiency (Ahmed & Alian, 2023; Antonious, 2024; Liu et al., 2024). In parallel, the valorization of sweet potato processing residues, especially peels, has attracted attention as a model for circular bioeconomy and industrial upcycling (Jiang et al., 2024).

The effectiveness of biopreparation-based fertilisation systems is closely linked to the physical properties of soil, including bulk density, porosity, moisture retention capacity, and aeration. These factors significantly influence microbial colonization and rhizosphere activity. Long-term tillage practices can alter the structure of bacterial communities and improve soil physicochemical characteristics. In particular, rotary and chisel tillage reduce compaction, increase organic matter content, and enhance phosphorus availability. These improvements create a favorable environment for beneficial microorganisms, stimulating their metabolic activity in the root zone. Maintaining a structured and biologically active topsoil is essential for sustaining stable microbe-plant interactions and ensuring the success of microbial inoculants under field conditions (Sun et al., 2023).

Recent research confirms the synergistic effects of combining reduced tillage with microbial and organic inputs. These integrative systems promote microbial biomass, elevate soil organic carbon levels, and improve nutrient availability, which collectively enhance yield and soil resilience (Kanarek et al., 2022). Field studies have also documented productivity and quality gains when microbial treatments are used alongside composts,

humic substances, or digestates, particularly in low-input and organic farming systems (Williams et al., 2020; Yang et al., 2022).

Despite these promising advances, field-level data on the combined use of microbial biopreparations and organo-mineral fertilisers under Ukrainian agroecological conditions remain scarce, especially for underutilized yet high-potential crops like the sweet potato and Jerusalem artichoke. Preliminary findings suggest that products such as Mykofriend, Help-Rost, and Humifriend can improve not only yields but also key biochemical parameters. However, their consistent performance across diverse environments and crop phenophases requires further validation.

This study aims to evaluate the agronomic performance of selected microbial and humic biopreparations on *Ipomoea batatas* and *Helianthus tuberosus* grown in steppe soils of eastern Ukraine. The goal is to develop practical recommendations for sustainable fertilisation systems that enhance productivity, nutrient use efficiency, and product quality while minimizing environmental impact.

Materials and Methods

Field experiments were carried out from 2021 to 2024 at the Donetsk Experimental Station of the Institute of Vegetable and Melon Growing, NAAS of Ukraine, to assess the effects of selected biopreparations on the yield and biochemical quality of *Ipomoea batatas* and *Helianthus tuberosus*. The site is located on typical chernozem soils with 4.3% humus, hydrolysable nitrogen at 139 mg kg^{-1}, available phosphorus ranging from 106 to 119 mg kg^{-1}, and exchangeable potassium at 93 mg kg^{-1}. The soil had a slightly acidic reaction (pH 5.7 in KCl), hydrolytic acidity of 2.8 mEq per 100 g, and base saturation of 26.0 mEq per 100 g. These properties reflect a moderately fertile matrix responsive to microbial and humic amendments, especially under steppe climate stressors (Breza-Boruta & Bauza-Kaszewska, 2023; Vasylovych, 2024).

A randomized complete block design (RCBD) with three replications per treatment was used. Each plot measured 33.6 m², with a central accounting area of 21 m² for data collection. Soil preparation included deep rotary tillage and strip loosening (25–30 cm) using a method adapted to improve seedbed aeration, reduce compaction, and ensure uniform seeding conditions under field environments. The selection of tillage depth and type was based on regionally tested practices that demonstrated improved water retention and reduced soil density under traditional and chisel tillage systems (Syromyatnikov et al., 2023, 2024). Five treatment variants were applied to the sweet potato cultivar ‘Slobozhansky Ruby’. The control (Ctrl) received manure (20 t ha^{-1}) and wood ash (1 t ha^{-1}). The Ctrl+MF treatment added Mykofriend at 1 L ha^{-1} via fertigation. Ctrl+HR included two foliar applications of Help-Rost at 2 L ha^{-1}. Ctrl+MF+HR combined both Mykofriend and Help-Rost at the same doses. Finally, Ctrl+Hum+HR integrated Humifriend (1.5 L ha^{-1}) and Help-Rost (2 L ha^{-1}). Slips were planted in a (100+40) × 25 cm layout, reaching 58,000 plants ha^{-1}. Drip irrigation and black polyethylene mulch (120 μm) were used throughout the season to conserve moisture and control weeds, aligning with conservation agriculture principles (Romanowska-Duda et al., 2023).

A parallel treatment scheme was used for Jerusalem artichoke cultivar ‘Dietetic’. The unfertilized control (Ctrl) was compared to four biopreparation variants. In Ctrl+MF, tubers were soaked in Mykofriend (2 L t^{-1}) before planting. Ctrl+MF+Fert involved additional fertigation with Mykofriend (1 L ha^{-1}) during early vegetative growth. Ctrl+HR included three foliar sprays of Help-Rost (2 L ha^{-1}) at key growth stages: 5–6 leaves, and 25 and 35 days after. The combined Ctrl+MF+HR treatment used both tuber inoculation and foliar Help-Rost. Jerusalem artichoke was planted at 29,000 plants ha^{-1} using a 70 × 50 cm spacing. Soil pre-treatment followed the same tillage strategy as for sweet potato.

The biopreparations tested included Mykofriend, Humifriend, and Help-Rost. Mykofriend is a complex microbial inoculant containing *Glomus* spp., *Trichoderma harzianum*, and rhizobacteria (*Bacillus subtilis*, *B. megaterium*, *Paenibacillus polymyxa*, *Pseudomonas fluorescens*) at 1.0–1.5 × 10^9 CFU mL^{-1}. Humifriend is a humic-based biostimulant enriched with fulvic acids, amino acids, micronutrients, and microbial metabolites. Help-Rost is a foliar organo-mineral fertilizer containing essential nutrients, phytohormones, and growth regulators, suitable for organic farming (Nakielska et al., 2024).

Harvested tubers were evaluated annually for marketable yield (t ha^{-1}). Biochemical analyses were conducted on 1.5 kg composite samples per treatment. Dry matter was determined by oven drying at 105 °C to constant weight (AOAC 930.15). Starch was assessed enzymatically (AOAC 996.11), total sugars by Luff–Schoorl titration (AOAC 923.09), and vitamin C using 2,6-dichlorophenolindophenol titration (AOAC 967.21). All measurements were performed in triplicate. Statistical analysis involved one-way ANOVA using R software (v4.3.1). Normality and homogeneity of variances were checked via Shapiro–Wilk and Levene’s tests. Tukey’s HSD test ($p < 0.05$) was used for post hoc comparisons among treatments.

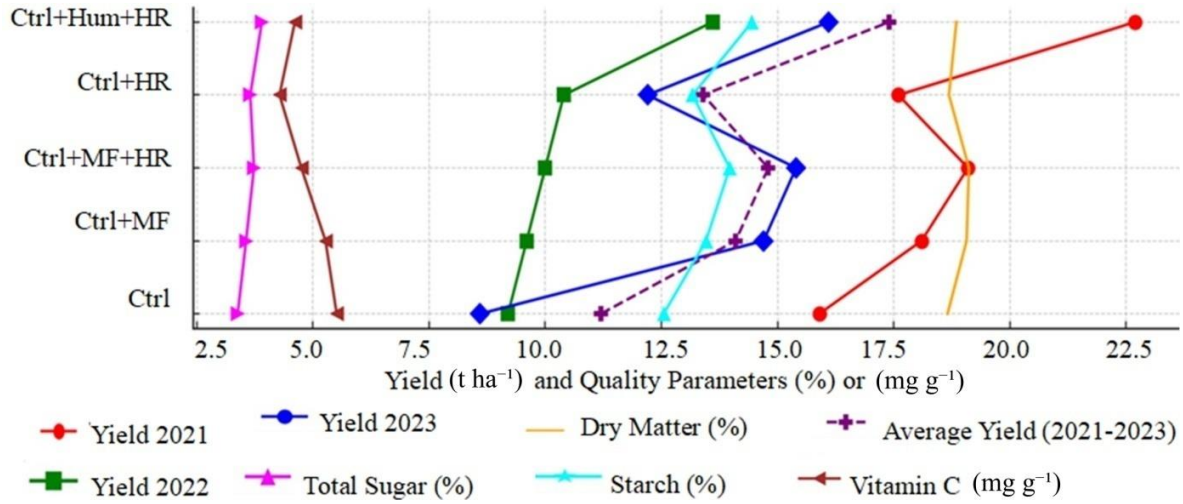
Results and Discussion

The effect of various fertilisation systems on the yield and quality of *Ipomoea batatas* was evaluated over the three-year period from 2021 to 2023. As shown in Figure 1, the average yield in the control treatment (Ctrl), which included only manure (20 t ha^{-1}) and ash (1 t ha^{-1}), was 11.2 t ha^{-1}. The lowest yield in this group was recorded in 2023 (8.6 t ha^{-1}), whereas the highest was observed in 2021 (15.9 t ha^{-1}). The treatment Ctrl+Hum+HR, which combined Humifriend (1.5 L ha^{-1}) and Help-Rost (2 L ha^{-1}), resulted in the highest

average yield of 17.4 t ha^{-1}, with respective annual values of 22.7, 13.6, and 16.1 t ha^{-1}. Other biopreparation-based treatments also demonstrated notable improvements in productivity, with Ctrl+MF+HR and Ctrl+Help consistently outperforming the control.

Figure 1

Sweet potato yield and quality indicators under different fertilisation treatments (2021–2023) Lines represent the same treatment across years and do not imply sequential dependence

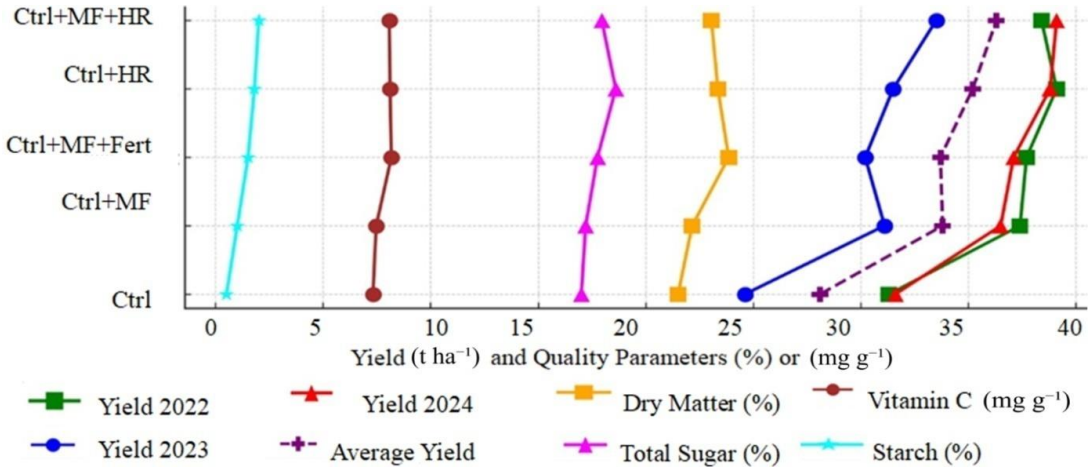


The analysis of tuber quality in sweet potato indicated that biopreparations positively influenced several key parameters. The highest dry matter content (19.12%) was recorded in the Ctrl+MF+HR treatment, whereas the highest starch content (14.45%) and total sugar content (3.90%) were observed in the Ctrl+Hum+HR variant. The vitamin C content was highest in the control treatment (5.51×10^{-2} mg g^{-1}) and lowest in the Ctrl+MF+HR treatment (4.75×10^{-2} mg g^{-1}).

The effects of the treatments on the yield and quality of *Helianthus tuberosus* from 2022 to 2024 are presented in Figure 2. In the unfertilised control, the average yield was 26.2 t ha^{-1}, increasing from 22.3 t ha^{-1} in 2022 to 31.6 t ha^{-1} in 2024. Application of Mykofriend (2 L t^{-1}) for tuber treatment (Ctrl+MF) resulted in an average yield of 31.5 t ha^{-1}, while Mykofriend fertigation (Ctrl+MF+Fert) produced 31.3 t ha^{-1}. The highest average yield (32.6 t ha^{-1}) was obtained with the combined application of Mykofriend and Help-Rost (Ctrl+MF+HR), which yielded 27.6, 31.5 and 38.8 t ha^{-1} in the respective years.

Figure 2

Jerusalem artichoke yield and quality indicators under different treatments (2022–2024) Lines connect values of the same parameter across independent treatments for visual clarity only



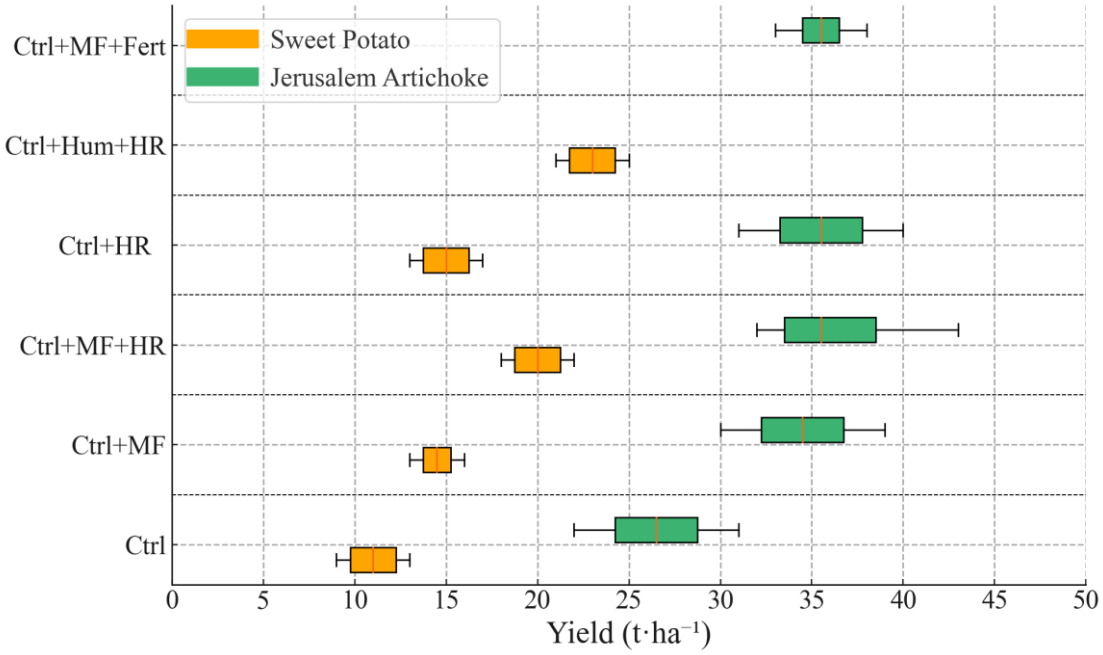
Quality analysis in Jerusalem artichoke demonstrated increases in dry matter, total sugar, and vitamin C levels following treatment. The control group exhibited a stable dry matter content of approximately

22.2%, whereas the Ctrl+MF+HR treatment raised this parameter to an average of 22.9%. Similarly, total sugar content increased from 17.3% in the control to 18.3% in Ctrl+MF+HR. The concentration of vitamin C, expressed in mg g^{-1}, rose from 7.53×10^{-2} in the control to 8.12×10^{-2} in the Ctrl+MF+Fert treatment.

Statistical analysis confirmed that the differences in yield between treatments were significant for both crops (the sweet potato exhibited a P-Value = 0.000004, whereas Jerusalem artichoke showed a P-Value = 0.027). The distribution of yield values by treatment is depicted in Figure 3. For the sweet potato, the highest median yield (22 t ha^{-1}) was obtained under the Ctrl+Hum+HR treatment, whereas Ctrl+MF+HR yielded 19 t ha^{-1}. The control treatment exhibited the lowest median yield at 16 t ha^{-1}. In the case of Jerusalem artichoke, the highest median yield (40 t ha^{-1}) was recorded for Ctrl+MF+HR, while the control showed the lowest value (27.5 t ha^{-1}). Broader interquartile ranges were observed in the treated groups compared to the controls, particularly for Jerusalem artichoke.

Figure 3

Yield Distribution of Sweet Potato and Jerusalem Artichoke Across Different Treatments



Quality parameters were also significantly influenced by the biopreparation treatments. The ANOVA results indicate strong statistical significance ($p < 0.001$) for dry matter, total sugar, and vitamin C content in both crops. Starch content was significantly affected only in the sweet potato, whereas in Jerusalem artichoke the differences were not statistically significant ($p = 0.332$). The detailed analysis of sweet potato quality is illustrated in Figure 4. Dry matter content increased from a median of 22% in the control to 24.5% in the Ctrl+Hum+HR treatment. Starch content also rose from 16% in the control to 17.2% under the same treatment. Total sugar content peaked at 4.9% in Ctrl+Hum+HR, compared to 4.5% in the control. Vitamin C content slightly decreased in the treated plots, with the control maintaining the highest median value (6.0×10^{-2} mg g^{-1}).

For Jerusalem artichoke, the distribution of quality parameters is presented in Figure 5. Dry matter content increased from 19% in the control to 21.5% in the Ctrl+Hum+HR treatment, while starch content remained low across all treatments. The highest total sugar content (4.3%) and vitamin C concentration (5.4×10^{-2} mg g^{-1}) were observed in Ctrl+Hum+HR. Although the vitamin C content was generally lower in the treated groups than in the control (5.5×10^{-2} mg g^{-1}), the differences observed remained within the range of acceptable biological variability.

The application of biopreparations significantly improved the yield and quality of both *Ipomoea batatas* and *Helianthus tuberosus* under Ukrainian agroecological conditions. Among all variants, combined treatments particularly Ctrl+Hum+HR and Ctrl+MF+HR consistently delivered superior outcomes. The sweet potato yield increased from 11.2 t ha^{-1} in the control to 17.4 t ha^{-1} in Ctrl+Hum+HR, while Jerusalem artichoke yield rose from 26.2 t ha^{-1} to 32.6 t ha^{-1} under Ctrl+MF+HR. These results correspond with findings by (Antonious, 2024), who reported enhanced sweet potato productivity and nutritional quality following applications of biochar and organic fertilizers an effect attributed to improved nutrient availability, soil structure, and microbial activity.

Dry matter and total sugar content also increased significantly under the biopreparation treatments, supporting their role in promoting carbohydrate accumulation. The treatments Ctrl+Hum+HR and Ctrl+MF+HR showed the highest gains in both parameters. These effects align with the findings of (Ahmed & Alian, 2023), who reported that Jerusalem artichoke harvested later in the season accumulated more sugars and inulin. This may reflect improved root function and extended vegetative growth stimulated by microbial and humic amendments.

Figure 4
Impact of Biopreparations on Key Quality Attributes of Sweet Potato

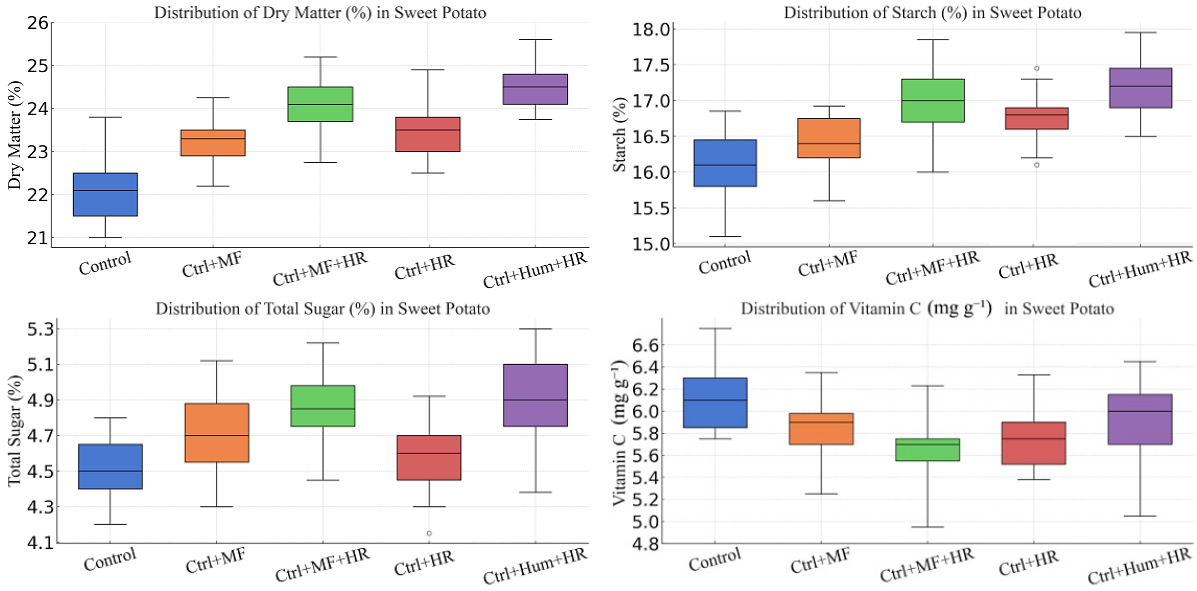
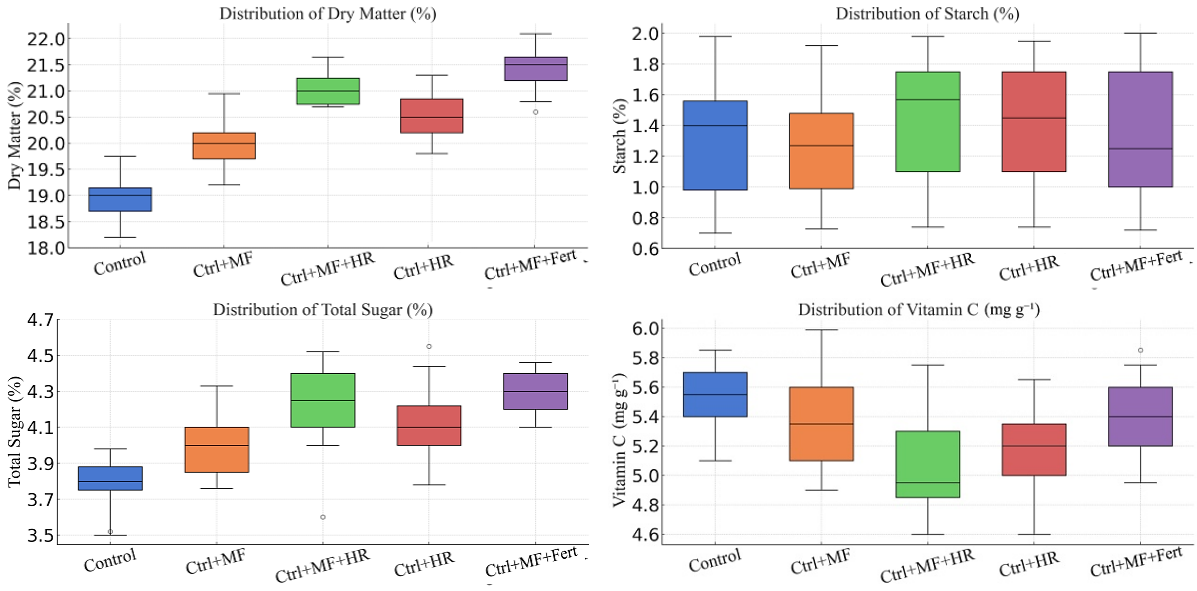


Figure 5
Effect of Biopreparations on Key Quality Parameters of Jerusalem Artichoke



Vitamin C trends varied between crops. In the sweet potato, the control retained the highest ascorbic acid content, while biopreparation-treated plots showed a modest decline. This may indicate a physiological shift towards increased carbohydrate biosynthesis at the expense of antioxidant accumulation, as also observed by (Antonious, 2024). In contrast, Jerusalem artichoke vitamin C content improved in the Ctrl+MF+Fert and Ctrl+MF+HR treatments, suggesting that foliar nutrient application may alleviate oxidative stress and promote antioxidant metabolism consistent with outcomes seen in organically grown root crops (Romanowska-Duda et al.,

2020). Statistical analysis confirmed strong treatment effects ($p < 0.05$) on yield, dry matter, total sugar, and vitamin C content, highlighting the synergistic potential of microbial inoculants and humic stimulants. The role of Mykofriend containing arbuscular mycorrhizal fungi, *Trichoderma harzianum*, and beneficial rhizobacteria in supporting root growth and nutrient uptake appears central to these results, especially when combined with Humifriend and Help-Rost (Breza-Boruta & Bauza-Kaszewska, 2023; Nakielska et al., 2024).

These synergistic effects are echoed in the work of (Romanowska-Duda et al., 2023), who demonstrated that integrating digestate and ash with biopreparations enhanced yield and physiological performance in sorghum. A similar mechanism may explain the high performance of Jerusalem artichoke in our Ctrl+MF+HR variant, where repeated foliar sprays sustained metabolic activity during tuber formation. The pathogen-suppressive and stress-mitigating properties of microbial consortia, as shown in strawberries (Nakielska et al., 2024), may also explain the improved stability and quality observed in treated plots. Starch content in Jerusalem artichoke remained statistically unchanged across treatments ($p > 0.05$), in line with earlier findings by Yang et al., 2022, who indicated that starch and inulin profiles are more sensitive to harvest timing and environmental factors than to fertilizer treatments. Our data reflects this, showing increases in sugar content without proportional gains in starch. Yield variability observed in Figure 3 indicates that Jerusalem artichoke responded more strongly to environmental modifications induced by biopreparations than the sweet potato. This may be due to the greater adaptive plasticity of *H. tuberosus*, as suggested by Anwar et al. (2020), who reported that compost application and canopy management significantly influenced yield and biochemical composition.

While our findings confirm the agronomic benefits of microbial and humic formulations, they also highlight areas for further research. The physiological basis for the observed reduction in vitamin C in sweet potato remains unclear and warrants investigation. Future work may employ chlorophyll fluorescence techniques as proposed by (Pszczółkowski et al., 2023) to non-invasively monitor photosynthetic performance and clarify plant responses to biopreparation treatments under field conditions.

Conclusions

1. The integrated application of biopreparations enhances crop yield and quality. The combined use of microbial inoculants (Mykofriend, Help-Rost) and humic substances (Humifriend) significantly improved the yield and nutritional quality of sweet potato (*Ipomoea batatas*) and Jerusalem artichoke (*Helianthus tuberosus*). Treatments such as Ctrl+Hum+HR and Ctrl+MF+HR demonstrated the highest efficacy, particularly in increasing dry matter, starch, and total sugar content. While vitamin C levels slightly declined in the sweet potato, they were maintained or increased in Jerusalem artichoke under fertigation regimes.
2. Statistical validation confirms the effectiveness of biological treatments. The observed differences in agronomic and quality parameters were statistically significant, supporting the efficacy of biopreparation-based fertilisation strategies. These treatments offer a sustainable alternative to conventional fertilisers, reducing dependence on synthetic agrochemicals while maintaining high productivity and crop value.
3. Future optimisation should focus on physiological mechanisms and monitoring tools. Further studies should explore the underlying physiological basis for changes in antioxidant content and assess the utility of chlorophyll fluorescence as a non-invasive tool for monitoring plant responses. The findings support broader adoption of biopreparation-based technologies in organic and low-input farming systems to improve soil health, enhance crop performance, and promote sustainable agricultural development.

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EUTROPHICATION OF STRENČU INLAND DUNE TRACT IN LATVIA

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Abstract
Climate change and humans affect changes in biotopes, which cause loss in habitat diversity. One of the factors that is considered vulnerable to biodiversity in Europe is eutrophication. It affects both aquatic and terrestrial habitats, by enriching them with nutrients, causing their flora and fauna to change. Eutrophication is usually detectable in places where nutrient poor habitats are slowly disappearing, for example, lichen rich pine forests that can be found in inland dunes. The aim of this study is to assess the impact of eutrophication on *Cladinoso–callunosa* and *Vacciniosa* forest type on flat terrain and on dunes. A total of 12 plots have been established, six in each forest type. Sample plots are square, sized 400 m^2 each. In all plots, the height and diameter of the growing trees were measured, and all plant species, the projective cover of moss, herbaceous, shrub and tree layer and individual species were recorded. In addition, four soil profiles were created and 21 soil samples were analysed. The hypothesis of the work is that the eutrophication of *Cladinoso–callunosa* is more rapid in flat and lower terrain than in dune tops. This study showed that terrain does not significantly affect tree heights and diameters, but it does affect the soil. The soil in dune tops is less acidic than in the plains. The effect of eutrophication is not noticeable in the *Cladinoso–callunosa* forests, but only in the *Vacciniosa* forests, where it is higher in the plains.
Keywords: eutrophication, inland dunes, *Cladinoso–callunosa*, *Vacciniosa*, soil.

Introduction

Latvia is located in the boreal biogeographic region, hemiboreal zone, which borders on the continental geobotanical region (Esseen et al., 1997; Cervellini et al., 2020). Boreal forests occupy about 29% of all forest areas and about a third of the world's timber exports are obtained from these forests (Kayes & Mallik, 2020). The dominant species are Scot's pine, Norway spruce, birches and aspen, but in total about 20 tree species grow in this region, which is less than in other biogeographic regions of Europe (Puumalainen et al., 2003; Kayes & Mallik, 2020). In the hemiboreal zone, the dominance of deciduous trees typical of the temperate zone is increasing in the Baltic States, but the amount of coniferous forests is decreasing (Jõgiste et al., 2018). Pine stands are decreasing most in Latvia. They are being replaced by birches; in some cases, it can be replaced also by spruce and other deciduous trees. In total, coniferous forests occupy about 45% of the forest area in Latvia (Laiviņš et al., 2021).

Pines can grow in poor soils where there is not much competition although they grow best in moderately rich forest types - *Myrtillosa*, *Hylocomiosa* (Dreimanis, 2016). Conifers, especially pines, are characterized by podzol sand soils, where the amount of nutrients depends on the fallen deadwood and plant litter, its composition and meteorological conditions. Podzols are acidic, poor-reaction soils, which are usually formed on carbonate-free sandy mother rocks (Kārkliņš, 2008). In the soil horizons, including fungi form organic acids that degrade minerals, except quartz, and leach clay particles and nutrients from the upper horizons, forming a grey low-fertility leaching horizon and a wash-in, or illuvial horizon, in which fulvic acids with iron, aluminium hydroxides can form a dense iron sedimented horizon layer. Coniferous soil is acidic and low in nutrients; therefore, some plants have adapted to fixing nitrogen, such as *Pleurozium schreberi* (Brid.) Mitt. and *Hylocomium splendens* (Hedw.) B., S. et G., which contain cyanobacteria capable of fixing atmospheric nitrogen (Stuiver et al., 2015).

Since the degradation of organic matter in boreal coniferous forests is slow, the fallen deadwood and plant litter layer is thick and interferes with the growth of seedlings, forest fires are necessary for the natural regeneration of forests (Kayes & Mallik, 2020). Due to proper forest management, the number of wildfires has decreased, but under the influence of climate change the number of wildfires may increase due to the increased amount of forest debris and higher temperatures (DeAngelis, 2008; Manton et al., 2022). After forest fires the amount of potassium and phosphorus increases in oligotrophic soils (Gilliam, 1991). In mesotrophic soils, after ground and surface fires soil fertility, species diversity and soil moisture increase (Laiviņš et al., 2019).

Cladinoso–callunosa is an oligotrophic dry site forest type that is rare in Latvia (Liepa et al., 2014). It occupies approximately 1% of all Latvian forests. In this forest type, the ground cover is dominated by small shrubs, mosses and lichens typical of boreal forests (Laiviņš, 1998) - more than 50 plant species (Liepa et al., 2014). In the forest stand, only pine is purposefully grown for forestry, and they form forest stands of quality class IV-V (Bušs, 1981). The average standing volume of *Cladinoso–callunosa* pine stands is 150 m^3 per 1 ha (National forest monitoring, 2018). Naturally *Cladinoso–callunosa* pine regenerates slowly, only 10% after final felling can regenerate within 10 years (Bušs, 1981); therefore, *Cladinoso–callunosa* is most often regenerated artificially – by seeding or planting (Dreimanis, 2016). *Cladinoso–callunosa* is a very poor mineral soil, formed by quartz sand (Bušs, 1981). The organic top layer of the soil is thin, approximately 1-3 cm thick (Liepa et al., 2014). In *Cladinoso–callunosa* podzol is formed - a soil type in which leaching of nutrients from the upper soil horizons is a distinct feature. As for oligotrophic soils, *Cladinoso–callunosa* nutrients penetrate the soil with

atmospheric precipitation (Liepa et al., 2014). In Latvia, *Cladinoso–callunosa* is most often found in dune landscapes and wind-borne sand dunes, with the largest areas occurring at the seaside (Bušs, 1981).

Vacciniosa is an oligomesotrophic dry forest type that occupies approximately 3% of Latvian forests (Liepa et al., 2014; National forest monitoring, 2018). More than 80 plant species are found in the *Vacciniosa* ground cover (Liepa et al., 2014). The forest stand is mainly composed of pine, which forms the stands of site index or site quality class III although low-value birch or spruce stands can also be formed (Bušs, 1981). The average standing volume is 200 m^3 per 1 ha (National forest monitoring, 2018). Understorey is rare, and it comprises spruce, birch, juniper and mountain ash (Liepa et al., 2014).

Vacciniosa soil is slightly more fertile than that of *Caldinoso-callunosa;* it is podzolized, with an approximately 4 cm thick organic top layer, most often sandy bedrock (Liepa et al., 2014). On slopes and in places with greater water inflow, soil horizons are more clearly distinguishable and deeper (Bušs, 1981). The soil is poor in minerals, an iron sedimentation horizon layer may form in it. *Vacciniosa* as well as *Cladinoso-callunosa* are found in dune areas and inland sand drifts (Bušs, 1981). In *Vacciniosa* a small overgrowth is formed after the final felling, which does not interfere with forest regeneration (Bušs, 1981). Forests are regenerated artificially by sowing pine seeds in furrows or planting two-year-old seedlings (Dreimanis, 2016).

Eutrophication is an increase in the biomass of living organisms and an increase in the intensity of biological processes caused by an increase of nutrients. As a result of climate change, the vegetation period increases, the amount of precipitation increases and growing conditions for some species improve and for some – worsen. Forest eutrophication is a process that occurs naturally very slowly, but it is accelerated by climate changes and anthropogenic factors. Under the influence of eutrophication and other factors, nutrient-poor forest areas in which stable stands of *Pinus sylvestris* are formed, decrease. They may become unstable, and an admixture of other less economically valuable trees and shrubs can form in those stands, which can overshadow and compete with the desired stands of *Pinus sylvestris.* When these stands become more fertile, the number of herbaceous plants increases, thus increasing competition (Laiviņš, 1998). The process of eutrophication also occurs in soils, where soils change from oligotrophic to mesotrophic. One of the forest types where the disappearance and replacement of characteristic ground vegetation species can be observed is *Cladinoso–callunosa*, which transforms into *Vacciniosa* in the process of eutrophication.

Nitrogen emissions are one of the major air pollutants affecting the eutrophication process (Bonten et al., 2016). In Europe, eutrophication is considered one of the most serious environmental threats. Although the areas affected by eutrophication are slowly declining, they still threaten a large number of Latvian ecosystems - about 85% compared to other European countries. Eutrophication processes and their development are clearly indicated on poor forest types, whereas proportion of these forest types have been decreasing in Latvia since 1940 (Laiviņš, 1998). Eutrophication of Latvian forest ecosystems is caused by an increase in the amount of atmospheric nitrogen in the soil and pollution, as a result of which the plant community typical of conifers is replaced by that of broad-leaves. This eutrophication is sometimes difficult to notice because plants that grow in nitrogen-rich soils cannot survive in drought (Reinecke et al., 2013). Forest eutrophication is positive if the purpose of forest cultivation is the introduction of new species or the cultivation of broad-leaved trees. As a result of human-influenced eutrophication, the change of tree species occurs in coniferous forests - hardwood species appear in the undergrowth or in birch or aspen stands start to appear instead of conifers. *Cladinoso–callunosa* and *Vacciniosa* birch admixture, which can occur due to eutrophication, reduces wood production. With each tenth of admixture, wood production decreases by approximately 7% (Bušs, 1981). The increase in nitrogen in the soil not only negatively affects the productivity of pine and other oligotrophic plant areas, but also increases the plant intolerance to various pathogens, causing additional stress (Lupi et al., 2013). By changing the plant composition of the ecosystem, eutrophication also changes the access to light and increases competition between plants, creating winner-plants that are more shade-tolerant, and loser-plants that are light tolerant species (Johnson et al., 2008). Although the replacement of coniferous forests by hardwood forests is predictable, the current speed of change is negatively affecting not only the productivity of forest stands, but also animal habitats and ecosystem services.

As nutrients in the soil increase, areas can become overgrown with shrubs and vascular plants, which interfere with the establishment of living spaces for partridges, capercaillie and other birds that require mosaic patches with open area (Smith et al., 1999). With the change in tree species, many birds find it difficult to establish nesting sites (DeAngelis, 2008).

One of the biotopes threatened by eutrophication and the biotic homogenization caused by it in Central Europe is lichen-rich pine forest, where lichens are replaced by mosses and small shrubs (Stefańska-Krzaczek, 2018).

Vegetation in forests is most affected by the amount of nitrogen in the soil, which is increased by the effects of eutrophication (Reinecke et al., 2013). An increase in the amount of nitrogen in the soil promotes graminification, which is the spread of grasses outside grasslands. *Dactylis glomerata* L., *Veronica chamaedrys* L. and *Artemisia vulgaris* L. can be used as indicator species for graminification (Laiviņš, 1998). Additional species observed in the studies on

the effects of nitrogen on vegetation are *Deschampsia flexuosa* (L.) Nees, less commonly *Chamaenerion angustifolium* (L.) Scop and *Rubus idaeus* L. (Van Dobben et al., 1999). In Central European forests, it has been observed that under the influence of increased amount of nitrogen forests are slowly changing their taxonomic group from less to more fertile. In particular, the replacement of lichen-rich oligotrophic forests by mesotrophic forests has been observed (Reinecke et al., 2013). This indicates a possible replacement of *Cladinoso-callunosa* by *Vacciniosa*, and replacement of *Vacciniosa* by *Myrtillosa*, thus reducing the vegetation characteristic of *Cladinoso-callunosa* and increasing the vegetation of more fertile forest types in forest stands.

In peri-urban forests, eutrophication, due to pollution, is visible not only in the ground cover, but also in the undergrowth (Laiviņš et al., 2021). In coniferous forests, the presence of *Acer platanoides* L. and other deciduous trees in the undergrowth is observed (Laiviņš et al., 2021). In addition, due to the succession of the undergrowth and ground cover, forests become wetter and darker or shadier, which reduces the number of sun-loving species in the ground cover (Laiviņš, 1998). Lichens suffer the most from the increased amount of shade, they are replaced by mosses, small shrubs and grasses (Van Dobben et al, 1999; Stefańska-Krzaczek et al., 2018). In urban forests, ground cover species such as *Impatiens parviflora* DC., *Chelidonium majus* L., *Stellaria media* (L.) Vill., *Urtica dioica* L., *Geum urbanum* L., *Plantago major* L., *Artemisia campestris* L. and *Berteroa incana* (L.) DC. may be used as eutrophication indicator species in pine forests (Laiviņš, 1998). Eutrophication also has a positive effect on the spread of invasive species, especially in peri-urban forests. The impact of eutrophication on invasive species in Latvia has not been directly studied, but it has been observed that unstable ground cover plant communities, where invasive species can be introduced, are usually peri-urban forests (Laiviņš, 1998).

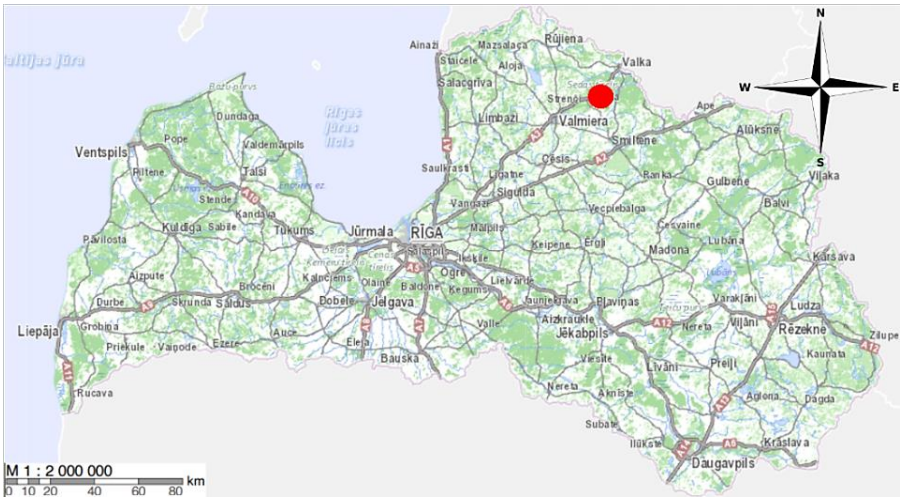
Vegetation succession caused by eutrophication occurs slowly but at a noticeable rate. In Germany, the studies on the eutrophication of oligotrophic forests found that over a 45-year period, most of the studied areas had faced a complete or partial vegetation replacement, thus locally increasing the number of species in ground but decreasing them regionally (Reinecke et al., 2013). Although eutrophication most often has irreversible effects on vegetation, in some places the decrease of vegetation replacement is possible as forest stands grow. A decrease in grasses was observed in mature pine forests in Sweden, but this did not change the irreversible effects on lichens (Jonsson, 2021). Under the influence of eutrophication, light demanding species and oligotrophic species disappear, shade-tolerant and nitrogen demanding species appear, and the areas in which oligotrophic species can survive are reduced, thus reducing the diversity of regional species and creating biotic homogenization (Reinecke et al., 2013). The aim of the study was to compare the impact of eutrophication on vegetation and soils on different microrelief, specifically, on dune tops and on plain sites of *Cladinoso-callunosa* and *Vaccinios* forests.

Materials and Methods

The territory of the research is the Strenči area of dunes, located in Valmiera region, where the dominant forest types are *Cladinoso-callunosa* and *Vacciniosa*. The forests there are located in the Seda plain, approximately 60-65 meters above sea level, in a place where inland dunes have formed. The average air temperature in Valmiera region is + 6.5 °C, the average temperature in July, the warmest month, is +17.8°C, but in February, the coldest month, -3.9 °C. The total amount of precipitation on average is 685.5 mm. The duration of the vegetation period is 192 days ‘Figure 1’.

Figure1

Location of the research site



12 square sample plots measuring 20 x 20 meters were established. The sample plots were located in the 70-year-old *Cadinoso-callunosa* and *Vacciniosa* forest stands in the inland dune area - three and three on the dune tops and three and three on plains, respectively. In each plot, all growing trees were listed and their species determined. The diameter of the trees was measured with a calliper at a height of 1.3 meters from the root collar or at breast height, with an accuracy of ±0.1 cm. A Suunto altimeter was used to measure the height of the trees, with an accuracy of ±0.1 m. All species were determined in the sample plots. The projective covers of each vegetation layer and each separate species, except for lichen and moss species, were estimated by sight and recorded in percentages. Four vegetation layers were used: E3 - tree layer, which includes all woody plants taller than 7 m, E2 - shrub layer, which consists of shrubs and trees 0.5-7 m high, E1 – herbaceous plant layer, which includes herbaceous plants, small shrubs and young woody plants not exceeding 0.5 m, and E0 – moss and lichen layer (Mueller-Dombois & Ellenberg, 1974).

In addition, soil profiles were created in four sample plots – respectively on the *Cladinoso-callunosa* dune tops and plain and also the same for *Vacciniosa* forests. Descriptions were created for the soil profiles. Soil analysis was performed to study the soil. A potentiometer was used to determine soil reaction or active and exchange acidity. Based on the results obtained, it was determined which soil group each soil sample corresponds to. The content of organic substances for the soil horizons was determined using the ashing method. Hydrolytic acidity, the amount of potassium and phosphorus in the soil and the aluminum concentration were calculated (Kārkliņš, 2008).

For each plot the average tree diameter, average tree basal area, volume, growing stock and number of trees per ha were calculated using generally accepted formulas in forest inventory.

To compare the calculated and measured values of the *Cladinoso-callunosa* and *Vacciniosa* hills and plains, a one-way ANOVA with a 95% confidence level or significance level $\alpha = 0.05$ was used.

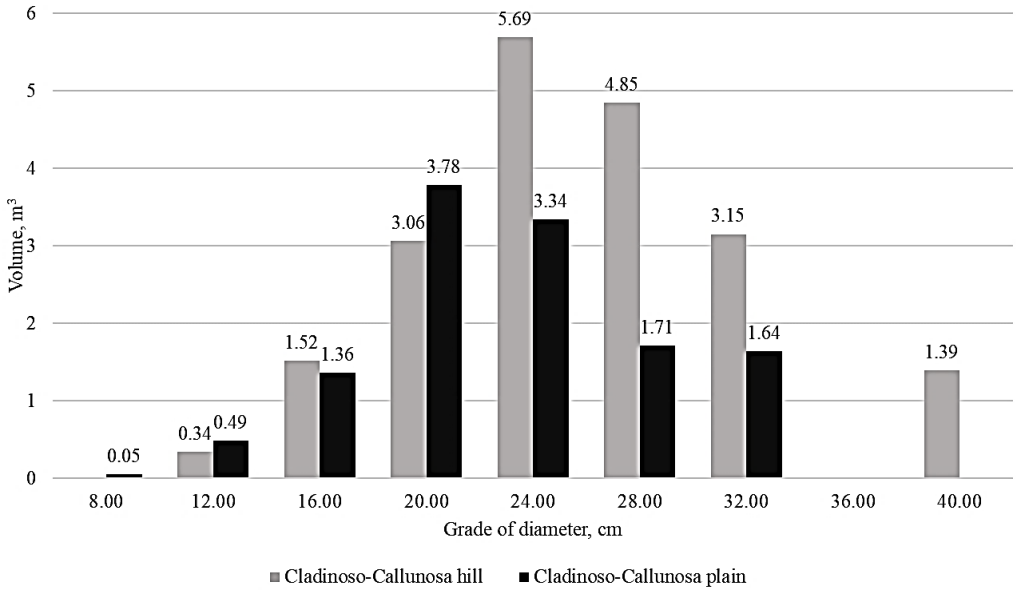
Results and Discussion

Growing trees. In total, 53 trees were measured in the plots of *Cladinoso-Callunosa* dune tops, of which 52 are *Pinus sylvestris*. The average diameter of trees on *Cladinoso-Callunosa* dunes is 21.72 cm, the diameter in the sample plots varies from 10 to 39.4 cm. Most trees correspond to the diameter grade of 24 cm. This diameter grade also has the largest standing volume, which can be observed in ‘Figure 2’.

The average diameter corresponds to the site quality class IV, which is 20.9 m. The average height is 18.35 m. In the sample plots, the heights vary from 12 to 25 m.

Figure 2

Distribution of the volume by diameter grades in the hills and plains of Cladinoso-Callunosa forests



Comparing the average height to the average height of 61-70-year- old *Pinus sylvestris* which is 21.73 m, it is much smaller, but comparing it to the average height of the pines on the first layer according to the site quality classes, it can be observed that such a height corresponds to the stands of the site quality class III, where the average height is 16.74 m. The height of the trees is definitely affected by both site quality class and age (National forest monitoring, 2018). The average standing volume per hectare is 160.3 m^3. The obtained volume per ha is similar to the one obtained by the National Forest Monitoring cycle III, where the average standing volume per ha in *Cladinoso-Callunosa* is 158 m^3 ha^{-1} (National forest monitoring, 2018). The average number of trees per hectare in these sample plots is 441.

A total of 41 trees were measured in the sample plots of *Cladinoso-Callunosa* plain, and all of these trees are *Pinus sylvestris*. The average diameter in the sample plots is 19.75 cm, the diameter there varying from 9.9 to 32.8 cm, and most trees are in the 20 cm diameter grade. The average diameter is slightly smaller than the average diameter of *Pinus sylvestris* of the site quality class IV obtained by the National Forest Monitoring - 20.9 cm, but much larger than the average diameter of that of *Pinus sylvestris* of the site quality V, which is 17.39 cm. The average height is 18.69 m. In the sample plots, the height varies from 12 to 22.1 m. Unlike the height on the *Cladinoso-Callunosa* hill, this height corresponds to the 61-70-year-old *Pinus sylvestris* of the first layer, whose average height is 21.73 m. The average standing volume per hectare is 98 m^3, which is much less than that obtained on the hills and by the National Forest Monitoring, and the number of trees per hectare is 341 (National forest monitoring, 2018).

Comparing the *Cladinoso-Callunosa* hill and plain, it can be observed that although the average diameter is larger on the hills than on the plains, when checking these values by univariate analysis of variance, it can be found that the differences are not significant at 95% confidence level ($p=0.109>0.05$). No significant differences exist in heights between the sample plots ($p=0.514>0.05$). The greatest difference is observed in the standing volume and the number of trees. On the plains the standing volume is by 62 $m^3 ha^{-1}$ smaller than in the hills, but when checking the data of the sample plots with univariate variance analysis, at 95% confidence level, no significant differences are found ($p=0.426>0.05$). This difference is most likely affected by the small number of trees in some sample plots. It can be concluded that no significant differences have been found between *Cladinoso-Callunosa* hills and plains regarding the parameters of forest stand and growing trees.

In the sample plots of *Vacciniosa* hill forests, 58 trees are listed, three of which are *Betula pendula* and 55 – *Pinus sylvestris*. In all sample plots, the forest stand is divided into two layers. In the sample plots, the diameter varies from 8.4 to 39.9 cm, but the average diameter is 22.11 cm, which is a little smaller than the average diameter of the pines. *Pinus sylvestris* of the site quality class III of the National Forest Monitoring obtained in the III rd cycle, which is 22.58 cm, but larger than that of the site class IV class pines - 20.9 cm (National forest monitoring, 2018). Most trees are in the 24 cm diameter grade - with a diameter from 22 to 25.9 cm respectively. On the hills, the 24 cm diameter grade accounts for the largest standing volume. The height, which varies from 11 to 31 m, is 19.53 m on average, which is less than the national average height of 61-70-year-old Ist layer *Pinus sylvestris* (21.73 m), but it corresponds to the average height of the site quality class III pine stands (National forest monitoring, 2018). The standing volume for the first layer per hectare is 177.23 m^3, but for the second layer - 14.86 m^3. The total standing volume which is 192.09 $m^3 ha^{-1}$ is slightly less than 219.22, which is the average standing volume per hectare obtained in the III cycle by the National Forest Monitoring (National forest monitoring, 2018). The number of trees per ha is 457.

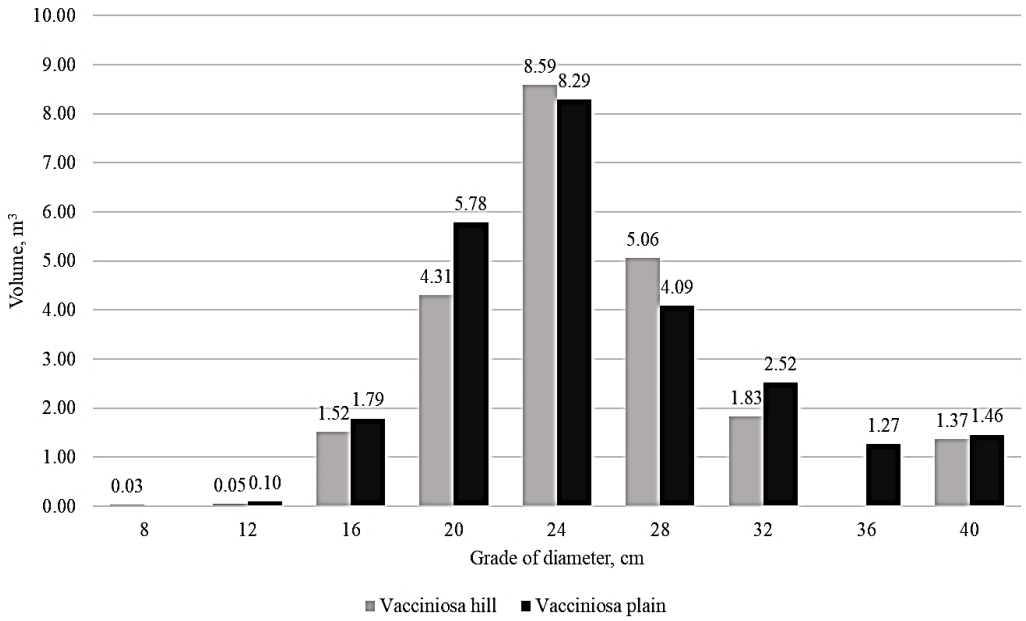
A total of 66 trees, all of which are *Pinus sylvestris*, were measured in the sample plots of the *Vaccinosa* forest plains. In all plots, trees are divided into two layers based on tree heights. The average diameter is 21.75 cm, and in the sample plots the diameter varies from 13.6 to 38 cm, but most trees are from 18 to 21.9 cm in diameter, which is the 20 cm diameter grade, but this diameter grade is not the one with the largest volume. The highest standing volume is for the 24 cm diameter grade. Comparing the obtained diameter, it can be concluded that this stand is most likely of the site quality class IV, since this diameter is the average between the average diameters of pines of the site quality class III and site quality class IV obtained by the National Forest Monitoring, respectively 22.58 cm and 20.9 cm 'Figure 3' (National forest monitoring, 2018).

The height varying from 13.2 to 32 m, is 19.46 m on average. The height is lower than that of 61-70-year-old pines of the first layer, which have an average height of 21.73 m, but higher than the average heights of the pines of the first layer of the site quality class III and IV, for the site quality class III - 16.74 m, for the site quality class IV - 14.81 m (National forest monitoring, 2018).

The standing volume per hectare for the first layer trees is 188.3 m^3 and for the second layer trees - 14.67 m^3. The total standing volume is 202.97 m^3 ha^{-1}, which, as on the *Vaccinosa* hills, is slightly less than the average in *Vaccinosa* plains - 219.22 m^3 ha^{-1} (National forest monitoring, 2018). On average, there are 550 trees per ha on the plains of *Vaccinosa*. Comparing the plain and the hill of *Vaccinosa*, no significant differences were found either in diameters ($p=0.702>0.05$) or in heights ($p=0.902>0.05$). There are no significant differences also between standing volume ($p=0.738>0.05$) and number of trees ($p=0.239>0.05$). There are no significant differences in the indices of inventory and growing trees between *Vaccinosa* hill and plain forests.

Comparing *Vacciniosa* with *Cladinoso-Callunosa*, there are significant differences in the diameters of the hills of *Vacciniosa* and *Cladinoso-Callunosa* ($p=0.034<0.05$), where the diameter in *Vacciniosa* is significantly larger than in *Cladinoso-Callunosa*, but there are no significant differences in tree heights on the hills ($p=0.14>0.05$). The opposite can be observed for the plains of *Cladinoso-Callunosa* and *Vacciniosa*: there are no significant differences in the diameters ($p=0.179>0.05$), but a significant difference has been found in the heights ($p=0.049<0.05$); the height of the trees growing on the plains of *Vacciniosa* is greater than that of the trees growing on the plains of *Cladinoso-Callunosa* forests. Judging by these data, it can be concluded that the location of the place in the relief does not significantly affect the course of tree growth and the parameters of forest stand inventory that is affected by the forest type and the factors related to it.

Figure 3
Distribution of the stock by diameter grades in the hills and plains of Vacciniosa



Soil characterization and analysis. Four soil profiles were established in the research area: on the hill of and on the plain of *Cladinoso-Callunosa* and on the hill of and on the plain of *Vacciniosa*.

A typical podzol was found on *Cladinoso-Callunosa* hill, according to the FAO soil classification - Dystric Arenosol. The soil profile created on *Cladinoso-Callunosa* plain was classified as ortstein podzol, according to the FAO soil classification - Albic Rustic Ortsteinic Podzol.

According to the soil classification, the profile created on *Vacciniosa* hill is an illuvial humus podzol or, according to the FAO soil classification Dystric Arenosol. According to the Latvian classification, the soil profile on *Vacciniosa* plain is peaty podzolic glayish soil, according to the FAO soil classification - Hemic Folic Histosol.

Comparing all soils, it was concluded that the most alkaline soil is on *Cladinoso-Callunosa* hill, where already at a depth of 50 cm the pH H_2O is approximately 6.7, which is close to neutral acidity. The most acidic soil is on *Vacciniosa* plain, where at a depth of 50 cm the pH H_2O is only 2.9, but higher up it is 2.475, which is the lowest pH of all the samples or horizons. The highest level of pH in *Cladinoso-Callunosa* could be due to human influence, since charcoal was found in the soils of *Cladinoso-Callunosa*, indicating burning. *Vacciniosa* hill has a more neutral soil than that of *Cladinoso-Callunosa* plain, but the differences are not significant. When testing pH H_2O with univariate analysis of variance, it was found that, at 95% confidence level, there are significant differences between the soils, which, upon additional testing, are formed exactly by *Vacciniosa* plain ($p=0.034<0.05$). There are also significant differences not only between the soil of *Vacciniosa* plain and other soils but also between pH KCl ($p=0.034<0.05$). Since both the exchange and active acidity in this profile are significantly lower, the hydrolytic acidity in the soil is also significantly higher. These differences could indicate that the site is not correctly assessed as *Vacciniosa*, but it should be separated and the forest type changed. All soils have very acidic upper horizons. Compared to the forest soil study conducted in 2012, where on average the pH H_2O in the horizons of the organic top layer of *Vacciniosa* and *Cladinoso-Callunosa* is from 3.6 to 4.2, they are more acidic, but in the lower layers they correspond to the study of 2012 (Kasparinskis, 2012). A potential cause of soil acidification is the increase in nitrogen concentration in the soil, which changes the vegetation. There is no significant difference for potassium concentration in soils at 95% confidence level. When comparing the concentration of phosphorus (V) oxide in the soil, it can be concluded that there are significant differences between the soil of *Vacciniosa* plain and the other soils ($p=0.007<0.05$). The soil of *Vacciniosa* plain contains significantly less phosphorus (V) oxide than the other soils, which means that *Vacciniosa* plain presumably contains smaller amount of nitrophilic plants, since nitrophilic species require sufficient amount of phosphorus to survive (Roth et al., 2021). The same is true regarding the concentration of aluminium in soils, but the concentration of aluminium on *Vacciniosa* plain is significantly higher than in other soils ($p=0.0005<0.05$).

Number of vegetation species. In total, 24 plant species have been determined in all 12 sample plots: two - in tree layer, four - in shrub, nine - in herbaceous plant and nine - in moss and lichen layers. Five species occur in all sample plots: *Pinus sylvestris*, *Calluna vulgaris* L.Hull, *Cladina arbuscula*, *Cladina rangiferina* and *Pleurozium schreberi*. About 50 plant species can be found in *Cladinoso-Callunosa* and about 80 species in *Vacciniosa*

(Liepa et al., 2014). On average, 13 plant species are registered in one sample plot. In all places, the number of species in the moss and lichen layer is the same, but the species differ slightly. The greatest number of species can be found on *Vacciniosa* plain, while the smallest is found on *Cladinoso-Callunosa* plain.

Projective cover of vegetation species. *Vacciniosa* plain has the largest projective covers of herbaceous plant and tree layers (Table 1). *Cladinoso-Callunosa* hill and *Vacciniosa* plain have the same projective cover of shrub layer - 4%, but in *Cladinoso-Callunosa* it is made up only of *Betula pendula*.

In *Vacciniosa* this cover is made up of five species. The largest projective cover of mosses and lichens occurs on the plain of *Cladinoso-Callunosa*, but the smallest on both reliefs of *Vacciniosa* forests. *Cladinoso-Callunosa* hill and plain have the same projective tree layer cover. *Pinus sylvestris* (mean projective cover 55%) and *Betula pendula* were found in the tree layer of *Cladinoso-Callunosa* hills.

Betula pendula also occurs in the shrub layer together with *Juniperus communis* L. *Calluna vulgaris* L., *Vaccinium vitis-idea* L. and *Vaccinium myrtillus* L. occur in the herbaceous layer.

Table 1

Projective coverage of vegetation layers, %

Layer	*C-C hill*	*C-C plain*	*V hill*	*V plain*
E3	55	55	69	74
E2	4	1	2	4
E1	40	48	32	73
E0	97	98	94	94

Abbreviations: *C-C – Cladinoso-Callunosa*; *V – Vacciniosa*.

On the plains of *Cladinoso-Callunosa*, only *Pinus sylvestris* has been found in the tree layer (mean projective cover 55%). On the plains of *Cladinoso-Callunosa*, no shrub layer has been found. *Calluna vulgaris*, *Vaccinium vitis-idea* and *Vaccinium myrtillus* occur in the herbaceous layer.

In the tree layer of *Vacciniosa* plain, the dominant tree is *Pinus sylvestris* (average projective cover 67%). The shrub layer includes *Juniperus communis* that has been found in all sample plots, *Betula pendula* and *Picea abies*. *Calluna vulgaris*, *Vaccinium vitis-idea*, *Vaccinium myrtillus*, *Festuca ovina* occur in the herbaceous layer. Only pines are listed in the tree layer of *Vacciniosa* plain (mean projective cover 74%). There are five species in the shrub layer with a very small projective cover - *Juniperus communis*, *Betula pendula*, *Picea abies*, *Frangula alnus* Mill. and *Salix cinerea* L. In the herbaceous plant layer, the largest projective covers are made by *Calluna vulgaris*, *Vaccinium vitis-idea*, *Vaccinium myrtillus*, *Festuca ovina* and *Deshampsia flexuosa*, *Ledum palustre* L. was also found.

All sites have approximately the same projective cover of the moss and lichen layer and the same number of species, only the species differ. In *Cladinoso-Callunosa* and on *Vacciniosa* hill, *Cetraria islandica* is found. *Polytrichum commune* is not found on *Cladinoso-Callunosa* hills, and *Polytrichum juniperinum* is found only on *Vacciniosa* plain.

When comparing the projective covers, it can be concluded that in the tree layer of both *Cladinoso-Callunosa* and *Vacciniosa* birch admixture is rarely found. It has been found only on hills. The largest projective cover of the shrub layer is on *Cladinoso-Callunosa* hill and on *Vacciniosa* plain, but on the plain of *Vacciniosa* this layer is made up of more species, some of which are not typical for *Vacciniosa*. On *Vacciniosa* plain, the projective cover of the herbaceous plant layer is considerably larger. The distinct dominance of the herbaceous plant layer is most likely the reason why *Cetraria islandica* (L.) Ach. was not found on the plain of *Vacciniosa*. In *Vacciniosa* - especially on *Vacciniosa* plain - the amount of lichens decreases, but the variety of mosses increases. Also, in Germany, the findings from studies on the succession of pine forests report about the replacement of lichens by herbaceous plants in oligotrophic forests (Reinecke et al., 2013).

The studies on the species occurrence ratio and the consistency classes show that there are species that often appear in the sample plots and are present in all the sample plots. More common species (groups V and IV) are typical of *Cladinoso-Callunosa* and *Vacciniosa*, whereas the species that occur more rarely are those which are not typical of *Vacciniosa* and *Cladinoso-Callunosa* (*Frangula alnus* is typical of *Myrtillosa* and *Salix cinerea* is more typical of wetter soils (Straupe & Indriksons, 2014). Another atypical species is *Ledum palustre*, which has been found in all *Vacciniosa* sample plots, but it typically grows in swampy areas (Straupe & Indriksons, 2014). By projective cover it is most often found just on *Vacciniosa* plain. In the areas which have been defined as *Vacciniosa*, the soil can be atypically peaty, with a thick top layer of peat, which is why *Ledum palustre* can be found there.

The following indicator species of graminification *Deshampsia flexuosa* was found both - on the hill and on the plain of *Vacciniosa*. Atypical species are found exactly in those sample plots which have lower lichen projective cover and number of species, indicating a possible increased amount of nitrogen in the soil, which can promote succession (Laiviņš et al., 2008; Reinecke et al., 2013). Since the occurrence of graminification indicator species is low, the process of graminification in *Cladinoso-Callunosa* is probably much slower than in *Vacciniosa*, regardless of the relief of the site. Other study in 1998 verified that in oligotrophic forests, the process of graminification is slower than in mesotrophic and eutrophic forests (Laiviņš, 1998) – thus, the process of graminification is slower in less fertile forests. Since the soil in *Cladinoso-Callunosa* and *Vacciniosa* is very acidic, many nitrophilous species are unable to establish in such soil and the increase in nitrogen in the soil is rather difficult to observe (Diekmann et al., 1999). The

increase in nitrogen concentration and acidity in dry and acidic soils is difficult to notice by using indicator species. It can be observed by studying changes in the distribution of plants of the genus *Vaccinium* (Diekmann et al., 1999). When studying the projection cover of forest atypical species and graminification indicator species, it can be concluded that succession is easier to observe, so the impact of eutrophication as well as the impact of people is the greatest on the *Vacciniosa* plains, but the impact of eutrophication is not observable in *Cladinoso-Callunosa*.

Conclusions

1. The relief does not significantly affect the height, diameter and standing volume of trees. Tree heights and diameters depend on the forest type. Tree diameters on *Vacciniosa* hills are significantly larger than on *Cladinoso-Callunosa* hills, but there are no differences between the heights. Tree heights are significantly greater on *Vacciniosa* plains than on *Cladinoso-Callunosa*, but there are no differences in tree diameters.
2. Forest soils differ in different reliefs; on hills the podzolization process is slower and no ortstein layer is formed, on plains the soil is more acidic than on hills.
3. A statistically significantly higher concentration of aluminium in the soil and lower concentration of P_2O_5 has been found on *Vacciniosa* plain than on *Vacciniosa* hill and in the soils of Cladinoso-Callunosa.
4. The peaty soil found on *Vacciniosa* plain and *Ledum palustre* growing in the sample plots of Vacciniosa indicate the possible water-logging of the soil.
5. When studying the differences in soil properties, it can be concluded that succession is influenced by the accumulation of organic substances and not by the increase in the concentration of nutrients in the soil. This fact is also confirmed by the low occurrence of graminification indicator species.
6. The impact of eutrophication has been more observed on *Vacciniosa* plain than on *Vacciniosa* hill or in *Cladinoso-Callunosa*. No impact of eutrophication was observed in *Cladinoso-Callunosa*. To observe eutrophication and succession of vegetation in *Cladinoso-Callunosa*, repeated larger-scale studies would be necessary.

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VARIATION IN STEM WOOD DENSITY OF JUVENILE *POPULUS SPP.* CLONES

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Abstract
Wood from *Populus spp.* has been widely utilized in Europe for years. Tree stem density is a crucial aspect of understanding wood quality and mechanical properties such as strength. Density patterns are influenced by the genetic traits of clones and environmental conditions. Stem density mostly tends to increase in the direction from the pith to the bark and decrease from the base toward the top. The research aimed to assess the wood density variations of various poplar clones. Empirical material was obtained from a 12-year-old *Populus spp.* plantation in the eastern part of Latvia. In the spring of 2024, 27 clones were analysed using one randomly chosen, healthy tree from each. The analysis involved measuring tree height and determining the variance of weighted stem density in both radial and longitudinal directions. In total, 881 specimens from crosscut discs were analysed. Despite the variation of mean weighted stem density among *Populus spp.* clones, ranging from 291 kg m^{-3} to 382 kg m^{-3} (mean 320.8 kg m^{-3}), no significant differences were found. While previous research has extensively examined variations in poplar wood density along the stem length, our findings indicate that the average density tends to increase towards the upper part of the stem. Although variation of mean wood density within tree stem relative heights is not statistically significant, there is a significant variation (p=0.03) of mean density at different distances from the pith (radial position). Our study shows that the wood density of poplar clones is highest near the pith, then gradually decreases before increasing again closer to the bark.
Keywords: *Populus spp.*, clones, weighted stem density, cross-cut discs, relative height.

Introduction

Sustainable forestry management practices, including short-rotation forestry (SRF), play a crucial role in carbon sequestration and biomass production, aligning with both environmental and economic objectives. Among the tree species utilized in SRF, poplar (*Populus spp.*) is recognized for its rapid growth cycle of 10 to 15 years, high productivity, and versatile wood applications, making it an attractive option for plantation forestry also in Latvia (Šēnhofa et al., 2019). Europe's only native poplar species, the black poplar (*Populus nigra*), has a wide distribution, stretching from the Mediterranean to approximately 64° north latitude, covering areas including Denmark and southern Sweden, but excluding the Baltic region (Vanden Broek, 2003). Although poplar is not indigenous to Latvia, forestry regulations permit its use in forest plantations, and it is currently being cultivated in SRF systems. The introduction of poplars in Latvia began in the early 20th century (Saliņš & Smilga, 1960). Experimental studies have demonstrated that various clones, derived from both European and North American species and their interspecific hybrids, exhibit significant economic potential in the region (Jansons et al., 2014; Adler et al., 2021).

Poplar wood is characterized by its lightness and moderate strength. It has excellent workability, making it suitable for veneer production and plywood manufacturing (Goli et al., 2014). However, its low durability requires treatment for outdoor applications (Md Rowson et al., 2021). Its fine grain and ability to take stains and finishes make poplar popular for furniture, cabinetry, and mouldings (Balatinecz et al., 2001). The high cellulose content and ease of pulping make poplar an essential resource for paper production and packaging materials (Boeva-Spiridonova et al., 2007).

Despite the fact that the main purpose of cultivating short-rotation poplar plantations is for biofuel production, this wood has potential applications in higher value-added products such as plywood, wood panel production, the furniture industry, and bio refineries. Therefore, it is very important to study not only the productivity and suitability of various poplar clones potentially grown in Latvia to local growing conditions but also the wood quality, which would allow evaluating the suitability of this wood for different applications.

The aim of this study is to evaluate the wood density of different poplar clones and the variation of stem-wood density in radial and axial directions. The results of the study will be used to make decisions about the suitability of different clones for various wood utilization purposes.

Materials and Methods

The study site is a poplar plantation located in eastern Latvia (56.716861, 27.681861), established in 2013 on former arable land with sandy loam soil. The plantation was designed as a randomized four-block experiment, consisting of 108 different *Populus spp.* clones, with five trees per clone in each block. The trees were planted in rows at a density of 3 × 3 meters using one-year-old containerized seedlings. Initially, the site was fenced, and ground cover vegetation was treated with herbicides. The soil was prepared through ploughing and continuous cultivation before planting.

In May 2024, when the plantation reached 12 years of age, 27 of the most productive clones were selected for further wood property analysis. Only healthy, undamaged trees (without stem or branching defects) were chosen as sample trees for felling. The study included four hybrid groups:

Populus deltoides×*P.trichocarpa* (DxT) – 'Belg-B10';

P.maximowiczii×*P.trichocarpa* (MxT) – 'Lisa (OP42)', 'OP24 (LG)';
Hybrids of *P. trichocarpa* from the Swedish University of Agricultural Sciences ($T \times T_{SLU}$) – 'SLU-15.8', 'SLU-1559', 'SLU-20.2', 'SLU-21.8', 'SLU-21.9', 'SLU-23.4', 'SLU-23.5', 'SLU-23.6', 'SLU-230', 'SLU-25.5', 'SLU-25.6', 'SLU-26.1', 'SLU-27.8', 'SLU-44.13', 'SLU-59.3', 'SLU-66.4', 'SLU-72.9', 'SLU-722.16';
Clones from natural *P.trichocarpa* populations (T) – 'SRF-2', 'SRF-20', 'SRF-21', 'SRF-45', 'SRF-47', 'SRF-68'.
Each tree stem was divided into sections of different lengths, starting from the base and extending toward the top of the tree. In total, 7 to 8 wooden discs were taken from each tree. The positions of the discs along the stem represented different height levels: 10%, 30%, 50%, 70%, and 90%, as well as at 0.2 m (stump height), 1 m, and 1.3 m above the root collar. All sawn discs were 2 to 3 cm thick. The sample discs were transported to LSFRI Silava for further basic density analysis.
The extraction of the wooden specimens necessary for the study was carried out according to methodology described in Liepiņš et al. (2018). Initially, each cross-sectional disc diameter was measured along two perpendicular directions (diameter with bark). This was followed by the preparation of specimens from cross-sectional wooden discs, as shown in Figure 1. The number of specimens obtained from a single disc depended on its radius. Each specimen had a width of 20 mm.
Not only wooden specimens but also bark specimens were obtained, with the last wooden specimen being debarked. If the last wooden segment was less than 5 mm wide, it was not separated as an individual specimen but combined with the previous one. If the diameter of the analysed cross-sectional disc was less than 2 cm, it was not divided into separate segments - only debarked (resulting in one wood and bark segment). If the cross-sectional diameter was less than 5 mm, the basic density analysis was conducted with the bark. All specimens were assigned an individual code, and it was crucial to avoid including knots and wood defects in them. In total, 668 wood and 213 bark specimens were obtained from 215 cross-cut discs.
Subsequently, all wooden specimens were immersed in water for 24 hours. This was followed by density measurements using Precisa XB 220A scales, equipped with a density measurement set (Precisa, Part No: 350–8556). The specimens were then oven-dried at 103–105 °C for a minimum of five days until a constant weight was reached to calculate basic density. The dry weight was measured immediately after removing the specimens from the oven.
The equation by Liepa (1996) was used to calculate the volume of each sample tree.
The basic density of the wooden specimens was determined by calculating the ratio of the specimen's dry mass to its green volume.

Figure 1
Preparation of basic density specimens from sample discs

The average density of each cross-sectional disc, based on the wooden and bark specimens and their corresponding areas on the cross-sectional disc, was calculated using equation (1):

$$\rho_{disc} = \frac{S_1 \times a_1 + S_2 \times a_2 + S_n \times a_n + S_b \times a_b}{a_1 + a_2 + a_n + a_b} \quad (1)$$

where ρ_{disc} is cross-sectional wooden disc average basic density, g cm^{-3}; S_1, S_2, S_n are wooden specimen basic density g cm^{-3}; S_b – bark specimen basic density g cm^{-3}; a_1, a_2, a_n is area occupied by wood specimen in a cross-sectional disc cm^2; a_b – area occupied by bark wood specimen in a cross-sectional disc cm^2.
The weighted average formula (Equation 2) was applied to determine the mean density of each sample disc with bark, based on the specimens and their respective areas. The weighted density values from the sample discs were used to illustrate the axial variation in stem density. The density of each stem section was averaged using the values from the cross-sectional discs at both ends of the section, except for the top segments, where the density of the base sample disc was utilized (Liepiņš et al., 2017).

$$Weighted\ Average\ Density = \frac{\sum_{i=1}^{n}(D_i \times V_i)}{\sum_{i=1}^{n} V_i} \quad (2)$$

where D_i – density of wood/bark specimens, g cm^{-3}; V_i – volume of stem section m^3; n – number of different specimens.
The volume of each stem segment (located between two sample discs) was calculated using Smalian's formula (Equation 3):

$$V_{si} = \frac{l_{si}(g_{1i} + g_{2i})}{2} \quad (3)$$

where V_{si} – volume of stem section, m^3; l_{si} – length of stem section i, cm; g_{1i} – lower surface's cross-sectional area of an ellipse of section i, mm^2; g_{2i} – upper surface's cross-sectional area of an ellipse of section i, mm^2; g – cross-sectional area of an ellipse, m^2.
The normality of the data distribution was tested using the Kolmogorov-Smirnov test, which confirmed that the dataset did not follow a normal distribution. Consequently, the Kruskal-Wallis test was employed

to determine statistically significant differences between the mean values.

Results and Discussion

This study examines the wood density of various poplar clones at a juvenile age (density data represented in 'Figure 2', with analysis conducted on a single tree per clone. The highest stem density was observed for 'SLU-26.1' - 382 kg m^{-3}, while the lowest was for 'Belg-B10' - 291 kg m^{-3}, indicating moderate variations among the studied clones. While the findings provide initial insights into clone-specific variations in wood density, the limited sample size presents significant constraints on data interpretation. The results may not fully capture intra-clonal variability, as factors such as environmental influences and growth conditions could lead to variations within the same clone (Pliura et al., 2007; Nielsen et al., 2014; Karacic et al., 2021). Additionally, analysing only one tree per clone restricts the ability to draw broader conclusions about the species or to establish statistically robust comparisons. There is a need for multiple density measurements due to significant within-stem variations in basic density based on measurement height and radial position.

The economic and technological feasibility of poplars largely depends on having a reliable feedstock supply and maintaining its quality characteristics. In Sweden, poplar feedstock is combined with other tree species during the pulping process, while its tops and branches serve as fuel in combined heat and power plants (Karacic et al., 2021). Heat and power plants have been promoted to use biomass as an energy source through lower taxes on biomass compared to fossil fuels. Along with the widespread use of firewood for household heating, woody biomass already plays a significant role in the Scandinavian energy sector (Nielsen et al., 2014).

Since the beginning of poplar plantation cultivation, these trees have primarily been used for producing wood for mechanical pulp and plywood. However, in recent years, their use in solid wood products has also been explored (Pliura et al., 2007). Fast-growing species like poplar are widely used for pulp production due to their high cellulose (>50%) and low lignin (<20%) content, ensuring a steady fibre supply for the pulp industry. Additionally, poplars require less bleaching due to their naturally light-coloured wood.

Wood density have outright impact on the fibre elasticity. The characteristics of pulp are closely linked to wood density. Low-density wood produces paper with high sheet density and strong tensile, bursting, and folding properties (Balatinecz & Kretschmann, 2001b; Yadav et al., 2022). In our study, 'Belg-B10', 'SLU-23.5', 'SLU-72.9' and 'Lisa', 'OP42' exhibited lower densities (291, 296, 298, 302 and 303 kg m^{-3}, respectively), making them potentially more suitable for paper and pulp production. In contrast, kraft pulp, used for making strong cardboards and paper, can benefit from higher-density raw material. Adler et al. (2022) highlight the potential for poplar biomass cultivation on marginal lands for the production of biomaterials and biofuels. Poplar wood is also a sustainable raw material for producing cellulose fibres, such as viscose, which is used in textile manufacturing. Fibre production from poplar in Northern Europe could replace 42% of global cotton production while also contributing 5.2 million m^2 of biofuel annually.

Mean density of poplar wood varies widely between clones. While some have low density of around 300 kg m^{-3}, others can reach even 600 kg m^{-3} (Balatinecz et al., 2014). Poplar wood stiffness and bending strength can be compared to species like pine and spruce (Balatinecz & Kretschmann, 2001b). For plywood and veneer production, poplar clones with density of at least 300 kg m^{-3} should be selected (Balatinecz et al., 2014). In the current study, almost all clones met this requirement. However, the following clones exhibited higher density values: 'SLU-26.1', 'SLU-21.9', 'SLU-21.8', 'SLU-1559', with densities, 382, 363, 348, 347 kg m^{-3}, respectively. These characteristics make them more suitable for applications in furniture, construction, and bioenergy.

In Latvia, one of successfully used poplar clones for bioenergy is *P.maximowiczii* × *trichocarpa* known as 'OP42' (*Populus trichocarpa* × *Populus maximowiczii*). Its propagation does not require royalty payments, and it demonstrates promising biomass growth increments under short-rotation forestry management, which maintains high interest in this clone. Liziniewicz (2023) reports that the wood density of 'OP42' clone is around 354 kg m^{-3}, while in our research it was lower – 303 kg m^{-3} ('OP42'), 302 kg m^{-3} ('Lisa').

The mean weighted stem density among different origin groups varies from 270 to 340 kg m^{-3} Figure 3.

The highest mean weighted stem density was observed for TxT group (hybrids of *P.trichocarpa* from Swedish University of Agricultural Sciences) – 325 kg m^{-3}, followed by T group (clones from individuals from natural *P.trichocarpa* populations) – 319 kg m^{-3}, the MxT group (*P.maximowiczii x P.trichocarpa*) – 302 kg m^{-3} and the DxT (*P.deltoides x P.trichocarpa*) - 291 kg m^{-3}. TxT and T groups have the highest stem densities, suggesting that these origin groups produce denser wood. There are no significant differences between the mean densities of different origin groups ($p>0.05$).

Nielsen et al. (2014) reported a high mean stem density of 365 kg m^{-3} for the *P. trichocarpa* x *P. deltoides* origin group in 13-year-old poplar clones. In our study, this specific group was the least represented, with only one clone ('Belg-B10'), which had a weighted stem density of 291 kg m^{-3}.

To improve data interpretation, additional data is needed - either more clones from this origin group or more investigated trees from the 'Belg-B10' clone.

The variation in wood density along the height of the tree must be considered when selecting parts of the tree for different applications.

Figure 2
Weighted stem density of analysed 27 Populus spp. clones (Horizontal line represents mean stem density of all analysed clones)

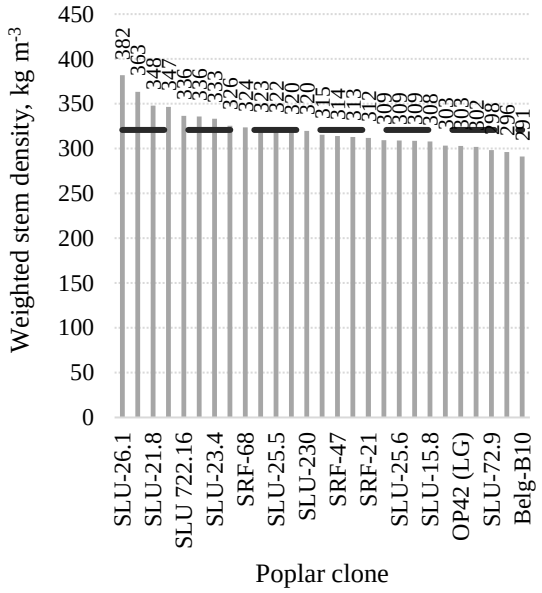
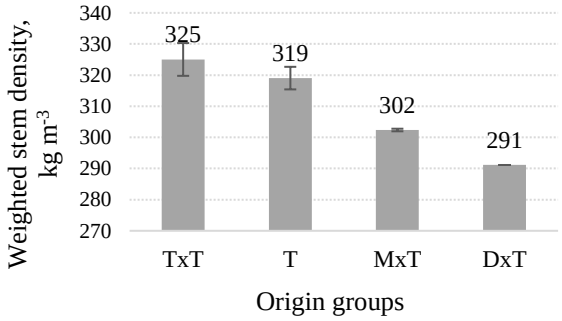


Figure 3
Weighted stem density by origin groups of analysed Populus spp. clones (Whiskers denote ± standard deviation intervals)



The highest density is found at the top of the tree, or 90% height level, 338 kg m^{-3}, while the lowest density occurs in the lower-mid section, or at the 10% and 30% height levels, 316 kg m^{-3} (Figure 4). Although the variation in mean wood density across relative stem heights is not statistically significant ($p>0.05$), a significant variation ($p=0.03$) in mean density was found at different distances from the pith (within tne radial position).

This confirms that wood density increases toward the top. The upper parts of the tree are typically exposed to stronger winds and environmental stresses, which may influence their structure, making them denser in some tree species to withstand these forces. Although the variation in mean wood density across relative stem heights is not statistically significant ($p>0.05$), a significant variation ($p=0.03$) in mean density was found at different distances from the pith (within the radial position).

Figure 4
Wood density at six relative heights and at stump height (Whiskers denote ± standard deviation intervals. Horizontal line represents the estimated mean of wood density in the entire stem)

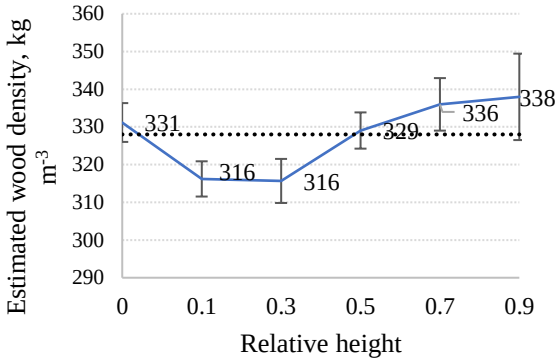
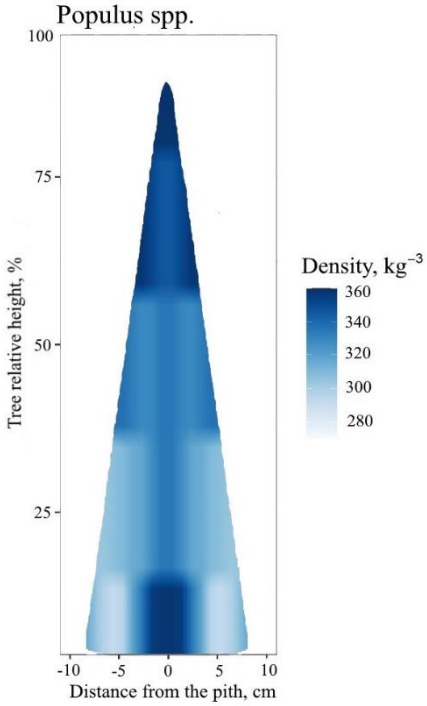


Figure 5
Variation in stemwood density of Populus spp



Ištok et al. (2016) and Kord et al. (2010) report that poplar tree density tends to decrease from the base upwards the stem, and increase from the pith toward the bark. This statement is partially contradictory to the results of the current study. Higher wood density was found in the upper part of poplar trees and at the pith of the stem base, similar to the findings of Pliura et al. (2007) and Taeroe et al. (2015).

A radial density pattern was observed at the stem base level - density decreased from the pith to the bark. However, from the middle of the tree to the top, wood density decreased in the opposite direction, from bark to pith Figure 5. Nevertheless, our study's findings on radial density variations align with Einspahr et al. (1972), who reported that *P. tremuloides* wood density is highest near the pith, followed by a slight decrease before increasing again closer to the bark. Kord et al.

(2010) also noted that wood density may increase from the pith to the bark as the tree ages, since juvenile wood typically has a lower density than mature wood. A similar tendency is described for axial variation. Wood density varies not only within the tree stem but also due to multiple factors, including tree age, growing density, environmental conditions such as precipitation, temperature. Petráš et al. (2010) confirms that poplar wood density increases with tree age.

For the trees we measured, the stem diameter at breast height (DBH) ranged from 8.6 to 20.3 cm (mean 13.9 cm), while tree height varied from 13.3 to 19.6 m (mean 16.7 m). Tree volume ranged from 0.04 to 0.31 m^3 (mean 0.13 m^3). Liziniewicz (2023) describes a low correlation between diameter and wood density in hybrid aspen and poplars. Similarly, in our study, the correlation between DBH, tree height and wood density was very weak and statistically insignificant.

Conclusions

1. The highest density was recorded for 'SLU-26.1' (382 kg m^{-3}), and the lowest for 'Belg-B10' (291 kg m^{-3}). However, analysing only one tree per clone limits the ability to fully capture intra-clonal variability. Clones with lower density, such as 'Belg-B10' and 'OP42', may be preferable for pulp and paper production due to their impact on fibre elasticity. Meanwhile, higher-density clones like 'SLU-26.1' and 'SLU-21.9' are more suitable for plywood, veneer and solid wood products.

2. Our study reveals that the wood density of poplar clones is highest near the pith, then slightly decreases before increasing again closer to the bark. Despite extensive prior research on poplar wood density variation along the stem, our findings indicate that mean density increases toward the top of the tree. As density variation increases with tree age, it is important to analyse stands of different ages in the future studies and expand the sample size to improve data accuracy.

Acknowledgements

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THE IMPACT OF STORAGE DURATION ON CHANGES IN THE QUALITY OF ENERGY WOOD IN LATVIA

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Abstract
Energy wood is a key component of Latvia's renewable energy sector, contributing 76.2% of total renewable energy consumption in 2023. Although energy wood is harvested year-round, its demand and quality vary seasonally, influenced by storage duration, weather conditions, and storage practices. This study aimed to assess how storage duration and weather conditions impact the quality and value of energy wood stored in windrows. To achieve this, 10 deciduous stands managed by JSC 'Latvia's State Forests' (LVM) were selected. Ten windrows of energy wood were created for long-term storage. Monthly laboratory analyses were conducted on wood samples from the windrows and during chipping to measure moisture and ash content, and calorific value. The findings reveal notable seasonal fluctuations in the relative moisture content of energy wood, driven by meteorological conditions. Intensive drying during spring and summer reduced the average moisture content from 39.58% in spring to 33.57% in summer. Conversely, autumn and winter showed an increase in moisture content, rising from 42.20% in autumn to 49.52% in winter. The study also confirmed that the net calorific value of energy wood improves as its moisture content decreases. These findings emphasize the importance of selecting optimal storage locations and planning appropriate drying durations to maximize the energy efficiency of energy wood. By addressing moisture content monitoring and storage challenges, Latvia can further enhance the sustainability and efficiency of its energy wood production processes.
Keywords: energy wood, moisture content, ash content, calorific value, windrows.

Introduction

Energy wood is primarily sourced from less productive trees, undergrowth, and logging residues (Lazdāns et al., 2008a; Lazdiņš, 2012; IRENA, 2018). Its efficiency is influenced by quality factors such as moisture content, calorific value, and ash content, which change during storage (Pettersson & Nordfjell, 2007; Routa et al., 2016). Moisture content, the key determinant of quality, affects calorific value, storage duration, and transportation costs. Freshly prepared energy wood typically contains 50-60% moisture, decreasing to 20-30% in warm seasons but rising again in autumn and winter due to hygroscopic properties (Gautam et al., 2012; Routa et al., 2015, 2016; Eliasson et al., 2019). Optimizing drying and minimizing reabsorption are essential for maintaining quality (Routa et al., 2015, 2016). Ash content varies by tree species, site conditions, and age. Younger trees and hardwoods tend to have higher ash content, ranging from 1.0% to 3.0% (Thörnqvist, 1985; Pettersson & Nordfjell, 2007). Calorific value is also species-dependent, with softwood generally having higher energy content (Thörnqvist, 1985; Būmanis, 2008). In Latvia, energy wood production primarily involves logging residues and small-diameter wood from thinning and regeneration fellings (Iwarsson Wide et al., 2008; Lazdāns et al., 2008b; Kalēja et al., 2014). JSC 'Latvia's State Forests' (LVM) manages 50% of state-owned forests, promoting energy wood production to enhance energy independence. Given Latvia's climatic conditions, LVM has developed guidelines for optimal production and storage, including stacking logging residues along forest roads for efficient transport (Latvian State Forests, 2016, 2021). The LVM guidelines specify a maximum energy wood length of 4 m, with partial delimbing for easier chipping (Latvian State Forests, 2016). Storage occurs in three stages: initial piling in the felling area (1–6 months), roadside stacking with optional covering for conifer-rich wood (Latvian State Forests, 2021), and windrow storage (3–12 months) with at least three months in spring or summer to facilitate drying. The final step involves chipping and delivery to consumers. A key challenge remains the lack of systematic moisture content monitoring during storage. Addressing this requires predictive modelling based on empirical data on moisture content, ash content, and calorific value changes over time. This study aims to evaluate the impact of storage duration and weather conditions on energy wood quality.

Materials and Methods

To obtain the empirical data necessary for achieving the study aim, 10 stands were selected in areas managed by LVM, where overgrowth removal and energy wood preparation had been carried out. For the trials, deciduous stands were selected (with a conifer admixture not exceeding 20%) where the average diameter of dominant trees did not exceed 12 cm, or where thicker trees had been felled and removed either before or after the preparation of energy wood from small-diameter trees.

In planning the trial sites, areas were selected where storage yards could accommodate multiple energy wood piles, each containing 60–80 LV m³ (loose cubic meters) of deciduous energy wood. The piles were positioned to ensure similar exposure to the forest edge, prevailing winds, and terrain. According to guidelines developed by LVM (Latvian State Forests, 2021), the planned width of the unloading area was up to 5 m.

Harvesting was conducted in September 2021 using a mid-sized harvester, John Deere 1070D, equipped with a Bracke C16 harvesting head. At the trial sites, harvesting involved preparing whole, unbranched stems, with the option to cut the trunks into multiple

segments as needed. Energy wood was forwarded in September–October 2021 using a mid-sized forwarder, John Deere 1010D, equipped with Intermercato grapple scales XW 50 PS, immediately after material preparation.

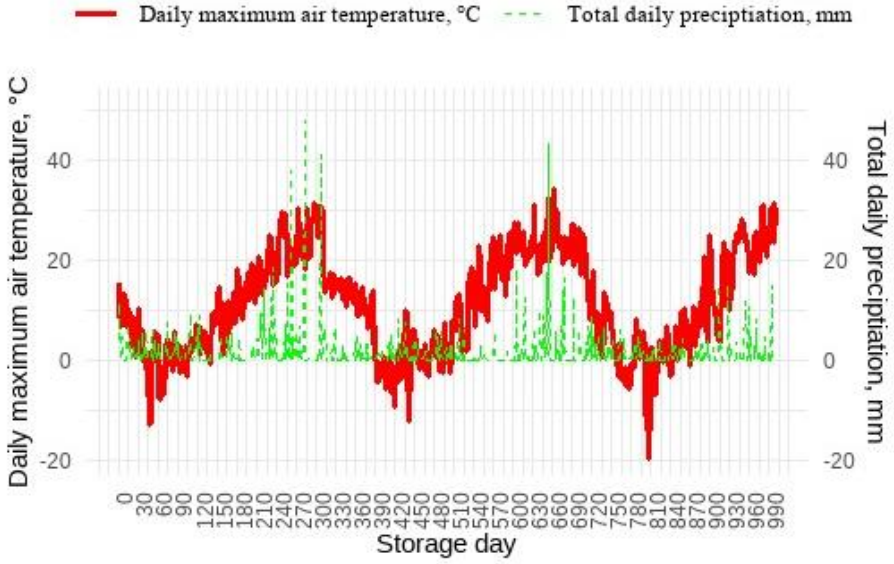
The trial design specified that the windrows of energy wood would have a maximum length of 18 m (with actual lengths ranging from 12 to 16 m), a maximum width of 8 m, and a maximum height of 4 m. In total, 10 windrows of energy wood (coordinates for windrows 1–5: 56.35184° N, 24.0751° E; coordinates for windrows 6–10: 56.36618° N, 24.05872° E) were created for long-term storage as part of the trial. To assess energy wood residues after chipping and enhance moisture control, the designated areas for energy wood stacks were covered with a paper-based laminate before the formation of windrows (Eliasson et al., 2019). The methodology involves chipping one pile every three months.

The storage period of energy wood was divided into three phases. The first phase began on the first day of storage (October 2021) and lasted for 343 days (until September 30, 2022). The second phase started on the 344th day of storage (October 1, 2022) and lasted for 364 days (until the 708th day of storage, September 30, 2023). The third storage phase began on the 709th day of storage and lasted for 297 days (until the 1006th day of storage, July 23, 2024).

Weather data 'Figure 1' were collected from the nearest meteorological station in Bauska (coordinates 56.3791° N, 24.2217° E), approximately 20 km from the trial site (LVĢMC, 2024).

Figure 1

Changes in daily maximum air temperatures and total precipitation during the storage of energy wood



To more accurately characterize the impact of meteorological conditions on changes in the quality of energy wood during storage, the Forest Fire Weather Index (FWI) system was utilized, which is widely applied for assessing forest fire risks (Van Wagner & Pickett, 1985; Miller, 2020). The FWI system relies on daily meteorological data (LVĢMC, 2024) including maximum daily air temperature (°C), minimum daily relative humidity (%), average daily wind speed (km h^{-1}), and total daily precipitation (mm). It models how weather conditions influence the moisture content of forest biomass and the potential for fire spread. To predict changes in the moisture content of energy wood, the components of the FWI system were calculated using Canadian FWI formulas (Van Wagner & Pickett, 1985; Miller, 2020). These formulas are used to compute the Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), and Drought Code (DC). A higher FFMC value, on a scale from 0 to 101 (representing very dry material), indicates lower moisture content in energy wood (Van Wagner & Pickett, 1985).

After the formation of the energy wood windrow, as well as during the survey and measurement of windrows, wood samples were collected from each windrow for laboratory analysis. Samples were taken from six locations: two at the ends, two from the top, and two from the front section of each windrow. The wood samples were collected to ensure representation of different wood diameter groups. Industrially processed chip samples were collected from multiple locations within the chip pile. The samples, primarily consisting of branches and a few stem sections, were processed using a gardening chipper. The resulting chips were thoroughly mixed, and a single sample was collected from each windrow. Moisture and ash content, as well as the calorific value, were determined in the laboratory for wood samples taken from energy wood windrows once a month and for samples collected during energy wood chipping.

The data from continuous measurements were prepared for analysis. As part of the study, ISO standard methods and CEN technical specifications adapted to Latvian standards were used in the laboratory to test wood samples obtained from energy wood windrows and crushed under laboratory conditions, as well as industrially crushed (chipped) wood samples. The LVS EN ISO 18134-2:2024 standard (LVS EN ISO 18134-2:2024, 2024) was used to determine the moisture content of the wood. Wood samples were dried using the oven dry method in the atmosphere at a temperature of 105 °C until a constant mass was reached, and the percentage moisture content was calculated based on the mass loss of the samples. The relative moisture content (W_0, %) of the wood samples was calculated using Equation 1.

$$W_0 = \frac{m_{moist} - m_{dry}}{m_{moist}} \times 100\% \quad (1)$$

where:
W_0 – relative moisture content of wood, %;
m_{moist} – weight of naturally moist wood, g;
m_{dry} – weight of dry matter, g.

The LVS EN ISO 18122:2022 standard (LVS EN ISO 18122:2022, 2022) was used to determine the ash content. Wood samples (air-dried ground wood materials) were ashed in a muffle furnace at a temperature of 550 °C, following the muffle furnace manufacturer instructions and pre-set programs. The ash content (P, %) of the analysed sample was calculated using Equation 2.

$$P_{\%} = \frac{a \times 100}{b} \times K_m \quad (2)$$

where:
a – mass of ashes, g;
b – weight of air-dry sample, g;
100 – conversion coefficient;
K_m – moisture coefficient.

The LVS EN ISO 18125:2017 specification (LVS EN ISO 18125:2017, 2017) was used to determine the gross calorific value (MJ kg^{-1}) of energy wood. The test samples were burned in a high-pressure constant volume oxygen bomb calorimeter. A system calibration procedure was performed before processing each sample to ensure the reliability of the results. The gross calorific value of the test sample was calculated by considering the calorific value of the calorimeter, determined during the calibration process, and the temperature change caused by the combustion of the test sample, including corrections for ignition energy, burner efficiency, and thermal by-products such as nitric acid and sulfuric acid. The PARR Instrument 6200 calorimeter used in the tests automatically calculates the gross calorific value (Equation 3), applying the correction factors specified by the equipment manufacturer to adjust the results.

$$H_c = \frac{WT - e_1 - e_2 - e_3}{m} \quad (3)$$

where:
H_c – gross calorific value, MJ kg^{-1};
T – observed temperature rise;
W – effective heat capacity of a calorimeter;
e_1 – heat of combustion of air in the combustion tank forming nitric acid;
e_2 – heat generated by the reaction of sulfur dioxide, water and nitrogen to form nitric acid;
e_3 – heat generated by the burner;
m – mass of the sample, g.

For statistical calculations, data analysis, and visualization, the R software was used. As the data follow normal distribution, one-way analysis of variance (One-way ANOVA) was applied to compare the mean values obtained in the calculations and to determine significant differences. Tukey's Honestly Significant Difference test (Tukey HSD) was used to identify which group means are statistically significantly different.

Results and Discussion

Moisture content

The energy wood was prepared in September 2021, with the first storage period beginning upon its delivery in October 2021. Data on the relative moisture content (MC) from 10 piles of energy wood indicate that the initial MC of the delivered material ranged from 41.1% to 50.2%.

Assessing changes in the relative MC of energy wood over storage seasons, the average relative MC increased during winter (December–February) compared to autumn (September–November) by 5.06% (1st storage period) to 8.55% (2nd storage period), depending on the storage period. During winter, the highest average relative MC (50.34±0.92%) was observed in the 1st storage period, while the lowest (48.55±2.74%) was recorded in the 2nd storage period.

In spring (March–May) and summer (June–August), the drying of the material becomes more intensive, significantly influenced by higher maximum daily air temperatures and lower total daily precipitation. Comparing the average relative MC recorded in spring to that in winter, the spring values were 8.84% (2nd storage period) to 10.09% (1st storage period) lower. During spring, the highest average relative MC (40.29±1.64%) was observed in the 1st storage period, while the lowest (38.75±0.38%) was recorded in the 3rd storage period.

As the drying process continues in summer, the average relative MC of energy wood further decreases. Comparing the winter values to those recorded in

summer, a reduction of 13.69% (1st storage period) to 17.24% (3rd storage period) was observed. During summer, the highest average relative MC (36.69±2.51%) was found in the 1st storage period, while the lowest (31.64±2.78%) was recorded in the 2nd storage period.

Compared to summer, the average moisture content in autumn increased by 8.36% (2nd storage period) to 8.90% (3rd storage period). During autumn (excluding the 1st storage period when the material was initially transported), the highest average relative moisture content (41.30±2.17%) was observed in the 3rd storage period, while the lowest (39.99±1.93%) was recorded in the 2nd storage period.

'Figure 2' reflects the changes in average relative MC of energy wood depending on the storage season, with quartile distribution used to characterize the data. From the presented data, it is evident that relative MC is highest during the winter season, with a median of 49.6%. The values are concentrated within the range of 49.1% to 50.0%, indicating low variability. In the summer season, MC is the lowest, with a median of 32.4% and a wider range of fluctuations (Q1–Q3: 32.0–34.5%), indicating greater variability. During the autumn season, relative MC is relatively high, with a median of 41.3%, and a greater spread in the data is observed (Q1–Q3: 40.6–43.3%). The spring season does not differ significantly, with a median of 39.7% and a small spread (Q1–Q3: 39.2–40.0%). The created diagram effectively illustrates the relative MC trends, variability, and central values for each season, which may be significant when selecting appropriate storage conditions for energy wood.

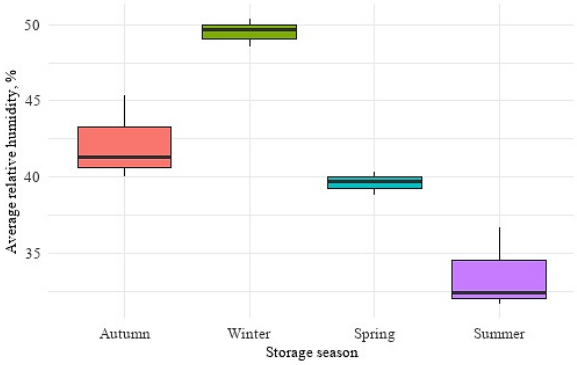
In deciduous stands, the average MC of energy wood prepared in September and stacked in fresh windrows in October was 47.29±1.37%.

To more precisely characterize changes in the relative MC of energy wood during storage, the FWI index 'Figure 3' was applied, incorporating meteorological observations for the respective period (LVĢMC, 2024) and data from the FWI system (Van Wagner & Pickett, 1985; Miller, 2020). The results show that during the 1st storage period, the average relative MC increased to 52.56% by the 101st storage day (January 2022), attributed to a low FWI index indicating unfavorable drying conditions. From the 102nd to the 190th storage day (February 2022), the MC decreased to 32.90%, driven by a rising FWI index, indicating favorable drying conditions starting in April (approximately six months after storage began).

Between the 191st and 251st storage days (May 2022), the MC increased to 42.16%, coinciding with a period of a relatively low FWI index. Subsequently, from the 252nd to the 313th storage day (July, August 2022), the MC decreased to 34.94%, explained by seasonal effects reflected in the FWI index. At the onset of autumn (314th storage day, September 2022), the MC increased again, reaching 37.54% by the end of the 1st storage period (343rd storage day, September 2022).

Figure 2

The seasonal variations of the average relative MC of energy wood during storage



At the start of the 2nd storage period, seasonal effects led to repeated moisture absorption, continuing until the 466th storage day (January 2023), with the moisture content reaching 53.1% due to a low FWI index. Between the 467th and 494th storage days (February 2023), the average MC decreased to 50.9% as the FWI index gradually increased. From the 526th to 647th storage days (April – July 2023), intense drying occurred, with the average MC dropping to 24.1%, explained by the high FWI index characteristic of summer. During the latter half of summer (647th–678th storage days, July, August 2023), the FWI index decreased, causing the MC to rise to 35.37%. At the end of the 2nd storage period (708th storage day, September 2023), the MC was 30.75%.

At the beginning of the 3rd storage period, the MC increased rapidly due to seasonal effects, reaching 54.5% by the 831st day (January, 2024). From the 832nd storage day (February, 2024), the moisture content began to decline, reaching 43.1% by the 921st day (April, 2024) and further decreasing to 28.9% by the 952nd storage day (May, 2024), driven by an increasing FWI index. From the 953rd storage day (Jun, 2024), the MC increased again, reaching 33.85% by the 1006th storage day (July, 2024).

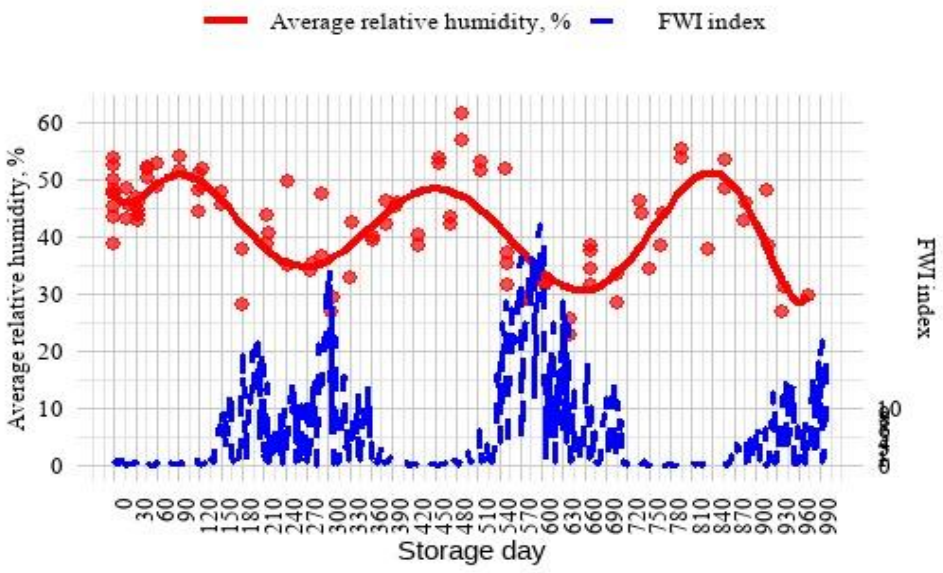
The drying process of energy wood intensifies in spring and summer due to higher temperatures, lower precipitation, solar radiation, and wind, accelerating water evaporation from wood fibers. Routa et al. (2016) noted that drier conditions in these seasons can reduce wood moisture content (MC) by 20–30%, especially in well-stacked, ventilated materials.

In summer, higher temperatures and lower humidity further increase evaporation, making it the most effective period for MC reduction (Pettersson & Nordfjell, 2007). Previous studies (Pettersson & Nordfjell, 2007; Gautam et al., 2012; Routa et al., 2016; Eliasson et al., 2019) confirm these trends, aligning with this study's findings.

Conversely, in autumn and winter, energy wood absorbs moisture due to its hygroscopic properties, increased humidity, and lower temperatures (Gautam et al., 2012). Afzal et al. (2010) explained that low

temperatures reduce evaporation, leading to moisture retention, increased weight, and lower net calorific value. Seasonal climatic variations significantly impact wood MC (Eliasson et al., 2019).

Figure 3
Changes in the average relative moisture content of energy wood during storage



Effective storage and drying planning are crucial for optimizing energy efficiency. Gautam et al. (2012) and Eliasson et al. (2019) highlighted that proper storage location and drying duration can enhance drying rates. The initial MC of freshly prepared energy wood varies by region and is influenced by stand location, species composition, and preparation time.

This study found an initial MC of 47.29±1.37%, similar to Canadian (45.5±5%) findings (Afzal et al., 2010) but differing from Swedish (Nilsson et al., 2013) data (25.6±4.3% to 43.8±6.5%) and Finnish (Nurmi, 1999) data (56%). Regional climate conditions during preparation and stacking significantly affect initial MC, with higher values observed in wetter climates (Afzal et al., 2010; Nilsson et al., 2013). Species composition also plays a role, as coniferous residues retain more moisture due to needle structure (Nurmi, 1999).

For a more accurate assessment of energy wood MC during storage, multiple influencing factors should be considered. The FWI index (Van Wagner & Pickett, 1985; Miller, 2020) used in this study helps evaluate drying dynamics under varying climatic conditions and the long-term impact on wood quality (LVĢMC, 2024).

Ash content

Changes in the ash content (AC) of energy wood during storage are presented in ‘Figure 4’ and can be attributed to changes in energy wood quality and the influence of the surrounding environment.

Overall, the ash content (AC) of energy wood during storage is variable, with observed fluctuations in AC throughout the material improvement process ranging from approximately 1% to 2%. Although differences in AC of energy wood during storage exist, they are not statistically significant.

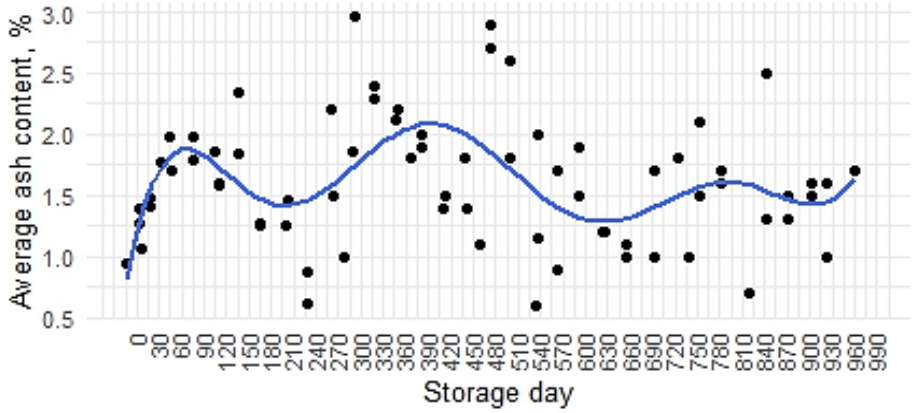
The obtained results show that the average AC of freshly prepared deciduous energy wood is 0.97%. Following the transportation of the material, an increase in ash content is observed by the 160th storage day (March 2022), reaching an average of 2.10%. The intensive drying of energy wood affects its quality, resulting in a decrease in average AC from the 161st storage day (April 2022), reaching an average of 0.75% by the 251st storage day (June 2022). An increase in the average AC of energy wood is observed again starting from the 252nd storage day (July 2022), and by the end of the first storage period (343rd storage day, September 2022), the average AC reaches 2.35%.

The second storage period begins with a gradual decrease in AC, reaching an average of 1.45% by the 435th storage day (December 2022). A repeated increase in AC is observed starting from the 436th storage day (January 2023), reaching an average AC of 2.20% by the 525th storage day (March 2023). This corresponds to the trends observed in AC changes during the first storage period (an increase in AC from January to March). Starting from the 526th storage day (April 2023), the average AC of the material ranged from 1.07% to 1.70%, and by the end of the second storage period (708th storage day, September 2023), the average AC was approximately 1.35%.

Overall, during the third storage period, the average AC of energy wood ranged from 1.20% (983rd–1006th storage day, July 2024) to 1.80% (709th–739th storage day, October 2023).

The study found that the average ash content (AC) of deciduous energy wood ranged from 1.48±0.54% to 1.58±0.57% across three storage periods, consistent with previous research (Thörnqvist, 1985; Pettersson & Nordfjell, 2007), which attributes higher AC in deciduous wood to its greater bark content.

Figure 4
Changes in the average AC of energy wood during storage



No significant AC changes were observed over 1,006 days, though the highest AC appeared in the second storage period, similar to findings from Sweden and Canada (Pettersson & Nordfjell, 2007; Afzal et al., 2010; Gautam et al., 2012). A slight increase may result from dust and soil deposition during extended drying (Lehtikangas, 2001). While seasonal effects and drying duration can slightly raise AC, proper storage can help minimize these changes.

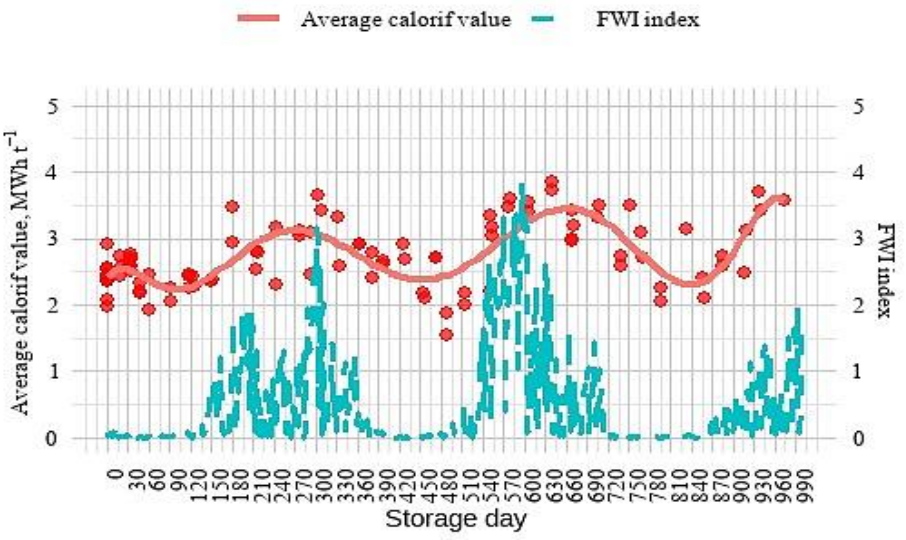
Calorific value

Changes in the net calorific value (CV) of energy wood during storage are shown in 'Figure 5' and can be explained by the influence of favorable or unfavorable conditions for wood drying, as indicated by changes in the FWI index during the respective period.

The obtained results show that the net CV of freshly prepared deciduous energy wood is on average 2.38 MWh t^{-1}.

During the 1st storage period, until the 160th storage day (March 2022), the average CV of energy wood ranged from 2.15 MWh t^{-1} (72nd–101st storage day, January 2022) to 2.62 MWh t^{-1} (10th–40th storage day, November 2021). Starting from the 161st storage day (April 2022), an increase in the CV of energy wood was observed, ranging from 2.71 MWh t^{-1} (191st–221st storage day, May 2022) to 3.20 MWh t^{-1} (161st–190th storage day, April 2022). By the end of the 1st storage period (343rd storage day, September 2022), the average CV of energy wood reached 2.95 MWh t^{-1}.

Figure 5
Changes in the net calorific value of energy wood during storage



The 2nd storage period (beginning on the 344th storage day, October 2022) started with a gradual decrease in CV until the 525th storage day (March 2023), with observed average CV values ranging from 2.09 MWh t^{-1} (495th–525th storage day, March 2023) to 2.90 MWh t^{-1} (344th–374th storage day, October 2022).

A repeated increase in the CV of energy wood was observed starting from the 526th storage day (April 2023) and continued until the end of the 2nd storage period (708th storage day, September 2023), with the average CV values ranging from 2.94 MWh t^{-1} (526th–555th storage day, April 2023) to 3.78 MWh t^{-1} (617th–647th storage day, July 2023). By the end of the 2nd storage period (708th storage day, September 2023), the average CV of energy wood was 3.40 MWh t^{-1}.

Overall, during the 3rd storage period (beginning on the 709th storage day, October 2023), the average CV of energy wood ranged from 2.14 MWh t^{-1} (770th–800th storage day, December 2023) to 3.57 MWh t^{-1} (709th–739th storage day, May 2024).

The results indicate that during the 1st storage period, the net CV of energy wood (with the following average parameters: relative MC of 44.43±6.79%, AC of 1.48±0.54%, and HC of 19.04±0.56 MJ kg^{-1}) was 2.59±0.39 MWh t^{-1}.

An increase in the net calorific value was observed during the 2nd storage period (with the following average parameters: relative MC of 39.97±9.73%, AC of 1.58±0.57%, and HC of 19.13±0.42 MJ kg^{-1}), reaching 2.87±0.59 MWh t^{-1}.

A further increase in the net CV was observed during the 3rd storage period (with the following average parameters: relative MC of 41.28±8.53%, AC of 1.51±0.41%, and HC of 19.69 ± 0.40 MJ kg^{-1}), reaching 2.88 ± 0.51 MWh t^{-1}.

Conclusions

1. The study results confirm significant seasonal changes in the relative MC of energy wood influenced by meteorological conditions. During spring and summer, as intensive drying occurs, the relative MC can decrease from an average of 39.58% (spring) to 33.57% (summer). In autumn and winter, an increase in the relative MC is observed, rising from an average of 42.20% (autumn) to 49.52% (winter), largely influenced by the hygroscopic properties of the material.
2. The average AC of deciduous energy wood during storage ranged from 1.48% to 1.58%. However, changes in the average AC values are not statistically significant and could be explained by the deposition of dust and mineral soil particles on the stored material.
3. When planning the storage of energy wood, seasonal fluctuations should be considered. Also, the obtained results show that the average net CV of energy wood increases during storage, and the relative MC of the material is one of the main factors influencing the net CV of energy wood.
4. The findings highlight that the effective selection of storage locations and appropriate drying durations can significantly improve the energy efficiency of energy wood. To provide recommendations for the optimal storage duration of energy wood, it is also necessary to evaluate the impact of mass loss on the quality of energy wood.

Acknowledgements

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AUTOMATED FOREST HARVESTING ALGORITHMS: ECOSYSTEM-BASED ALTERNATIVES TO CLEAR-CUTTING METHODS

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Abstract
This research focuses on developing an innovative, multi-criteria approach to forest harvesting planning, providing an alternative to traditional clear-cutting and selection-cutting methods. The study integrates automated planning algorithms with geospatial analysis to promote more sustainable forest management practices that prioritize ecological integrity and social value, particularly in areas with significant natural and recreational importance. The proposed approach is based on the use of open-source algorithms, enabling individual forest owners or users to select logging areas by weighing ecosystem service indicators and remote sensing criteria specific to each forest stand. By incorporating adaptive harvesting parameters, this method allows for tailored decision-making that reduces the environmental impact of forestry activities while maintaining flexibility in addressing various forest management objectives. The primary objective of this research is to create a scientifically validated framework that balances timber extraction with the preservation of diverse forest ecosystem services. The approach accounts for available biodiversity data, supports recreational use, and considers other social-ecological functions of forests. The study includes the development and testing of data processing and analysis algorithms that optimize forest harvesting strategies based on ecosystem service assessments. The proposed methods are field-tested in managed forest areas to verify their practical applicability in real-world conditions. This research contributes to advancing sustainable forest management by offering data-driven, ecosystem-based solutions that address contemporary challenges in balancing timber production with broader social-ecological values, while also empowering forest owners to make more informed, site-specific harvesting decisions.
Keywords: automated planning algorithms, ecosystem services, sustainable forest management, timber harvesting planning.

Introduction

Forests are managed to fulfil various economic and social objectives, with some areas prioritized for timber production, others dedicated to biodiversity conservation or recreation, and many designed to support multiple functions (Lindenmayer et al., 2012). Achieving these diverse goals while adapting to different environmental conditions requires forest owners to apply a variety of silvicultural practices (Eyvindson et al., 2021). Although several advanced planning systems are available to support multifunctional forest management by integrating eco-geographical variables and optimizing harvesting strategies (e.g., Mason et al., 2018; Marto et al., 2019; Tahri et al., 2021; Lämås et al., 2023), their practical application remains limited. Many rely on region-specific datasets or proprietary data formats, reducing their adaptability in diverse forest conditions (Eriksson et al., 2014). Additionally, the scarcity of open-source solutions and dependence on openly accessible data further restricts access to effective planning tools, particularly for regions seeking flexible, low-cost alternatives or aiming to prioritize ecosystem services alongside timber production.

In Latvia and the broader boreal region, clear-cutting with subsequent stand regeneration by planting is the primary logging practice. This method is widely applied to promote timber production, particularly for key species such as *Pinus sylvestris* and *Picea abies*, ensuring efficient stand renewal and forest productivity (Pach et al., 2018).

The dominance of clear-cutting reflects both economic considerations and the limited implementation of advanced planning tools that account for multifunctional objectives. Expanding the use of data-driven planning approaches that integrate ecosystem services, biodiversity data, and terrain constraints could support a shift toward more sustainable and multifunctional forest management practices (Larsen et al., 2022).

The aim of this paper is to present a workflow for a mixed-method approach to automated small-scale clear-cutting that considers diverse eco-geographical conditions and ecosystem services. The proposed method supports sustainable forest management by modelling logging operations in a way that incorporates site-specific environmental factors, terrain constraints, and ecosystem service values. The workflow integrates multiple open data sources relevant to forest structure, ecological features, and landscape conditions. A customized meta-heuristic algorithm is used to identify harvesting sites while balancing multiple constraints, refining outputs through iterative, randomized search strategies.

The research tasks addressed in this study include:

- developing and implementing an automated algorithm that generates spatially explicit clear-cut units while accounting for ecological and legal constraints;
- integrating remote sensing and ecosystem service

- indicators with forest inventory data to guide harvesting decisions at the stand level;
- testing the workflow in managed forest areas and evaluating the resulting harvesting phases in terms of spatial balance, consistency of environmental metrics, and operational feasibility.

Materials and Methods

The following methods outline the data sources, processing tools, and workflow steps used to develop an automated small-scale clear-cutting approach that considers eco-geographical conditions and ecosystem services.

Table 1

Summary of the data used

Dataset	***Description***	***Link***
State Forest Service Forest Compartment Data	Boundaries and attributes (stand composition, age, tree species etc.), of forest compartments. Vector data	https://data.gov.lv/dati/lv/dataset/meza-valsts-registra-meza-dati.jsonld
Latvian Geospatial Information Agency LiDAR Data	4 p/m² LAS data (base for DSM, DTM, TRI, TPI, slope, aspect, roughness, DTW)	https://s3.storage.pub.lvdc.gov.lv/lgia-opendata/las
Ministry of Agriculture Drainage Cadastre Data	Vector data of ditch networks, drainage pipes, and related infrastructure. Vector data	https://www.melioracija.lvhttps://lvmgeoserver.lvm.lv/geoserver/zmni/ows
Nature Conservation Agency Data …	OZOLS system data – information on protected nature territories, species distributions, and habitat data. Vector data	https://ozols.gov.lv/arcgis/services/OZOLS_DABASDATI_PUB_INSPIRE/MapServer/WFSServer
	Species Protection Plan data. Vector data	https://www.daba.gov.lv/lv/sugu-un-biotopu-aizsardzibas-plani
Information System 'Heritage' Data	Protected sites, landmarks, and areas of cultural significance and their protection zones. Vector data	https://geoserver.mantojums.lv/geoserver/ows
Latvian State Forest Research Institute 'Silava' Research data …	Data on ecosystem service assessments, SQL qyery	Lībiete et al. (2023)
	LIFE Programme Study – 'Demonstration of Climate Change Mitigation Potential in Fertile Organic Soils in the Baltic States and Finland' (LIFE OrgBalt, LIFE18 CCM/LV/001158). Raster data	https://silava.forestradar.com/data/rastra-dati/DTW/DTW_10ha_ https://silava.forestradar.com/data/rastra-dati/DTW/DTW_30ha_
OpenStreetMap data	road and trail network data with the option to supplement it with custom data for improved detail or accuracy	https://download.geofabrik.de/europe/latvia-latest-free.shp.zip

Table 1 summarizes key datasets, including forest compartments, LiDAR terrain models, drainage networks, biodiversity, cultural heritage, ecosystem services, and road data, ensuring broad coverage for forest planning. Table 2 lists data processing tools.

Table 2

Data Processing and Analysis Tools

Tool	***Description***	***Purpose***
Python >= 3.12	Programming language used as the foundation for data loading and processing code.	Core programming environment.
Geopandas	Library for analyzing and processing geospatial data, including geostatistics.	Geospatial data analysis and processing.
Pygro	Library for high-performance reading and writing of vector data in GDAL/OGR-supported formats.	Efficient vector data I/O operations.
Fiona	Library for spatial manipulation and querying of vector data.	Vector data manipulation and selection.
Rasterio	Library for processing and manipulating raster/image data.	Raster data handling and analysis.

Tool	***Description***	***Purpose***
Py7zr	Library for processing data archives in formats such as 7z, rar, and ZIP.	Archive extraction and compression.
Python-PDAL	Python API for PDAL (Point Data Abstraction Library) to manage and process point clouds and LAS data.	Point cloud and LiDAR data processing.
GDAL (gdaldem)	Command-line tool for terrain derivative generation (slope, aspect, TPI, TRI).	Terrain metric derivation from DEMs.
Shapely	Library for manipulation of geometric objects (polygons, lines, points).	Geometry operations and spatial filtering.
JSON / JSONschema	Configuration and validation format for pipeline execution.	Parameter definition and structured automation.
Requests	HTTP library for querying data services and downloading open geospatial data.	Automated access to online spatial data.
Pandas	Library for tabular data handling and analysis.	Attribute table processing, filtering, and statistics.

The data processing workflow begins with the user defining the area of interest, which triggers automated data acquisition from open sources. The core of the system is a modular Python library that handles data import, preprocessing, spatial analysis, and output generation. It operates through a sequence of defined steps that allow reproducibility and customization.

Preprocessing includes format harmonization, spatial alignment, and derivation of additional variables from primary data sources. Terrain metrics such as slope, aspect, roughness, topographic position index (TPI), and depth-to-water (DTW) are calculated from LiDAR-based digital elevation models using the GDAL ʻgdaldemʼ utility and PDAL library. Canopy height is derived from LiDAR point clouds and normalized height models. Vector datasets, such as forest compartments, protected areas, and drainage networks, are filtered, cleaned, and clipped to the area of interest using Fiona, Pyogrio, and Geopandas.

Data access and model execution are managed through a JSON-based configuration structure. This allows the user to define which datasets are downloaded, reused, excluded, or converted, as well as set key parameters such as spatial resolution, masking thresholds, and classification rules. Cached downloads and standardized folder structures improve reproducibility and computational efficiency.

The core algorithm is a customized meta-heuristic routine that generates and refines spatially explicit clear-cutting units. Candidate polygons are created by constrained Voronoi tessellation (Oar et al., 2016) within forest compartments. Each unit is evaluated with a scoring function combining canopy height, slope, and ecosystem service values derived from species distribution layers. Unsuitable units are filtered out based on thresholds (e.g., slope >10°, DTW <0.2 m, overlap with protected zones).

Harvesting units are grouped into three cutting phases. A distance-based adjacency constraint prevents spatial clustering by excluding neighboring polygons from being scheduled in the same phase. The algorithm iterates through randomized orderings and filtering steps until the spatial and ecological balance across phases is maximized.

An Operational Guidance Map is generated by combining raster and vector constraints into a unified planning layer. Wet areas (DTW <0.2 m) are classified as no-go zones, moderately wet soils (0.2–1.0 m) as caution zones, and accessible terrain as suitable. Additional exclusion layers include species habitats, cultural heritage zones, and terrain barriers.

The final output is packaged as a ZIP archive for integration with forest management systems. Users can select which background variables and classifications to include in the export. The processed units are transferred into operational maps and machine-readable plans to support harvesting logistics and ecological compliance.

The processing environment is implemented in Python (v3.12) and utilizes the following libraries: Geopandas, Fiona, Pyogrio, Rasterio, python-pdal, Requests, and Py7zr. Data interactions are managed via standardized protocols (e.g., HTTP, WFS), ensuring compatibility with Latvian national open-data services and spatial metadata frameworks.

Results and Discussion

The cutting sequence results ʻFigure 1ʼ illustrate a structured approach to timber harvesting, designed to achieve a balanced distribution of clearings over time. Each forest compartment was subdivided into tessellated planning units and scheduled for harvesting in three successive phases, with a 20-year interval between phases and a cumulative harvest share of 60% of the total area. These phases represent spatial batches designed to maintain ecological continuity and avoid operational overlap. The algorithm allocated each unit to a phase while avoiding adjacency and balancing ecological and terrain characteristics. The map visualizes this phase allocation, showing how

openings are spatially arranged to minimize the risk of large contiguous clear-cuts while ensuring gradual and distributed timber extraction.

To evaluate the performance of the spatial allocation algorithm, the model was configured to run 50 randomized iterations. Each iteration generated a different tessellation and harvesting phase assignment based on varying random seeds, while applying consistent ecological scoring and spatial constraints. This iterative setup allowed exploration of variability in polygon layout and indicator distribution. The result was selected based on achieving (i) minimal intra-phase variance in canopy height, depth-to-water, and ecosystem service values, and (ii) maximal spatial separation between cutting units within the same phase, as measured by adjacency index and unit dispersion. While no formal validation against field data was performed, all iterations adhered to legal and ecological constraints (e.g., exclusion of steep slopes and protected areas, non-adjacency rule). The consistency of ecological scoring and spatial constraints across runs suggests that the algorithm reliably produces feasible, ecologically balanced solutions. These internal checks serve as proxies for performance assessment in the absence of ground-truth validation.

Although precise estimation of timber volume is not directly possible, a wide range of metrics was calculated for each tessellation unit to support informed decision-making. These include canopy height model (CHM) values as a proxy for stand structure and biomass potential; depth-to-water (DTW) as an indicator of site accessibility and soil moisture conditions; and ecosystem service (ES) values representing ecological and social forest functions. For each harvesting phase, average and standard deviation values of these metrics are summarized in Table 4, providing an overview of how environmental conditions are distributed across the spatial schedule. Additionally, the Operational Guidance Map supports harvester and forwarder navigation by classifying terrain into suitable, caution, and no-go zones, based on combined constraints.

Figure 1
Harvesting phases

Tables 3 and 4 show that topographic conditions, canopy height, and ecosystem service potential are consistently distributed across all harvesting phases. Table 3 provides a summary of the spatial and environmental properties of the generated cutting units, including their area distribution and mean values for terrain and canopy structure indicators, which are relevant for planning feasibility and ecological balance. The low variation in average values and standard deviations between phases suggests that the algorithm maintained spatial balance and avoided front-loading of high-value or environmentally sensitive stands. This outcome supports the intended goal of distributing ecological and operational characteristics evenly across the planned harvesting timeline.

Table 3
Summary of area distribution and selected environmental metrics across harvesting phases

	Area (ha)	***Mean area (ha)***	***DTM (mean)***	***SLOPE (mean)***	***CHM (mean)***	***hCHM (mean)***
Total processed area	157.09	0.14	9.49	4.19	10.71	16.32
Area in Phase 1 (0–20 yrs)	66.15	0.12	9.64	4.25	10.60	16.37
Area in Phase 2 (20–40 yrs)	30.53	0.17	9.23	4.09	10.78	16.22
Area in Phase 3 (40–60 yrs)	30.77	0.16	9.41	4.20	10.98	16.36
No-harvest area	29.64	0.15	9.38	4.12	10.67	16.23

The developed workflow integrates eco-geographical data, ecosystem service values, and terrain constraints, offering a flexible, data-driven approach to sustainable forest management. This method supports mitigation of trade-offs between bioeconomy goals, biodiversity conservation, and ecosystem service provision by explicitly embedding ecological and spatial criteria in the scheduling process. Unlike conventional planning approaches that prioritize timber yield or compartment-based rotation, this workflow emphasizes spatial distribution of ecological value. The results show a balanced phase allocation that promotes gradual extraction while maintaining stable forest conditions and minimizing concentrated disturbance. While these outcomes are illustrative and not predictive, they demonstrate the workflow's ability to integrate complex spatial data into harvest planning. Further real-world evaluation is necessary to assess long-term ecological outcomes, particularly with respect to biodiversity, landscape connectivity, and changing environmental conditions.

Table 4
Summary of ecosystem service potential across harvesting phases

	Medical plants	***Forest berries***	***Fito-remediation***	***Cosmetics***	***Wind resistance***	***Aesthetics***	***Recreation***	***Noise reduction***	***Fire resistance***	***Bioremediation***	***Filtration/ accumulation***	***Flood mitigation***	***Climate control***
Total processed area	3.08	2.84	3.98	2.97	4.38	3.48	4.31	4.24	1.00	2.10	2.10	1.11	2.06
Phase 1 (0–20 yrs)	3.07	2.83	3.98	2.97	4.32	3.48	4.27	4.25	1.01	2.08	2.08	1.12	2.06
Phase 2 (20–40 yrs)	3.10	2.85	3.99	2.98	4.44	3.48	4.31	4.21	0.99	2.12	2.12	1.12	2.06
Phase 3 (40–60 yrs)	3.10	2.85	3.96	2.95	4.43	3.46	4.34	4.21	0.99	2.11	2.11	1.09	2.05
No-harvest area	3.10	2.84	3.98	2.97	4.42	3.48	4.39	4.28	1.01	2.13	2.13	1.12	2.06

Recent developments in spatial forest planning have emphasized the need to find a way to fulfill both timber production goals and ecological integrity goals, particularly through the use of optimization algorithms that can handle spatial constraints and multiple objectives. Borges et al. (2014) highlight how simulated annealing and related heuristics have become essential tools for spatial harvest scheduling, especially when seeking to avoid fragmentation, ensure connectivity, or control block sizes. This view is echoed in Bettinger et al. (2009), who stress that heuristic planning must be transparent in its assumptions and evaluated for spatial realism rather than pure computational output. While Borges' work focuses on simulated annealing in a context of minimizing habitat fragmentation and maximizing economic returns, the structure of the algorithm presented here shares the core principle of balancing spatial objectives through randomized and iterative allocation. However, our approach departs from theirs by prioritizing ecological indicators - such as canopy height, depth-to-water, and ecosystem service potential - rather than economic net present value. This shift reflects a broader move in forest planning toward embedding ecological constraints directly into the spatial allocation logic, rather than treating them as secondary filters. Schooler et al. (2023) demonstrate how multi-objective optimization can be used to balance timber yield with habitat suitability, using species-specific models as proxies for ecological value. While their focus is on single-species habitat dynamics, our method generalizes ecological considerations

through terrain metrics and ecosystem service indicators, allowing broader applicability across diverse stand types.

Moreover, the evaluation of cutting unit properties in our study - including shape complexity and adjacency index - resonates with Borges et al. (2014) emphasis on spatial feasibility and implementation cost. Our workflow ensures that harvested units remain compact, ecologically balanced, and non-adjacent within each phase. This supports both biodiversity retention and smoother field logistics, aligning with Janová et al. (2024), who argue that planning systems must account for how and when harvesting occurs, not just what is harvested. Wing et al. (2019) emphasize that the real value of spatial decision support lies in its adaptability to different data availability and management goals - something our open-source, data-driven design also enables. Finally, the spatial parity achieved across phases, as shown in Table 4, demonstrates that heuristic spatial scheduling can be guided by ecological value distributions rather than solely by timber yield or infrastructure constraints. This represents a practical contribution to ecosystem-based forest management, where spatial planning is responsive to both ecological integrity and operational needs.

Conclusions

1. The presented method demonstrates that it is possible to allocate small-scale clear-cutting phases in a way that maintains spatial balance across ecological indicators and minimizes spatial clustering. The results show low intra-phase variation in canopy height, terrain accessibility, and ecosystem service values, supporting the claim that spatially structured harvesting can be ecologically and operationally coherent.
2. Although developed for the Latvian context, the workflow's reliance on modular inputs and open geospatial tools makes it technically adaptable to other regions with compatible data layers. This positions the method as a prototype for broader applications in contexts where fine-resolution environmental data are available.
3. Future development should focus on adding dynamic components such as connectivity indices, temporal stand development, and cost-based constraints. This would extend the method from spatial prioritization toward full-scale operational forest planning under multi-objective criteria.
4. By embedding ecosystem service values into the decision logic, the method anticipates future policy directions such as payments for ecosystem services and biodiversity credits. While markets for such instruments remain emergent, this design enables alignment with incentive-based governance models that are increasingly discussed in European and global forest policy frameworks.

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SPATIAL COMPETITION BETWEEN *IPS ACUMINATUS* AND OTHER MAIN PINE TREE COLONIZING PESTS

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Abstract
The sharp-toothed bark beetle (*Ips acuminatus* (Gyllenhal, 1827)) is one of the major pests of Scots pine (*Pinus sylvestris* L.). In addition to *I. acuminatus*, several other pests attack healthy or weakened pine trees, including pine shoot beetles (*Tomicus* spp.), the six-toothed bark beetle (*Ips sexdentatus*), pine bark beetles (*Pityogenes* spp.) and pine weevils (*Pissodes* spp.). The results of two separate studies are presented in this paper. (1) We analysed how *I. acuminatus* breeding success is influenced by other major stem-colonizing pests in a pine stand affected by forest fire. The spatial distribution of the four most found insect pest species - *I. acuminatus*, *Tomicus piniperda*, *T. minor*, and *Pissodes* spp. - within the tree trunk was mapped. It was determined that the length of the stem section colonized by *I. acuminatus* is significantly affected by the presence of *Pissodes* weevils but not by *Tomicus minor* or *T. piniperda*. Although *Tomicus minor* typically colonizes the same part of the pine trunk as *I. acuminatus*, they were rarely found on the same tree. If *I. acuminatus* colonizes a pine tree first, *Tomicus minor* tends to avoid it. The length of the section colonized by *I. acuminatus* increases with tree height, with taller trees supporting longer infestations. (2) Additionally, data on *I. acuminatus* reproduction rates in pine waste after thinning activities was collected. On average, 2.19 ± 0.65 mother galleries per 1 m² of bark were found on the remaining treetops and branches, indicating that forest management practices contribute to the availability of suitable breeding material for this species.
Keywords: *Ips acuminatus*, forest fire, insect pests, stem colonisation, *Pinus sylvestris*.

Introduction

In recent years, bark beetle populations have been rising across Europe, causing widespread damage to forests and posing significant challenges to forest management and conservation efforts. Scots pine (*Pinus sylvestris* L.) is primarily attacked by bark beetle species from the *Ips* and *Tomicus* genera. However, other pests, such as *Pissodes* spp. weevils and *Phaenops* spp. jewel beetles, can also cause significant damage (Ozols, 1985; Vega and Hofstetter, 2015). All these insects are considered secondary pests, as they primarily attack hosts with impaired defences. Climate variability and weather extremes, such as floods, droughts and fires, accelerate pest outbreaks, by weakening trees natural defences (Hlávková & Doležal, 2022). In response to these stressors, trees accumulate and produce volatiles that might attract insect species and further weaken host trees. The sharp-toothed bark beetle (*Ips acuminatus* Gyllenhaal) has experienced a notable surge in population growth and the damage it causes within pine ecosystems (Grégoire & Evans, 2004; Papek et al., 2024). *I. acuminatus* predominantly targets mid- to mature-aged, weakened Scots pine stands, particularly the upper part and branches of the tree with thin phloem.

One key factor contributing to pest multiplication is the presence of logging residues, and their timely removal can help prevent outbreaks. *I. acuminatus* can successfully breed in pine logging residues left after final felling (Foit, 2015). Understanding *I. acuminatus* presence in logging residues and its interactions with other stem-colonizing insects in pine stands is crucial for assessing its impact on forest health.

This research consisted of two separate studies: (1) analysing the occurrence of *I. acuminatus* in logging waste after clearcuts, and (2) examining *I. acuminatus* interactions with other major stem-colonizing pests in fire-affected pine stands, while also mapping the spatial distribution of the four most commonly found insect pest species - *I. acuminatus*, the common pine shoot beetle *Tomicus piniperda* L., the lesser pine shoot beetle *T. minor* Hart., and *Pissodes* spp. weevils - within the tree trunk.

Materials and Methods

The occurrence of *I. acuminatus* and other stem-colonizing insects in fresh wood waste was evaluated in 11 pine stand clearcuts during the summer of 2003 and 2004. Samples of branches and treetops were collected from logging residues piled in stacks as well as from those placed on skidding trails. Each sample consisted of a 30 cm long section, which was fully debarked, and insect galleries were counted.

The densities of insect colonies (larval galleries and pupal chambers) were calculated per 1 m^2 of bark surface based on sample diameter. In total, 114 samples were taken from stacks and 68 from skidding trails. Sample diameters ranged from 2.1 cm to 37.2 cm, with an average of 7.5±0.4 cm.

For solitary larval galleries (e.g. *Monochamus* spp.), the number of galleries were recorded. For insect colonies (e.g. *I. acuminatus*), nuptial chambers were counted, while for *Pissodes* weevils pupal chambers were counted.

To assess the tree mortality and breeding success of pine pests, 9 permanent circular study sites, each covering 500 m², were established. The study area is in the northwestern part of Latvia, where an extensive forest fire occurred in Stikli Bog in July of 2018, affecting large areas of peatland and forest ecosystems. Study sites were all Scots pine dominated on dry and wet organic soils (*Myrtillosa* and *Caricoso-phragmitosa*).

At each study site, all standing trees, both dead and alive, with a diameter exceeding 12 cm at a height of 1.3 m were marked. For living trees (trees with a green crown), crown defoliation was assessed in 5% increments, interpreting defoliation intensity, (Table 1), and needle discoloration (yes/no). For both

living and recently dead trees, the presence of beetle exit holes on the visible part of the trunk bark was evaluated. Evaluation was done four times (2019 July and September 2020 January and August).

Table 1
Pine crown defoliation percentage and descriptive level

Needle loss percentage	***Defoliation level***
0–10 %	No defoliation
11–25 %	Mild defoliation
26–60 %	Moderate defoliation
61–99 %	Severe defoliation
100 %	Dead tree

In the area, data on species presence were obtained by felling pine trees with visible fresh crown discoloration: 22 trees in 2019, 25 in 2020, and 15 in 2022. Up to three pine trees were felled at each study site. Tree lengths were measured, and the bark was removed to assess the presence of bark beetles and weevils. Species or genus identification was based on their characteristic gallery systems.

For the *Tomicus piniperda*, *T. minor*, *I. acuminatus*, and *Pissodes* spp., the shortest distance from the felling point where the species was detected, and the trunk diameter at that location were recorded for each tree. Additionally, the farthest distance from the felling point and the trunk diameter at the last recorded location of the species were also measured. For the *Pissodes* weevils, no separation based only on pupal chambers was possible; therefore, all individuals were recorded as *Pissodes* spp.

To analyse the factors influencing *I. acuminatus* tree colonization success and potential competition from other major pine wood-boring pest species, a Linear Mixed-Effects Model was used (*lmer* procedure in R). The following model was applied:

model = lmer (Ia ~ L + Tm + Tp + P + (1 | Year)), family = gaussian,

where:

Ia – proportion of the pine stem colonized by *I. acuminatus* (% of total tree length),

L – pine tree length (m),

Tm – proportion of the pine stem colonized by *Tomicus minor*,

Tp – proportion of the pine stem colonized by *Tomicus piniperda*,

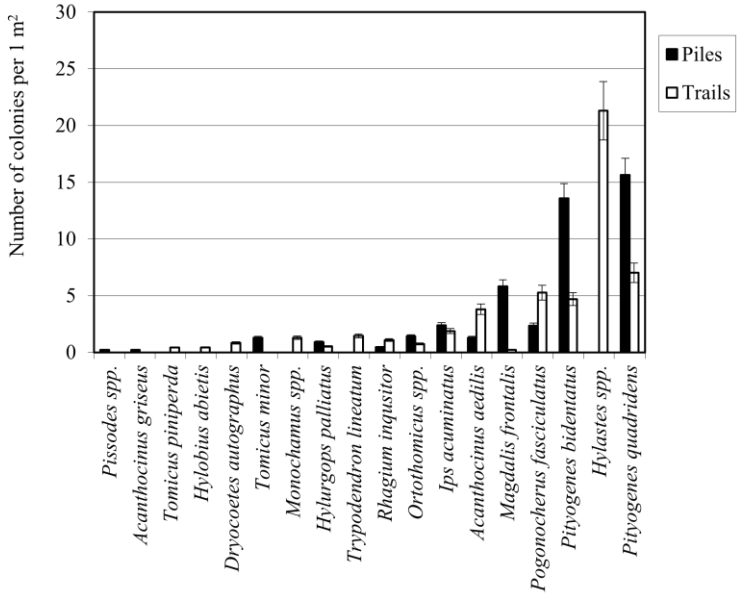
P – proportion of the pine stem colonized by *Pissodes* spp.,

Year – year in which trees were sampled (random effect).

Results and Discussion

The analysis of dendrophagous insect colonization in fresh logging residues revealed significant differences in species abundance between residues stored in stacks (piles) and those placed on skidding trails (trails). Overall, most species exhibited higher colonization rates in piles compared to trails, indicating a preference for stacked wood as a breeding habitat ‘Figure 1’.

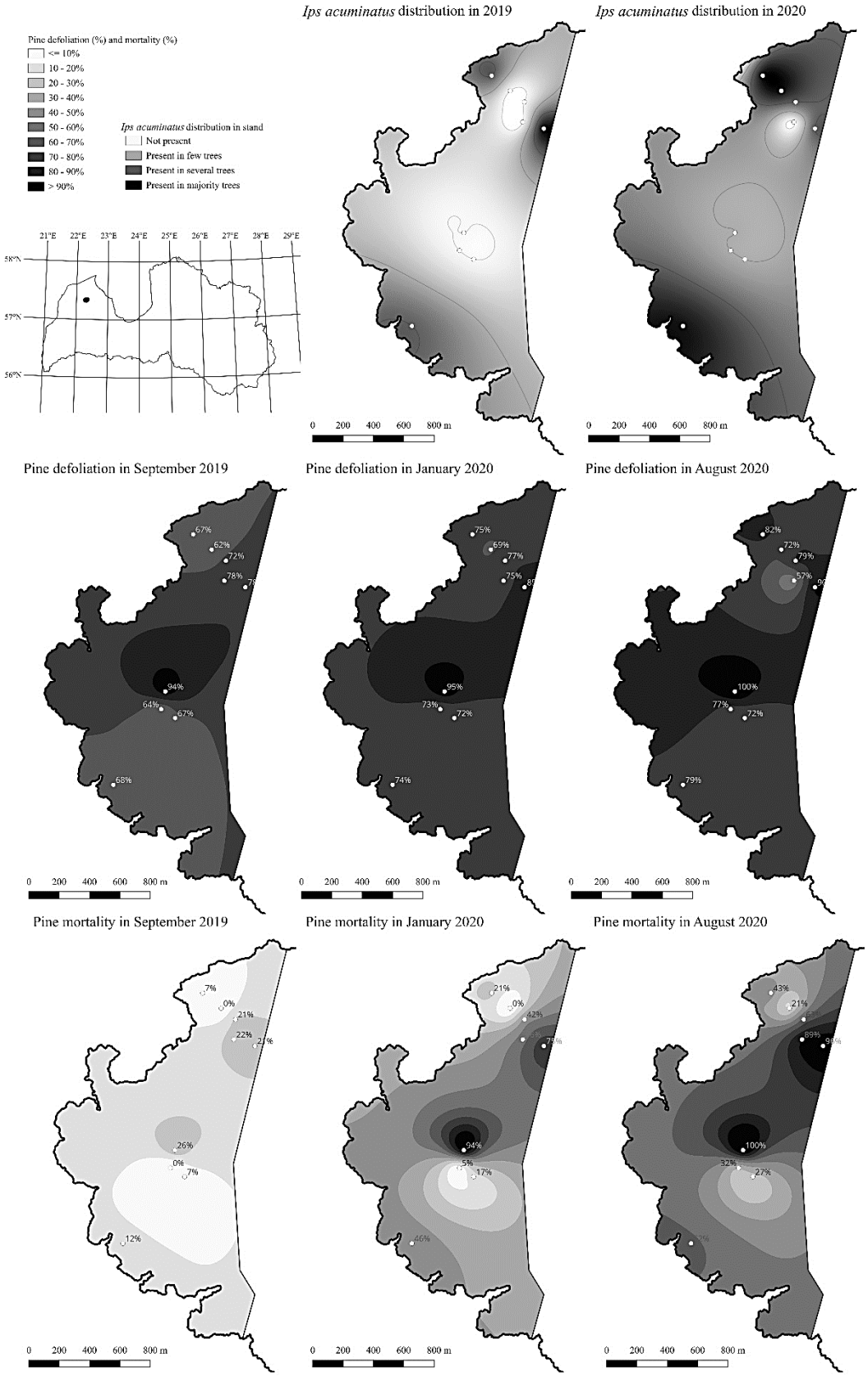
Figure 1
The occurrence of Ips acuminatus and other dendrophagous insects in fresh logging residues piled in stacks (piles) and placed on skidding trails (trails)



I. acuminatus were found in both wood waste storage conditions, with a slightly higher density in piles. On average, 2.19 ± 0.65 colonies (nuptial chambers and associated mother and larval galleries) per 1 m² of bark were found on the remaining treetops and branches, indicating that forest management practices contribute to the availability of suitable breeding material for this species.

Figure 2

Ips acuminatus distribution, pine defoliation and mortality over studied period in Stikli bog



A much higher occurrence of *I. acuminatus* in logging residues was reported in a study from the Czech Republic, where the sharp-toothed bark beetle was one of the most abundant species, surpassed only by *Pityogenes calcographus* (Foit, 2015). This difference may be partly explained by the fact that our data were collected in 2004. Since then, *I. acuminatus* populations have increased across Europe (Papek et al., 2024).

The most abundant species in the study were *Hylastes* spp., *Pityogenes bidentatus*, and *P. quadridens*, with densities reaching approximately 20 - 25 colonies per m² in piles. These species also showed considerable presence in trails, though at slightly lower densities. The significant presence of *Pityogenes* genus aligns with their known preference for fresh coniferous logging residues, emphasizing the role of storage conditions in influencing pest outbreaks. Conversely, species such as *Pissodes* spp., *Acanthocinus griseus* and *Tomicus* spp. who are less dependent on wood storage conditions exhibited relatively low overall densities

The observed variation in insect colonization highlights the importance of forest residue management in pest control. The higher densities of bark beetles and weevils in piles indicate that stacking fresh wood residues may unintentionally promote pest population growth.

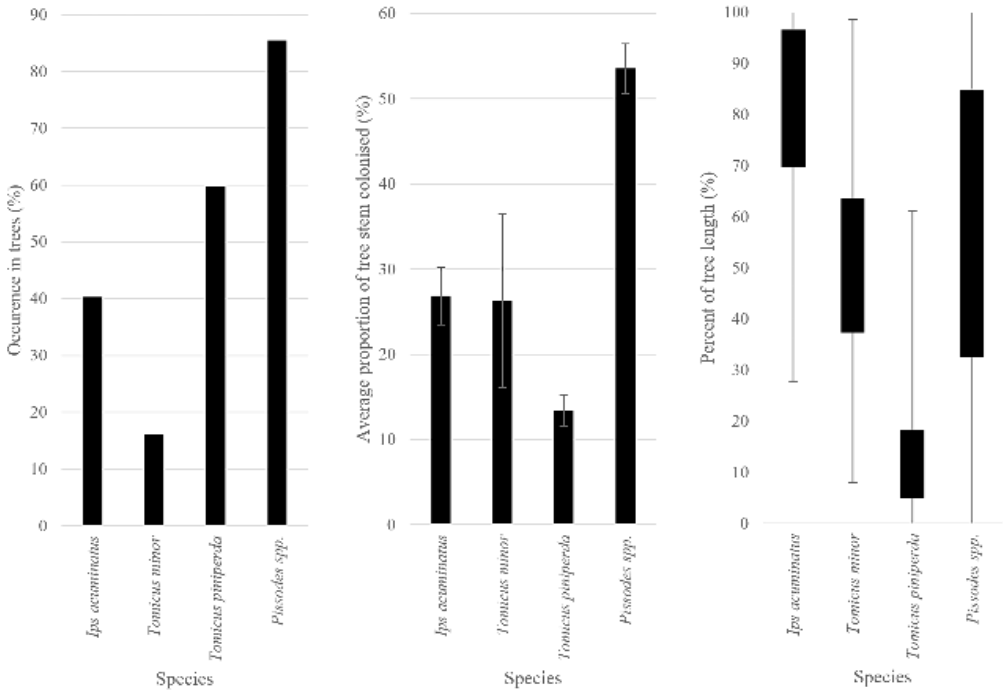
The study in Stikli bog revealed a slightly different tendency in *Ips acuminatus* distribution in the area.

The average tree defoliation in the sample plots at their establishment in the summer of 2019 in Stikli bog was 71.4%, with 8.4% of the assessed pine trees already dead. In September 2019, the average tree defoliation in the sample plots was 66.5%. By January 2020, it had increased to 72.9%, and by August 2020, it reached 75.6% ‘Figure 2’. Tree crown defoliation worsened significantly over a year and a half. The decline in tree crown condition is likely even greater than estimated, as several trees with severe defoliation had already died by the 2020 surveys and were therefore not included in the defoliation assessment. By January 2020, the proportion of dead trees in the sample plots had increased to 29% of all trees surveyed, and by August 2020, 59% of the trees had died ‘Figure 2’. At one sample plot the defoliation by January had reached 90% and all trees were dead by August, indicating more severe fire intensity at this location.

The most common pest species found in weakened pine trees were *Pissodes* weevils, occurring in 53 out of 62 sampled trees (85.5%) ‘Figure 3A’. However, it should be noted that *Pissodes* spp. were much less common in logging residues ‘Figure 1’, with pupal chambers found in only one out of 182 samples.

Figure 3

The occurrence (A), average proportion of tree trunk colonized (B), and location of colonized section (C – average top, maximum top, average bottom and maximum bottom) of major wood boring pest on pine tree trunks



I. acuminatus was recorded in 25 sampled trees, *Tomicus piniperda* in 37, and *Tomicus minor* in only 10 trees. No *Ips sexdentatus* galleries were found in the sampled trees. Contrary to our findings, *I. sexdentatus* was the most abundant pest species in pine stands two years after a forest fire in Ukraine (Andreieva et al., 2018).

Pissodes weevils were usually found on large sections of the tree trunk, sometimes colonizing the entire tree length ‘Figure 3B’. *I. acuminatus* typically colonized approximately one-quarter of the pine tree, primarily in the upper part of the trunk ‘Figures 3B’, C’. *Tomicus minor* occupied the section below *I. acuminatus* ‘Figure 3C’, with some overlap between their colonized areas. However, this conclusion is based on only two observed cases where both species were present in the same tree. *Tomicus piniperda* was typically found in the lower section of the trunk, where the bark is thicker, making direct competition with *I. acuminatus* unlikely ‘Figure 3C’.

The colonization success of *I. acuminatus* was found to be negatively affected by the presence of *Pissodes* weevils (Table 2). When *Pissodes* weevils colonized a larger proportion of the trunk, *I. acuminatus* occupied a shorter section ‘Figure 4’. In contrast, *Tomicus* species had no negative effect on *I. acuminatus*. It is possible that *Tomicus minor* avoids trees already colonized by *I. acuminatus* and vice versa. *T. minor* is considered relatively less aggressive than *I. acuminatus* (Wermelinger et al., 2008).

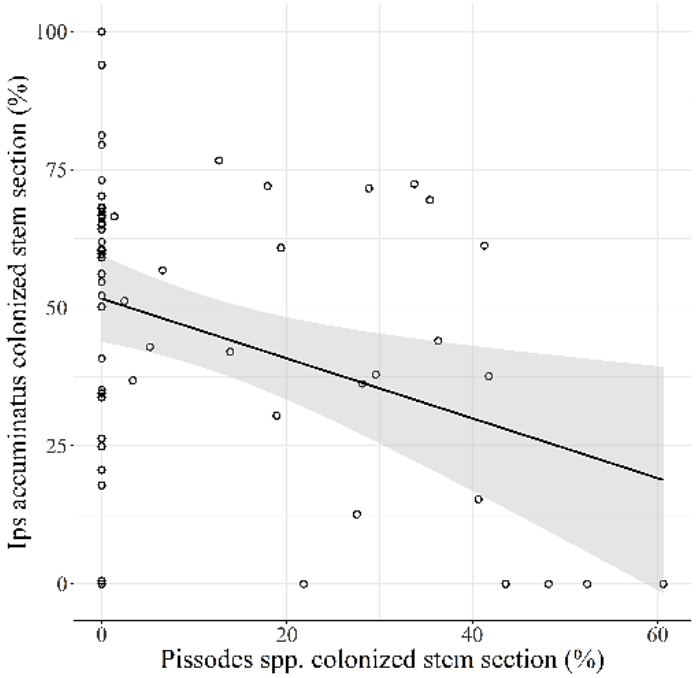
Table 2

*Analysis of Deviance Table (Type II Wald chi-square tests) of the model for factors influencing I. acuminatus tree colonizing success. Significant codes 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1*

Response: Ia			
	Chisq	Df	Pr(>Chisq)
Tree length	1.5679	1	0.211
Tomicus minor	3.1071	1	0.078
Tomicus piniperda	3.1794	1	0.075
Pissodes spp.	8.7079	1	0.003 **

Figure 4

Effect of Pissodes spp. presence on Ips acuminatus tree colonization success



Forest fire at the study site occurred on July 17. *I. acuminatus* second-generation beetles had opportunity to attack fire-weakened trees in the same year when forest fire occurred. *Tomicus* has only one generation per year (Vega & Hofstetter, 2015). Therefore, *Tomicus* beetles could colonize weakened pine trees only next spring. This may explain higher occurrence of *I. acuminatus* beetles in sampled trees.

Tree length had no effect on the section length that was colonized by sharp-toothed bark beetle.

Conclusions

1. *Ips acuminatus* can reproduce in pine logging waste after final felling; however, its occurrence in wood residues in Latvia is low.
2. The *Ips acuminatus* population and its damage to pine stands increase rapidly within 1 - 3 years after a forest fire.
3. *Ips acuminatus* competes with *Pissodes* weevils for breeding space when colonizing fire-weakened pine trees.

Acknowledgements

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OCCURRENCE OF SEVERAL NEEDLE PATHOGENS IN YOUNG FOREST STANDS OF SCOTS PINE IN LATVIA

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Abstract
This study aimed to investigate the spread of several needle pathogens from the genera *Dothistroma*, *Diplodia*, and *Lecanosticta* that have been introduced to Latvia in recent decades. The occurrence of these pathogens was assessed in 165 forest stands of Scots pine (*Pinus sylvestris* L.). Stands were selected across Latvia based on stand composition (pine monocultures), stand age (up to 20-year-old pines), and an approximate area of one or more hectares. Stands were surveyed during either the spring or autumn of 2021. The needle cast rate was determined in each stand by inspecting 10 random trees and collecting one representative sample from three symptomatic pines. Needle pathogens were identified based on morphological characteristics and molecular analysis with species-specific primers for four pathogens: *Dothistroma septosporum*, *Dothistroma pini*, *Diplodia sapinea*, and *Lecanosticta acicola*. The analysis revealed that *Dothistroma septosporum* and *Diplodia sapinea* were the most common pathogens found in 30% and 18% of stands, respectively. *L. acicola* was not detected in any of the analysed samples. Since all tested pathogens are recently established in Latvia, monitoring their spread and impact to local forests is important.
This work was funded by JSC Latvia's State Forests (project No. 5-5.9.1_007f_101_21_69) and Forest4LV (project No. VPP-ZM-VRIIILA-2024/2-0002).
Keywords: *Dothistroma septosporum*, *Dothistroma pini*, *Diplodia sapinea*, needle cast, *Pinus sylvestris*.

Introduction

Scots pine *Pinus sylvestris* is an abundant and economically important tree species in Baltic Sea region, hosting many pathogenic organisms (Ruotsalainen & Persson, 2013; Raitelaitytė et al., 2017). The main invasive fungal species causing pine needle and shoot diseases in the Baltic region are *Dothistroma septosporum*, *Dothistroma pini*, *Diplodia sapinea*, and *Lecanosticta acicola* (Drenkhan & Hanso, 2009; Adamson et al., 2015a, 2015b).

Dothistroma needle blight (DNB), or red band needle blight, is a major global pine disease (Mullett et al., 2021). It affects over 80 conifer species, with pines being the most common host (Raitelaitytė et al., 2017). Symptoms begin as yellow or light brown bands on needles that turn brick red before the needles die. Fruiting bodies develop within these bands, aiding disease spread, progressing from the lower crown upward and inner branches outward (Gonthier & Nicolotti, 2013).

First identified in Africa and North America in the 1950s–1960s, *Dothistroma* primarily affected *Pinus contorta*, *P. nigra*, and *P. radiata* (Gibson et al., 1974). Today, it has been reported on 109 *Pinaceae* species, including 95 pine species, some *Picea* spp., and *Larix decidua* (Drenkhan et al., 2016). While early outbreaks were mild, the disease has intensified in plantations (Harrington & Wingfield, 1998). Since the 1990s, outbreaks have increased across the Northern Hemisphere, affecting more species and regions, including the Baltic countries (Villebonne & Maugard, 1999; Hanso & Drenkhan, 2008). Severe infections reduce biomass growth, and tree mortality occurs when needle loss exceeds 85% (Gonthier & Nicolotti, 2013). Although *Dothistroma* alone rarely kills trees, it increases susceptibility to secondary infections, such as *Armillaria* spp. in young pine stands (Gonthier & Nicolotti, 2013). Two *Dothistroma* species cause needle blight: *D. septosporum* and *D. pini* (Barnes et al., 2004). *D. septosporum* is on the European and Mediterranean Plant Protection Organization (EPPO) quarantine list (EPPO, 2005). Both species occur in Latvia, with *D. septosporum* widespread and *D. pini* found in isolated western stands (Ķiesnere, 2014).

Diplodia sapinea is increasingly spreading across the Northern Hemisphere due to climate change, though initially, it was found only in southern regions. The first recorded cases of *D. sapinea* infection in Estonia date back to 2007, followed by reports in Sweden and Finland (Brodde et al., 2023). *D. sapinea* has a broad host range, but it primarily affects conifers. *Diplodia sapinea* induces various disease symptoms in conifers, such as needle browning, shoot blight, twig and branch dieback, crown wilt, and bark cankers in mature trees. It can also cause collar rot, root disease, seedling damping-off, and blue stain in sapwood. *Diplodia sapinea* is thought to be native to pine forests in the Northern Hemisphere, where it exists as an endophyte in pine shoots, becoming an opportunistic pathogen when the tree is under stress conditions, such as drought, insect damage, or frost (Adamson et al., 2021).

Lecanosticta acicola (Thüm.) Syd. (syn. *Mycosphaerella dearnessii* M. E. Barr) causes brown-spot needle blight, a major pine disease first identified in North America in 1876 (Tainter & Baker, 1996). It was first reported in Europe in 1942 in Spain, likely arriving through two historical infection routes: from the Mississippi region to Spain and from northeastern North America to Italy, then Northern Europe (Janoušek et al., 2014). Symptoms appear as small, irregular circular spots with well-defined margins, initially yellow or light gray green, later turning brown with a yellow halo (Van Der Nest et al., 2019). The disease has spread rapidly across Europe in recent decades (Drenkhan & Hanso, 2009; Jankovský et al.,

2009; Markovskaja et al., 2011; Hintsteiner et al., 2012; Adamson et al., 2015a; Adamčíková et al., 2021) and is listed as a quarantine organism by EPPO (EPPO, 2008). Initially *L. acicola* was found on ornamental pines in urban areas (Adamson et al., 2015a; Adamčíková et al., 2021), but it has since been observed in some *P. sylvestris* forest stands (Adamson et al., 2018). The disease spreads upward, driven by moisture, with spore dispersal starting at 2–3 °C (Tainter & Baker, 1996). In Latvia, *L. acicola* has been found only on ornamental pines, first reported in 2012 at the National Botanic Garden in Salaspils, with subsequent findings in 2016, and later near Daugavpils (Mullett et al., 2018; EPPO, 2021).

A better understanding of the distribution, impact, and contributing factors of these invasive pathogens is essential for developing effective management strategies. Therefore, this study aims to assess the occurrence and spread of pine needle and shoot diseases in Latvian pine forests, focusing on their potential impact on forest ecosystems.

Materials and Methods

The occurrence of needle diseases was assessed in young stands of Scots pine (*P. sylvestris*). In total, 165 survey sites were randomly selected across Latvia from the database of 'Latvia's State Forests' based on specific criteria: age up to 20 years, stand composition classified as pine monocultures, various forest types (Bušs, 1997), and an approximate area of one or more hectares. The selected stands were located near roads for easier accessibility. Stands were surveyed in 2021 (155 in spring and 10 in autumn).

Fieldwork methodology was adapted from previous studies of needle pathogens (e.g. Drenkhan & Hanso, 2009; Adamson et al., 2018). Each stand or planting site was visually assessed to evaluate overall vitality, presence of animal-caused damage, dead trees, and anthropogenic impacts. In each surveyed stand, 10 pines were randomly selected, and symptoms were recorded. Symptoms mainly included necrotic spots of varying shapes and colours. In symptomatic areas of needles, shoots, or cones, fungal reproductive structures (acervuli, pycnidia, or fruiting bodies) were examined.

In each surveyed stand, samples were collected from 2–3 symptomatic trees. If needles were already desiccated, they were collected along with a twig fragment. Samples were placed in labelled sterile bags and transported in a cooler box to the laboratory. Microscopic examination was conducted immediately or after storage at -20 °C.

For fungal identification, each needle sample was examined under a microscope for assessment of morphological characteristics of pathogenic fungi. In addition, fragments from symptomatic needles were analysed using molecular methods in collaboration with the Estonian University of Life Sciences (Prof. R. Drenkhan). Total DNA was extracted using the Thermo Fisher Scientific GeneJET Genomic DNA Purification Kit. Pathogens were identified through polymerase chain reaction (PCR) using species-specific primers for *D. septosporum*, *D. pini*, *L. acicola*, and *D. sapinea* (see Table 1).

The PCR cycling protocol (Adamson et al., 2015a) included an initial denaturation at 95 °C for 15 minutes, followed by 40 cycles of denaturation (95 °C for 30 s), annealing (for primers DStub2-F and R DPtef-F and R at 66 °C, but Latef-F and R DiSapiF and DiploR at 62 °C for 30 s), and extension (72 °C for 1 min), with a final extension at 72 °C for 10 minutes. PCR products (5 µl) were analysed on 1% agarose gel to confirm pathogen presence.

The relative proportion of symptomatic pines was calculated based on the total number of analysed trees in each forest type and compared among forest groups (dry, wet or over wet and drained (Table 2)) using the Chi-square test.

Results and Discussion

In total, 165 pine sapling stands were surveyed in 2021, covering an area of 382 hectares (Table 2). The tree ages ranged from 3 to 19 years. The majority of analysed stands (160 or 97%) showed some needle cast symptoms. The proportion of healthy and symptomatic pines in dry and drained forest types was close to predicted values of Chi-square test, but in wet or over wet forest sites more symptomatic pines than predicted were observed ($p<0.05$). Previous studies have suggested that selecting the right forest type for pine cultivation can help reduce the risk of needle blight in pines (Boateng & Lewis, 2015; Bulmann et al., 2016). Our findings support this, showing that pine saplings might experience more needle blight damage in wet or over wet forest types.

Invasive needle pathogens were detected in 50% of analysed stands in total. ***Dothistroma*** was identified as the dominant genus in collected needle samples based on microscopic characteristics, including characteristic red discoloration on needles, acervuli, and conidia. The disease was detected in 68 out of 165 pine stands surveyed. Infected stands varied in age and forest type. Crown damage was mostly minor and localized, affecting 0–50% of surveyed trees (on average, 0.3% per stand). Despite mild symptoms, some authors suggest that *Dothistroma* infections can still reduce biomass production in conifers (Gonthier & Nicolotti, 2013). While tree mortality in such cases is rare (2% of severe needle loss), the risk increases when *Dothistroma* co-occurs with other pathogens like *Armillaria* spp. or *Diplodia* spp. (Gonthier & Nicolotti, 2013).

The distribution map 'Figure 1' of molecularly identified *Dothistroma septosporum* indicates that it is widespread across Latvia (49 records). Molecular analyses confirmed that symptoms were primarily caused by *D. septosporum*, aligning with previous studies showing its dominance in Latvia (Ķiesnere,

2014). Although both *D. septosporum* and *D. pini* have been identified on Scots pine in Latvia (Ķiesnere, 2014), only *D. septosporum* was found in this study. The pathogen's adaptation and virulence are linked to its genetic diversity, influenced by sexual reproduction potential. Both mating types of *D. septosporum* exist in Latvia, but some stands may possess only one, limiting the sexual reproduction (Ķiesnere, 2014).

Table 1

Primers used for Dothistroma septosporum, Dothistroma pini, Lecanosticta acicola, and Diplodia sapinea identification

Target Organism	***Primers (Forward & Reverse)***	***Reaction Components***
Dothistroma septosporum	DStub2-F (5' – CGAACATGGACTGAGCAAAAC – 3') DStub2-R (5' – GCACGGCTCTTTCAAATGAC – 3') (Ioos et al., 2010)	4 µl HOT FIREPol® Blend Master Mix RTL With 10 mM $MgCl_2$ (Solis BioDyne) 0.5 µl of each primer 14 µl ddH_2O 1 µl DNA sample (50 ng/µl)
Dothistroma pini	DPtef-F (5' – ATTTTTCGCTGCTCG – 3') DPtef-R (5' – CAATGTGAGATG – 3') (Ioos et al., 2010)	0.2 µl HOT FIREPol® polymerase 2 µl HOT FIREPol® 10x Buffer B2 1.6 µl 25 mM $MgCl_2$ 0.5 µl of each primer 13.2 µl ddH_2O 2 µl DNA sample (50 ng/µl)
Lecanosticta acicola	Latef-F (5' – GCAAATTTTCGCCGTTTATC – 3') Latef-R (5' – TGTGTTCCAAGAGTGCTTGC – 3') (Ioos et al., 2010)	4 µl HOT FIREPol® Blend Master Mix RTL With 10 mM $MgCl_2$ (Solis BioDyne) 0.5 µl of each primer 14 µl ddH_2O 1 µl DNA sample (50 ng/µl)
Diplodia sapinea	DiSapiF (5' – CCCTTATATATCAAACTATGCTTTGT – 3') DiploR (5' – TTACATAGAGGATTGCCTTCG – 3') (Riit, 2014)	4 µl HOT FIREPol® Blend Master Mix RTL With 10 mM $MgCl_2$ (Solis BioDyne) 0.5 µl of each primer 14 µl ddH_2O 1 µl DNA sample (50 ng/µl)

Table 2

Characteristics of the surveyed pine stands in 2021 grouped by forest type (area, number, average age, and vitality)

Forest type according Bušs 1997 (D – dry, W – wet or over wet and Dr – drained)	***Total area, ha***	***Number of stands***	***Average age, years***	***Proportion of healthy trees, %***	***Proportion of trees with needle damage, %***
Hylocomiosa (D)	112.3	44	9.7	45%	55%
Myrtillosa (D)	132.8	53	9.2	39%	61%
Vacciniosa (D)	55.2	23	9.5	29%	71%
Cladinoso-callunosa (D)	1.6	1	8.0	40%	60%
Myrtilloso-sphagnosa (W)	9.7	5	10.4	34%	66%
Vaccinioso-sphagnosa (W)	13.8	8	10.1	16%	84%
Myrtillosa mel. (Dr)	31.8	14	9.1	51%	49%
Vacciniosa mel. (Dr)	14.5	9	10.6	27%	73%
Myrtillosa turf. mel. (Dr)	3.8	3	9.0	20%	80%
Vacciniosa turf. mel. (Dr)	1.8	1	13.0	0%	100%
Callunosa turf. mel. (Dr)	1.0	2	6.5	65%	35%
Caricoso-phragmitosa (W)	4.0	2	10.0	35%	65%

Several factors may explain the recent increase of *Dothistroma* needle blight incidence in the Northern Hemisphere, including climate change and expanding plantation forestry with susceptible tree species. In British Columbia, outbreaks have been linked to warm, wet weather patterns in the mid-to-late 1990s (Woods et al., 2005). Similarly, in Europe, prolonged rainfall has been associated with disease outbreaks (Kirisits & Cech, 2006; Hanso & Drenkhan, 2008; Drenkhan & Hanso, 2009; Welsh et al., 2014; Woods et al., 2016; Markovskaja et al., 2020). High humidity and excessive precipitation escalate *D. septosporum* spore germination and needle infection (Brown et al., 2003; Boateng & Lewis, 2015). In regions without distinct seasonal variations, infections persist and spread year-round (Rodas & Wingfield, 2020).

As a disease management strategies, copper-based fungicides are effective but are mainly used in managed forests in Australia and New Zealand (Bulmann et al., 2016). Other approaches focus on silvicultural interventions, such as thinning young pine stands and pruning. *Dothistroma* spores primarily disperse within a two-meter radius (Boateng & Lewis, 2015), so thinning young pine stands can reduce disease spread. Pruning young pine stands and selecting appropriate site conditions can help reduce disease incidence (Boateng & Lewis, 2015; Bulmann et al., 2016). In Europe, the most widely adopted strategy involves breeding resistant pine species and restricting the movement of infected planting material (Bulmann et al., 2016; Markovskaja et al., 2020).

Diplodia sapinea was detected in 29 of 165 or 18% of surveyed stands 'Figure 2'. In four of those stands, all trees appeared healthy, with no visible needle damage, and only one tree showed minor, localised crown damage. This could be due to the endophytic nature of the fungus, which is often found in pine branches, buds, and needles, becoming pathogenic only under stress conditions (Stanosz et al., 2001; Bußkamp et al., 2020; Oliva et al., 2020).

Our data indicated that the characteristic soil properties of different forest types have probably influenced the contrasting patterns of *D. sapinea* presence. Sites where *D. sapinea* was absent had soils with higher water-holding capacities, while affected sites were located on bedrock, possibly making them more vulnerable to drought stress. The previous study suggested that *D. sapinea* may contributed to the crown dieback, impacting trees' ability to recover after severe drought, but the predictions of future drought-fungus caused dieback varies by region, season, and emission scenario (Brodde et al., 2023).

The ecology and pathogenicity of this species is also related to its origin. A study on the genetic diversity of *D. sapinea* in Europe found that its origin in the Baltics could be attributed to its long history as an endophyte or asymptomatic organism (Adamson et al., 2021). The European *D. sapinea* population is dominated by a single haplotype and high genetic similarity across different regions, indicating significant gene flow between countries, except for Italy and Georgia. *Diplodia sapinea* in Latvia are genetically similar to Estonia's samples, suggesting that the infection may have originated from Germany (Adamson et al., 2021).

Removing infected trees showing symptoms is recommended to prevent further spread (Brodde et al., 2019; Rodas & Wingfield, 2020).

There were no records of ***Lecanosticta acicola*** in pine stands in this study. Based on these data, we conclude that in Latvia, as in other European countries, the disease is mainly or initially found in populated areas on ornamental pine plantings (Adamson et al., 2015a; Adamčíková et al., 2021). However, in Estonia, the infection of Scots pine and the spread of the disease in forest stands were already reported in 2016 (Adamson et al., 2018).

Currently, *Lecanosticta acicola* has been reported in 24 European countries, and its distribution is expected to increase (Tubby et al., 2023). *Lecanosticta acicola* is not typically a pathogen of *P. sylvestris*; it generally prefers other *Pinus* species. However, since *P. sylvestris* is an important species in Europe, monitoring the occurrence of *L. acicola* remains critical. To prevent widespread outbreaks, precautionary measures should include avoiding planting new trees near infected ones, developing resistant varieties, and applying fungicides (Van Der Nest et al., 2019).

Figure 1

Distribution of Dothistroma septosporum needle blight in surveyed forest stands: ● – forest stands, where the symptoms were caused by the fungus Dothistroma septosporum, ● – forest stands in which Dothistroma septosporum was not found

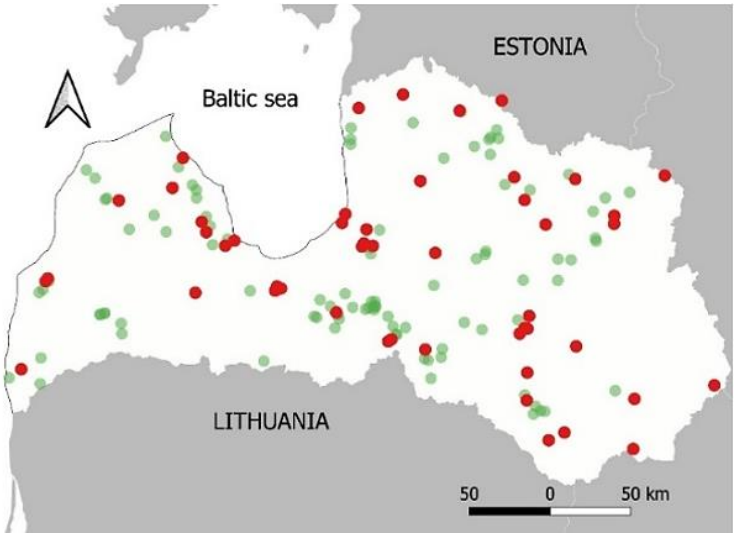
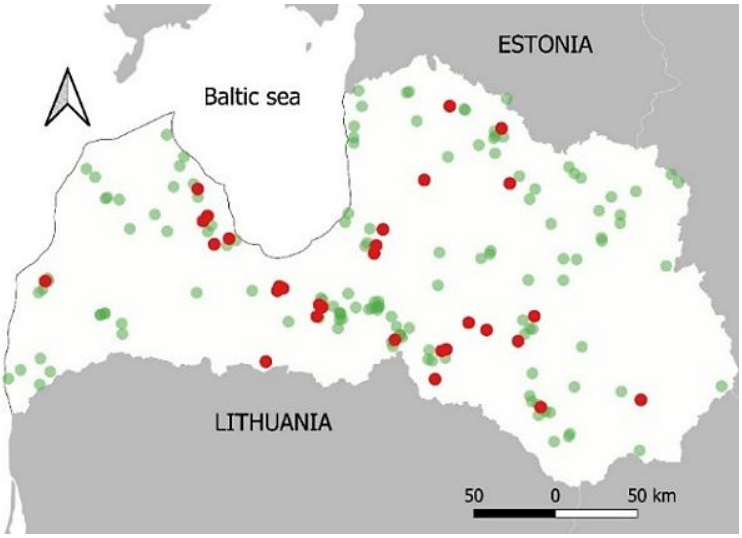


Figure 2
Distribution of Diplodia sapinea needle blight in surveyed forest stands: ● – forest stands, where the symptoms were caused by the fungus D. sapinea, ● – surveys where D. sapinea was not found



A recent genome-wide analysis of *Lecanosticta acicola* revealed genetic introgression between the southern and northern lineages, indicating active mating between them. Additionally, phenotypic differences were identified based on enzymatic activity, with introgressed strains resembling the southern lineage (Marcet-Houben et al., 2024). These results highlight ongoing genetic admixture in a recently expanded population, which could lead to the emergence of new traits in this fungal pathogen affecting conifers.

Conclusions

1. Based on surveys conducted in 2021, nearly all young pine stands analysed around Latvia showed some needle cast symptoms, and in 50% of the stands analysed the presence of invasive fungal pathogens was detected. The dominant invasive needle blight causing species was *Dothistroma septosporum*, which was found to be widespread across the country.
2. *Diplodia sapinea* was also frequently encountered, particularly in nutrient-poor and drought-prone sites. As this species is causing blue stain, its presence in the young plantings should also be considered in the relation to the further wood quality.
3. To reduce the impact of these pathogens, it is recommended to implement silvicultural practices, such as thinning or twig removal in infected areas, consider appropriate forest types and genetically resistant pine clones for planting.
4. Future research should focus on understanding the dynamics, virulence, spread and impact of these pathogens to local forest ecosystems as well as economic losses and further perspectives for infected stands.

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WOOD QUALITY THREATS FOR ECONOMICALLY IMPORTANT TREE SPECIES IN LATVIA: FINDINGS ON WOOD COLONIZING FUNGI

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Abstract
This study investigated the wood colonization by rot, blue stain or discoloration causing fungi, focusing on the quality of roundwood assortments of several economically important tree species in Latvia. A total of 105 trees were analysed across Latvia, including *Pinus sylvestris* (34), *Picea abies* (22), *Betula pendula* (10), *Alnus glutinosa* (29), and *Populus tremula* (10). Trees were randomly selected during or after felling based on visible signs of fungal infection: wounds, blue stain, wood discolouration, stem rot, cracks, and other symptoms. Wood-inhabiting fungi were isolated from different zones of one disc per tree (340 wood samples in total). Fungi were identified based on their morphological characteristics and molecular analysis (ITS region sequencing with primers ITS4 and ITS1F). A total of 56 fungal taxa were isolated from the wood samples. Among the rot-causing fungi, *Heterobasidion* spp. was frequently isolated from conifers; *Porodaedalea pini* and *Stereum sanguinolentum* were isolated specifically from pine and *Amylostereum areolatum* - from spruce. *Xanthoporia radiata* and *Eutypella cerviculata* were frequently isolated from black alder; while - *Phellinus tremulae* - from aspen wood. The blue stain causing fungi *Ophiostoma* spp. were isolated from pine, spruce and birch wood, while *Diplodia* spp. – only from spruce. This work was funded by JSC Latvia's State Forests (project No. 5-5.5.1_0009_200_24_7) and Forest4LV (project No. VPP-ZM-VRIIILA-2024/2-0002).
Keywords: *Picea abies*, *Pinus sylvestris*, deciduous trees, rot-causing fungi, blue stain fungi.

Introduction

Latvia's forests cover approximately 52% of the country's territory, making them a crucial component of the nation's landscape, biodiversity, and economy (Latvian State Forest Service, 2024). These forests are dominated by both coniferous and broadleaf tree species, 51% of the whole forest land is dominated Scots pine *Pinus sylvestris* and Norway spruce *Picea abies*, 30% is silver birch *Betula pendula*, 7% is European aspen *Populus tremula* and 4% is black alder *Alnus glutinosa* (Latvian State Forest Service, 2024). Given their economic and ecological importance, these tree species play a fundamental role in supporting forest biodiversity, regulating the carbon cycle, and providing valuable timber resources (Wani et al., 2021).

Forest ecosystems contribute significantly to soil stabilization and habitat formation, making them essential for global and regional environment. However, forest health is increasingly threatened by various biotic stress factors, including fungal pathogens that cause wood decay. Wood-decay fungi reduce the viability of trees and the commercial value of wood by causing structural damage, discoloration, and decomposition. These fungi include both saprotrophic species that degrade dead wood and pathogenic species that infect living trees and accelerate decay and mortality.

In Latvia, one of the biggest threats to coniferous forests are rot-causing pathogens, such as *Heterobasidion* spp., *Stereum sanguinolentum*, *Armillaria* spp. and *Porodaedalea pini* (Burņeviča et al., 2016; Szewczyk et al., 2016; Zaļuma et al., 2022; Klavina et al., 2023). Among these, *Heterobasidion* spp. is one of the most aggressive pathogens in whole Northern Europe, particularly affecting Scots pine and Norway spruce by causing root and butt rot, which leads to high tree mortality, reduced timber quality, and substantial economic losses (Asiegbu et al., 2005; Gaitnieks et al., 2008). In Europe alone, the estimated annual losses of *Heterobasidion* root rot is about one billion euro (Kovalchuk et al., 2022). *Porodaedalea pini* is a significant pathogen of Scots pine, causing heartwood decay that causes stem rot, and makes timber commercially unsuitable (Szewczyk et al., 2016). *Stereum sanguinolentum* is one of the most frequently isolated decay fungi in damaged spruce wood, following thinning operations in young stands across Central and Northern Europe (Mäkinen et al., 2007).

For deciduous trees common in Latvia, some studies have focused on rot fungi in grey and black alder stands (Arhipova et al., 2011; Arhipova et al., 2012). Recently, there have been sporadic studies about birch and aspen wood inhabiting fungi (Ciseļonoka et al., 2024, Miklašēvičs et al., 2024). The main rot-causing agents vary by species: *Xanthoporia radiata* (formely *Inonotus radiatus*) often colonizes alders, *Phellinus tremulae* is a primary agent of white trunk rot in European aspen, significantly reducing wood quality and shortening tree lifespan (Wikström, 1976), while *Armillaria* may cause root rot to several deciduous tree species (Guillaumin & Legrand, 2013).

Other problem, which cause decrease in wood quality, especially during timber storage is wood blue stain, discoloration and wood molding, caused by various Ascomycota genera (Highley, 2004; Uzunovic et al., 2008). This study aims to investigate fungal species associated with economically important tree species in Latvia, focusing on roundwood-colonizing fungi that cause blue stain, discoloration, rot and decay to strengthen the knowledge base of forest workers about fungal damage in timber.

Materials and Methods

While the age of the trees sampled in 2024 was not specifically determined as the study prioritized the analysis of visible symptoms, the investigation aimed to identify potential root rot and evaluate if it could degrade wood quality to the point of excluding it in the use of structural buildings. The wood disc samples were taken from 105 mature livingtrees (34 Scots pine *Pinus sylvestris* (average disc diameter – 30 cm), 22 Norway spruce *Picea abies* (average disc diameter – 28 cm), 29 black alder *Alnus glutinosa* (average disc diameter – 36 cm), 10 European aspen *Populus tremula* (average disc diameter – 39 cm) and 10 birch *Betula pendula* (average disc diameter – 32 cm). Trees were randomly selected during or after felling based on visible signs of fungal infection: wounds, blue stain, wood discolouration, stem rot, cracks, and other symptoms. From each tree, a single 2-3 cm thick wood disc was dissected from the cutting surface. Discs were marked, stored separately in plastic bags, and transported to the laboratory for pathogen identification. In the laboratory, 0.5-1 cm wood pieces were extracted from the wood discs, using a flame-sterilised chisel (Vasiliauskas & Stenlid, 1998). The top layer of wood was carefully removed from the disc's surface then sterilized again, and small pieces of the discolored and symptomatic wood were collected at one to five points per disc, depending on the disc size and the decay extent. The extracted samples were then flame sterilised with disinfected tweezers and placed on a sterile Petri dishes with Hagem agar media (5 g glucose, 0.5 g NH_4NO_3, 0.5 g $MgSO_4$ $7H_2O$, 5 g malt extract, 20 g agar, 1000 mL distilled H_2O at pH 5.5). Petri dishes with wood samples were incubated at room temperature (21 °C) and monitored every two days for fungal mycelium growth. Fungal colonies that could not be identified microscopically and were potentially associated with wood decay were individually subcultured on separate Petri dishes with Hagem agar media (5 g glucose, 0.5 g NH_4NO_3, 0.5 g KH_2PO_4, 0.5 g $MgSO_4$, 5 g malt extract, 20 g agar, 1000 mL distilled H_2O at pH 5.5) and subjected for molecular identification.

For molecular identification, fungal aerial mycelium was carefully scraped from pure cultures using a flame-sterilized scalpel and transferred into a 2 mL tubes. DNA extraction was performed at the LSFRI Silava Genetic Resource Center using a modified CTAB method (Arhipova, 2012). PCR reactions were performed in a volume of 10 µl containing approximately 50 ng DNA, 2 µl HOT FIREPol® Blend Master Mix (Solis BioDyne) (containing 10 mM $MgCl_2$), 0.3 µM the fungal-specific forward primer ITS1F (5'-CTTGGTCATTTAGAGGAAGTAA-3') and reverse primer ITS4 (5'-TCCTCCGCTTATTGATATGC-3') (White et al., 1990; Gardes & Bruns, 1993). PCR was carried out in a thermocycler (Eppendorf Mastercycler epgradient) using the following protocol: initial predenaturation step at 95 °C for 12 min, followed by 35 cycles of 95 °C for 30 s, 55 °C for 30 s, and 72 °C for 45 s and a final extension step of 72 °C for 7 min. The ITS region was Sanger sequenced in both directions using the same primers - ITS4 and ITS1F at the LSFRI Silava Genetic Resource Center. Nucleotide sequences were analyzed using the BLAST function in the UNITE and NCBI platforms (Altschul et al., 1997; Nilsson et al., 2018). The criteria to assign taxonomy for representative sequences was based on BLAST thresholds: family-level > 85%, genus-level > 90%, and species-level > 97%. Taxa falling below these thresholds were considered unidentified fungi at the respective taxonomic levels. To assign ecological functions and primary lifestyle to each fungal genus, FungalTraits database was used (Põlme et al., 2020).

The obtained sequences were deposited in GenBank with the accession number PV351336-PV351394.

We analysed percentage (%) of wood samples and proportion of wood discs colonized by each fungal species. Incidence of each fungal species was calculated for each tree species separately.

Results and Discussion

From the analysis of 105 wood discs and their corresponding 340 wood samples (116 from pine, 87 from black alder, 63 from spruce, 40 from aspen, and 34 from birch) a total of 56 fungal taxa were identified (Table 1 and 2). The most frequently isolated fungi across all tree species were from phylum Ascomycota such as *Alternaria*, *Cladosporium* and *Trichoderma.* These genera include saprotrophic, endophytic, and parasitic species, some of which are also plant pathogens (Põlme et al., 2020; Stępniewska et al., 2021). For example, some species of the genus *Alternaria* are widespread pathogens of leaves and young shoots (Matić et al., 2020). Additionally, several species from genera *Cladosporium* and *Fusarium* can become pathogenic to the plant under stress conditions such as prolonged drought, heat, or frost (Photita et al., 2004). *Ascocoryne* is very often present in spruce wounds as an endophyte or saprotroph (Vasiliauskas & Stenlid, 1998; Burneviča et al., 2016). *Schizophillum commune* was also identified; it is a common saprotroph in Latvia that grows on already dead deciduous wood, causing white rot but occasionally infects weakened living trees (Arhipova et al., 2011).

Several pathogenic fungi were identified, including *Botrytis cinerea* (Ascomycota), which causes grey mold (Williamson et al., 2007). While not a primary pathogen of adult conifers, it causes moldy needles in seedlings in nurseries (Lilja, 1986; Lilja et al., 2010). The pathogenic fungus *Neonectria tsugae* was also isolated from several samples. While this fungus does not cause wood decay, it is associated with canker formation in conifers, which weakens trees and increases their susceptibility to secondary infections

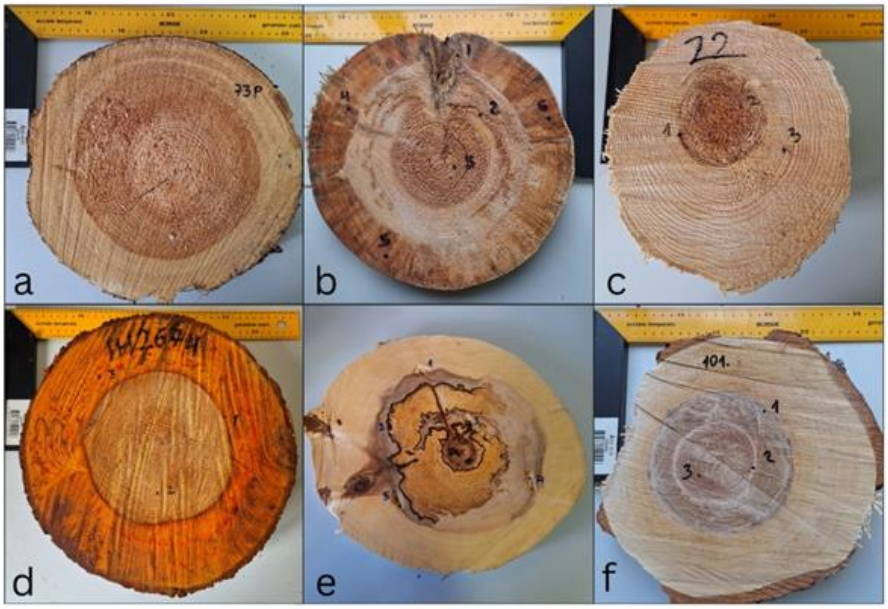
and environmental stress (González & Chaverri, 2017; Durodola et al., 2023).

Among the analyzed species, several blue-stain fungi of the genus *Ophiostoma* were isolated from Scots pine and European aspen samples. Another fungus *Aureobasidium pullulans* associated with blue-stain was isolated from Scots pine, European aspen and silver birch wood samples. *Aureobasidioum pullulans* is more widely known as black yeast that can penetrate wood surface coatings (Deshpande et al., 1992; Bardage, 1998). *Diplodia* sp. was also detected as blue stain causing for conifers (Brodde et al., 2019; Brodde, 2023). While these fungi do not cause mechanical degradation, they reduce the aesthetic and commercial value of the wood due to discoloration (Deshpande et al., 1992; Bardage, 1998; Brodde, 2023).

Eight wood-decaying and rot-causing fungi were identified in Scots pine and Norway spruce samples: *Amylostereum areolatum*, *Bjerkandera adusta*, *Cylindrobasidium evolvens*, *Heterobasidion* spp., *Porodaedalea pini*, *Sistotrema brinkmannii*, *Stereum sanguinolentum*, and *Trametes versicolor*, of which *Heterobasidion* spp., *P. pini* and *S. sanguinolentum* is considered one of the most severe pathogens of conifers. *Heterobasidion* spp. is among the most aggressive tree pathogens in Northern Europe, causing root and butt rot ʻFigure 1a'. *P. pini* is often referred to as ʻred-ring rot' due to the characteristic reddish-brown discoloration of the wood ʻFigure 1b'. It primarily infects the lower trunk, leading to significant structural weakening and rendering the timber commercially unsuitable (Szewczyk et al., 2016).

Figure 1

Evaluated wood discs: a - Scots pine (Heterobasidion spp. - white rot agent isolated), b - Scots pine (Porodaedalea pini - brown rot/red-ring rot agent isolated), c - Norway spruce (Amylostereum areolatum - white rot causing fungus isolated), d - black alder (Chondrostereum purpureum isolated), e - European aspen (Phellinus tremulae - white rot causing fungus isolated), f - e – silver birch (Pholiota spp. - white rot causing fungus isolated)



It spreads rapidly within the wood, with studies in Poland reporting that decay affects an average of 40% of the total trunk volume and nearly half of the cross-sectional area at the infection site. This leads to a significant reduction in the tree's mechanical stability and disrupts its physiological processes (Čermák et al., 2004). *Amylostereum areolatum* infects conifers, especially pines, causing white rot in living trees ʻFigure 1c'. This fungus primarily spreads via the invasive woodwasp *Sirex noctilio*, which inoculates trees with fungal spores while creating oviposition tunnels in the bark and laying their larva, making this a symbiotic relationship (Thomsen & Koch, 1999). Although neither *A. areolatum* nor the woodwasp currently cause widespread tree mortality in Northern Europe, they are considered to be a problem for the pine and spruce plantations in Central and Southern Europe (Vasiliauskas & Stenlid, 1999). In Latvia and Lithuania, *A. areolatum* is frequently isolated from damaged wood (Vasiliauskas, 1999; Burņeviča et al., 2016).

In black alder samples, the fungal pathogen *Chondrostereum purpureum* was detected ʻFigure 1d'. This species causes white rot and wood discoloration and is more commonly associated with birch. Although rarely considered a primary pathogen, it can significantly contribute to the decline of already weakened trees (Wall, 1991). The white-rot fungus *Xanthoporia radiata* was also identified. This species

is predominantly saprotrophic and does not typically pose a threat to healthy trees (Germain et al., 2002). However, some studies have reported its presence in frost-damaged or decayed alder trees, suggesting potential pathogenicity under specific conditions (Kodrík et al., 2006; Arhipova et al., 2011). Both *X. radiata* and *C. purpureum* have been frequently isolated in Latvia and Lithuania (Arhipova et al., 2011; Iršėnaitė et al., 2013). Overall, no serious pathogens or rot-causing fungi were detected in black alder tree samples.

European aspen samples were found to be infected with the white-rot fungus *Phellinus tremulae*, a primary agent of trunk rot that infects both sapwood and heartwood ʿFigure 1e'. The structural degradation of the wood caused by the fungus significantly shortens tree lifespan and reduces its commercial value (Wikström, 1976).

Silver birch samples revealed colonization of *Pholiota* sp., a wood saprotroph occasionally reported as a secondary root pathogen causing white rot ʿFigure 1f', and *Trametes versicolor*, predominantly saprotrophic but occasionally pathogenic in weakened trees (Terho et al., 2007; Bari et al., 2019; Kymäläinen et al., 2022). *Botrytis cinerea* was also isolated from silver birch samples, though it primarily affects conifer seedlings in nurseries rather than birch (Lija et al., 2010).

Bacteria were isolated from most of wood discs of all tree species. Some authors noted that bacteria could be involved in decay and discoloration processes in tree wood (Shortle et al., 1978; Clause, 1996; Zhang et al., 2022), but more researches needed to fully understand those impact to decay processes and interaction with decay causing fungi. However, not all causes of wood discoloration could be attributed to decay-cousin microorganisms or bacteria, as some symptomatic wood discs had not yielded any fungal or bacterial growth, remaining sterile, even after repeated samplings: 40% of birch and 40% of aspen wood disks, 17% of pine discs and 10% of spruce disks. Discoloration of wood, caused by factors other, than pathogens, previously reported for several tree species. For example, photochemical discoloration (caused by UV light) could occur in some species of pine, spruce and oak; biochemical discoloration is typical for alders; chemical (in contact with iron) occurs in oak wood; brownstain can develop in western hemlock, true firs and ponderosa pines after tree felling (Kreber, 1994). Also, discoloration could be associated with tree aging and stem injuries (Shigo & Hillis, 1973). Discoloration caused by factors other than fungal activity usually have an impact only on timber visual quality, but have no or little influence for mechanical wood properties, which made such discoloured wood suitable for many purposes, not only as firewood or pulpwood.

In sawmills, the quality assessment of timber for building structures is important, as it will be reflected later in the lifetime of the structure. When staining is detected, the sawn timber is often assessed to lower quality. If the cause of the staining is wrongly identified as a fungal decay that damages the wood structure, it causes economical losses which could be reduced with more precise identification and detection of decay type. Improved understanding of wood discoloration causing factors, as well as identification tool for different kind of discoloration is needed to help workers of forestry sector to evaluate timber assortment more precisely, thus reducing losses of valuable timber.

Table 1

Basidiomycetes and Mucorales fungi isolated from wood samples from five tree species (pine, spruce, alder, birch and aspen) in Latvia. Additional information about analysed material

Fungal species	***Pinus sylvestris***	***Picea abies***	***Alnus glutinosa***	***Betula pendula***	***Populus tremula***
	% of wood samples from which the fungus were isolated / % of wood discs from which the fungus were isolated				
Basidiomycota (decay causing fungi)					
Amylostereum areolatum	-	3.2/10.0	-	-	-
Bjerkandera adusta	0.9/2.8	-	2.3/6.9	-	5.0/10.0
Chondrostereum purpureum	-	-	1.1/3.4	-	-
Cylindrobasidium evolvens	-	1.6/5.0	1.1/3.4	8.8/10.0	-
Heterobasidion sp.	6.0/5.6	17.4/25.0	-	-	-
Phellinus tremulae	-	-	-	-	7.5/30.0
Phlebiopsis gigantea	2.6/5.6	-	-	-	-
Pholiota sp.	-	-	-	8.8/20.0	-
Porodaedalea pini	7.8/16.7	-	-	-	-

Fungal species	***Pinus sylvestris***	***Picea abies***	***Alnus glutinosa***	***Betula pendula***	***Populus tremula***
	% of wood samples from which the fungus were isolated / % of wood discs from which the fungus were isolated				
Schizophyllum commune	-	-	-	2.9/10.0	-
Sistotrema brinkmannii	0.9/2.8	4.8/5.0	-	-	2.5/10.0
Stereum sanguinolentum	0.9/2.8	-	-	-	-
Trametes versicolor	0.9/2.8	-	-	2.9/10.0	-
Xanthoporia radiata	-	-	29.9/58.6	-	5.0/9.1
Mucorales					
Mucor sp.	3.4/11.1	4.8/5.0	4.6/13.8	-	2.5/10.0
Umbelopsis sp.	5.2/13.9	6.3/15.0	12.6/34.5	2.9/10.0	-
Other data					
Bacteria	41.4/69.4	65.1/90	87.4/96.6	58.8/90.0	47.5/80.0
No fungal or bacterial growth detected	6.0/16.7	4.8/10	-	17.6/40.0	10.0/40.0
Number of samples/number of trees	116/34	63/20	87/29	31/10	43/10

Table 2

Ascomycetes isolated from wood samples from five tree species (pine, spruce, alder, birch and aspen) in Latvia

Fungal species	***Pinus sylvestris***	***Picea abies***	***Alnus glutinosa***	***Betula pendula***	***Populus tremula***
	Fungi (% of wood samples from which the fungus were isolated /% of wood discs from which the fungus were isolated)				
Blue-stain causing Ascomycota					
Aureobasidium pullulans	0.9/2.8	1.6/5.0	2.3/6.9	2.9/10.0	2.5/10.0
Ceratocystis minor	0.9/2.7	-	3.4/10.3	-	-
Leptographium piriforme	-	-	-	-	7.5/9.1
Ophiostoma sp.	4.3/8.3	-	-	-	5.0/20.0
Other Ascomycota					
Alternaria sp.	0.9/2.8	4.8/15.0	-	5.9/20.0	2.5/10.0
Ascocoryne sp.	6.0/13.9	3.2/10.0	4.6/10.3	-	7.5/30.0
Aspergillus sp.	-	-	1.1/3.4	-	-
Botrytis cinerea	-	-	-	2.9/10.0	-
Cadophora sp.	0.9/2.8	-	1.1/3.4	-	-
Cladosporium sp.	1.7/2.8	3.2/10.0	8.0/17.2	2.9/10.0	10.0/40.0
Cosmospora sp.	-	-	-	-	2.5/10.0
Cosmospora viridescens	-	-	1.1/3.4	-	-
Cytospora phialidica	-	-	-	2.9/10.0	-
Cytospora sp.	0.9/2.8	1.6/5.0	-	-	-
Diatrype sp.	-	-	-	-	2.5/10.0
Didymella sp.	-	-	1.1/3.4	-	-
Dydimellaceae sp.	5.2/16.7	-	3.4/10.3	5.9/20.0	5.0/20.0
Diplodia sp.	0.9/2.8	3.2/5.0	-	-	-
Endoconidiophora polonica	-	1.6/5.0	-	-	-
Epicoccum nigrum	-	3.2/5.0	-	5.9/10.0	-
Eutypella cerviculata	-	-	2.3/6.9	-	-
Fusarium sp.	0.9/2.8	1.6/5.0	-	-	2.5/10.0

Fungal species	***Pinus sylvestris***	***Picea abies***	***Alnus glutinosa***	***Betula pendula***	***Populus tremula***
	Fungi (% of wood samples from which the fungus were isolated /% of wood discs from which the fungus were isolated)				
Fusarium tricinctum	1.7/5.6	-	-	-	-
Hormonema sp.	-	1.6/5.0	-	2.9/10.0	-
Ilyonectria sp.	-	-	-	2.9/10.0	-
Leptodontidium trabinellum	-	-	-	-	7.5/20.0
Lophium arboricola	-	1.6/5.0	-	-	-
Neonectria tsugae	0.9/2.8	9.5/20.0	-	2.9/10.0	-
Penicillium sp.	13.8/36.1	25.4/55.0	26.4/72.4	8.8/30.0	30.0/70.0
Parafenestella sp.	-	-	1.1/3.4	-	-
Phialocephala dimorphospora	0.9/2.8	-	1.1/3.4	-	-
Pseudogymnoascus hyalinus	2.6/8.3	1.6/10.0	-	-	-
Pyrenochaeta xanthriae	-	-	-	-	2.5/10.0
Sordariaceae sp.	-	-	-	-	5.0/10.0
Sordariales sp.	-	-	5.7/13.7	-	-
Thyronectria cucurbitula	0.9/2.8	-	-	-	-
Thyronectria sp.	-	-	1.1/3.4	2.9/10.0	-
Trichoderma sp.	23.3/36.1	14.3/30.0	3.5/10.3	11.8/20.0	15.0/30.0
Truncatella angustata	-	1.6/5.0	1.1/3.4	-	-
Xylariaceae sp.	-	-	-	-	2.5/10.0

Conclusions

1. The analysis of fungal communities across five tree species revealed a diverse assemblage of fungal taxa. White-rot fungi were the most frequently isolated wood-decaying organisms across all studied tree species, suggesting their dominant role in wood decomposition processes in Latvian forests.
2. Prevalence of *Heterobasidion* spp. in Norway spruce and *Porodaedalea pini*, in Scots pine samples underscores the substantial economic and ecological impact of these fungi, particularly in conifer-dominated forests.
3. The presence of *Amylostereum areolatum* in Norway spruce samples also indicates potential threats to forest health. Furthermore, the presence of blue-stain fungi such as *Ophiostoma* spp. and *Aureo-basidium pullulans* highlights their importance in timber quality assessments. Moreover, wood discoloration caused by factors other than fungal activity, is also abundant in several tree species (mostly birch, aspen and pine).
4. Further research should focus on understanding the interactions between wood-decaying fungi and various host trees and age classes, as well as forest management strategies to mitigate these threats and sustain forest vitality and productivity.

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VIRTUAL STAINING FROM OPTICAL COHERENCE TOMOGRAPHY TO HEMATOXYLIN AND EOSIN STAINED SKIN TUMOR SAMPLES IN PETS

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Abstract
Recently, virtual staining has revolutionized histopathology by utilizing AI for efficient H&E staining, reducing the need for specialized personnel. The use of virtual staining in veterinary medicine, particularly in transitioning from OCT to H&E, is inadequately addressed in current research. We employed generative adversarial networks to convert OCT images from canine and feline soft tissue sarcoma paraffin blocks into representations akin to H&E staining. The models were trained on 512x512 pixel paired and unpaired image patches, using a manually H&E stained image as a reference and OCT images as inputs. The neural network model employing transfer learning failed to attain microscopic accuracy, necessitating a complete retraining without transfer learning. Subsequent evaluations with Pix2Pix yielded no improvements, prompting a transition to ResNet, U-net, and Dense U-net architectures, which also did not enhance performance. This study aimed to ascertain the feasibility of utilizing the existing OCT database to generate pilot virtual staining on C-scan images through neural networks. Given that our output images did not yield satisfactory results for veterinary oncology, further research is imperative to optimize the neural network for virtually stained OCT images, with a focus on enhancing the OCT dataset.
Keywords: OCT, veterinary oncology, neural networks, non-invasive imaging, tumor diagnostics.

Introduction

Recently, virtual staining (VS) has transformed the histopathology field, where specially trained artificial intelligence (AI) employs standard H&E (hematoxylin and eosin) staining as a reference (Li et al., 2021; Tavolara et al., 2023). In veterinary oncology, histopathology plays important role because it has been accepted as gold standard. But because of several important facts (sampling needs anesthesia, it is invasive procedure and, for obtaining results, time is needed), OCT (Optical Coherence Tomography) has demonstrated potential as an efficient technique which is more advanced because that can produce real-time, non-invasive tissue evaluation, outlining tumor margins during surgery and even assisting in tumor type diagnosis (Ribeiro et al., 2022).

Thus far, OCT has been used for evaluating normal skin structures in humans and various animals, as well as skin lesions with dermatological and oncological diseases (Winetraub et al., 2024). In veterinary oncology, OCT has been utilized for skin and subcutaneous tumors, demonstrating the capability to distinguish these tumors to a certain percentage accuracy (Cugmas et al., 2021).

VS in veterinary oncology leverages advanced deep learning techniques to digitally replicate traditional histological staining processes, offering a more efficient, cost-effective, and environmentally friendly alternative. This approach accelerates diagnosis, which is crucial for both - patients and veterinarians, and is environmentally sustainable by minimizing the need for chemical stains. This method involves training neural networks to transform unstained or differently stained tissue images into VS images that mimic conventional stains like H&E (Dupļevska et al., 2024) or immunohistochemical stains (Lahiani et al., 2019).

VS often employs generative adversarial networks (GAN), such as the Pix2Pix model, designed for image-to-image translation when paired datasets are available. In the context of virtual staining in veterinary medicine, Pix2Pix can be trained to convert images from unlabeled tissue images into virtually stained images that resemble traditional histological stains or translate multispectral fluorescence images into brightfield represantations without physically applying dyes (Isola et al., 2017). This approach helps save time and resources, and reduces the need for tissue destruction, what is crucial in veterinary oncology for diagnosing and surgically approaching tumors (Rivenson et al., 2019, 2020).

Beyond Pix2Pix, GANs in general are advanced neural networks that create realistic synthetic data by competing two models—the generator and the discriminator.

CycleGAN extends this concept to perform unpaired image translation. It is a type of artificial intelligence model used to translate images from one style or domain to another without needing exactly matched images (paired examples) (Zhu et al., 2020), which is especially useful when paired data is scarce. This capability is useful for enhancing diagnostic visualization, standardizing images from different sources, or creating digital stains that mimic traditional laboratory techniques, all while preserving important tissue details.

ResNet or Residual Network is a deep neural network architecture that is designed for transformation between structurally similar but visually different images (Xu et al., 2023b) and when trained effectively is often used for image classification tasks, such as diagnosing diseases from medical images. It includes 'skip connections' that help the network learn better by

preventing issues like vanishing gradients. When integrated with ResNet – forming CycleGAN with ResNet – the model gains deeper learning capacity and better detail preservation, improving the quality of virtually stained images.

For segmentation purposes during virtual staining or image analysis, architectures like U-Net are widely used to precisely delineate tissue structures. U-Net is a type of neural network which has an encoder-decoder architecture: the encoder captures context by progressively downsampling the image, while the decoder restores the spatial details and combines them with features from earlier stages through skip connections. This design enables precise localization even with limited training data. It is designed for image segmentation, which means it helps to precisely locate and outline features within images. It's widely used in medical and histological imaging because it helps to identify and outline specific structures within images, such as tissues or cells and can accurately segment complex shapes even with limited training data.

An even more advanced version, Dense U-Net, incorporates dense connections to improve feature reuse and segmentation accuracy. These models enable better visualization by improving the accuracy and color balance of the VS images (Dupļevska et al., 2024) and therefore improving diagnosis by accurately isolating specific tissue components in the virtually stained images.

Advanced neural networks can be re-trained using transfere learning (TL) to replicate immunohistochemical stains on unstained samples, enabling differentiation of tumor types where traditional histopathology falls short (Cho et al., 2017). TL is a powerful approach in deep learning that enables a pre-trained model to be adapted to a new task (Xu et al., 2023a).

The application of TL for VS from optical coherence tomography to H&E stained samples in veterinary medicine has not been explicitly documented in the provided research papers. The papers primarily focus on human medical applications, utilizing deep learning techniques to transform histological images from one stain type to another (Bai et al., 2023; Latonen et al., 2024). These studies highlight the potential of virtual staining in enhancing diagnostic workflows and reducing the need for physical staining processes, but they do not specifically address veterinary applications.

While the field currently focuses on human applications, the methodologies and technologies developed could potentially be adapted for veterinary medicine. In contrast to the focus on human medical applications, the potential for virtual staining in veterinary medicine remains largely unexplored in the current literature. The adaptation of these techniques to veterinary medicine would require the collection and annotation of veterinary-specific histological data to train the models effectively. This adaptation could lead to significant advancements in veterinary pathology, similar to those seen in human medicine.

By combining OCT with virtual staining, several benefits can be achieved, including rapid acquisition of real-time histological images in a non-invasive manner (Winetraub et al., 2021). Images can be obtained from multiple sites and sections as needed and sent digitally to a pathologist immediately after capture, potentially receiving feedback during surgery - thereby optimizing surgical technique and scope based on the acquired results. This integration of OCT and virtual staining could significantly enhance the accuracy of surgical margin assessment and improve patient outcomes in veterinary oncology (Fabelo et al., 2021). While early diagnosis and treatment are critical, there is a concern regarding the risks associated with anesthesia for histopathological sampling, which may lead to suboptimal surgical decisions if not properly managed. In some cases, it could help to distinguish between surgical and non-surgical treatment as appropriate depending on tumor type and location (De Nardi et al., 2022). Further exploration of the integration of OCT and virtual staining could lead to groundbreaking advancements in veterinary surgical oncology, ultimately benefiting both animal patients and their owners.

The goal of this study was to understand if the current OCT database could be used to produce the pilot virtual staining (based on the neural networks) on our C-scan images. We observed that STS tumor cells appear brighter in OCT images and hypothesized that the tumor becomes distinctive by applying the virtual staining.

Materials and Methods

Preparation of tumor samples

Formalin-fixed tumor samples were obtained from the biopsy submissions to a commercial veterinary pathology laboratory (Matise Veterinary Pathology service, Riga, Latvia). These samples originated from client-owned dogs and cats for which the veterinarian-clinician recommended excisional surgery. The details of the tumor sample preparation, processing and histopathological examination procedure have been reported previously (Dupļevska et al., 2024) with exception that histological sections after cutting were deparaffinized, stained with hematoxylin and eosin and coverslipped.

After trimming, skin tissue samples that were diagnosed as cancer (soft tissue sarcoma) in feline and canine submissions, were stored in 10% formalin and provided to veterinary pathology laboratory for tissue blocks preparation and histological sections staining with hematoxylin and eosin. In addition, detailed assessment of tumor in corresponding H&E stained histological sections was performed by a board-certified veterinary pathologist Ilze Matīse-van Houtana (Matise Veterinary

Pathology service, Riga, Latvia). Tissue paraffin blocks from 51 soft tissue sarcomas samples were used for further analysis by OCT scanning at Biophotonics laboratory (University of Latvia).

Image registration

Spectral-domain OCT (sd-OCT) images were acquired using Telesto II (Thorlabs, Newton, NJ, USA) OCT device equipped with 1325 nm/100 nm spectral bandwidth SLD excitation light source, yielding ~ 8-micron axial resolution in tissue. The lateral resolution of OCT-LK2 telecentric scan-lens (EFL = 18 mm Thorlabs) was ~7 μm. The tissue sample from paraffin block was placed on the OCT sample holder and the 3D OCT image cube was acquired comprising the multiple B-scan images, keeping the beam focus point approximately 50 μm below the tissue surface and slightly tilting the samples. Galvanometric mirror-based scan stage operated at a 5 kHZ scan rate, and used the maximum number of 20 A-scans and 6 B-scans for the averaging. The pixel size in XY direction was set manually for 2 microns and the pixel size in z direction was 2.25 microns. The OCT images were collected in 1 x 1 mm scan area, and up to 2 mm penetration depth. ThorImage OCT software (Thorlabs) was used to perform volume rendering of z-stacked OCT data, displaying the grayscale view within 20-95 dB dynamic range, and subsequently extracting and storing the 2D cross sectional XY plane images across the sample in png format. *Ex vivo* STS tissue block samples, prepared using standard paraffin technique, were analysed by OCT. The image features within the top crossectional XY plane from each 3D OCT rendering were correlated with histological structures identified in H&E stained slides, appearing as the mirror images to the corresponding cross sections in OCT.

Image preprocessing

Prior to feeding the raw data to the proposed neural network, it needs to be processed and registered. Thus, both OCT image data and H&E stained brightfield image data were spatially aligned. The raw input STS images were extracted with the open-source OpenSlide library. During the research, the necessity of both (OCT and H&E brightfield) raw data type pre-processing was established. The H&E stained data underwent only background pixel color standardization (white color) as this type of images was chosen as those that are referenced to during the registration process.

Initially, processed images were converted to grayscale. Then, the proposed algorithm initialized the ORB detector that detected keypoints and extracted descriptors for each image. The code created a descriptor matcher and matched descriptors between the two images using the Hamming distance. In addition, we filtered and matched descriptors based on their distances, discarding the matches that exceeded the chosen threshold. Finally, the algorithm extracted the corresponding keypoints from the matched keypoints.

When the matching process was completed, the RANSAC (Random Sample Consensus) algorithm (Derpanis, 2010) was used to find the homography matrix, which represents the transformation between the two images. Then the computed homography was applied to warp the OCT image and align it with the H&E stained one, resulting in the registered image data. The final step before using the registered data for the further virtual staining process was to split each image pair into tiles of 512×512 pixels.

Virtual staining

Since the images used for training were not automaticly paired, but same regions were manually cropped, where their accuracy cannot be objectively measured, several approaches were tested. First approach where we assumed that the manually marked areas do not form pairs and do not exactly match each other. We tried transfer learning in virtual staining tasks. Transfer learning was employed to investigate the applicability of previously trained virtual staining model originally trained on fluorescence images stained with H&E to a different input - OCT images (Dupļevska et al., 2024). The use of transfer learning aimed to evaluate whether a pre-trained model could generalize well enough to produce histologically meaningful virtual stains on new data without further fine-tuning or parameter adjustment.

As we speculated that the images could be paired by manual selection, an attempt was made to train the neural network anew without transfer learning using previous methods.

Additionally, the standard Pix2Pix architecture without dense components was tested. This is a classic Pix2Pix model with no prior customization.

After that, a modified Pix2Pix framework, a type of conditional generative adversarial network (cGAN) was used where the generator was based on a Dense U-Net architecture. The Dense U-Net replaced standard convolutional blocks with densely connected layers to enhance feature propagation and preserve fine tissue structures, such as nuclei and connective tissue boundaries. The model was trained on paired datasets consisting of multispectral fluorescence images (captured in DAPI) and their corresponding manually H&E-stained brightfield images. Training was performed on image patches of 512×512 pixels over 40 epochs, using 800 patches for training and 200 for validation. To stabilize training and improve detail retention, further enhancements were applied to both the generator and discriminator, including the use of instance normalization and spectral normalization.

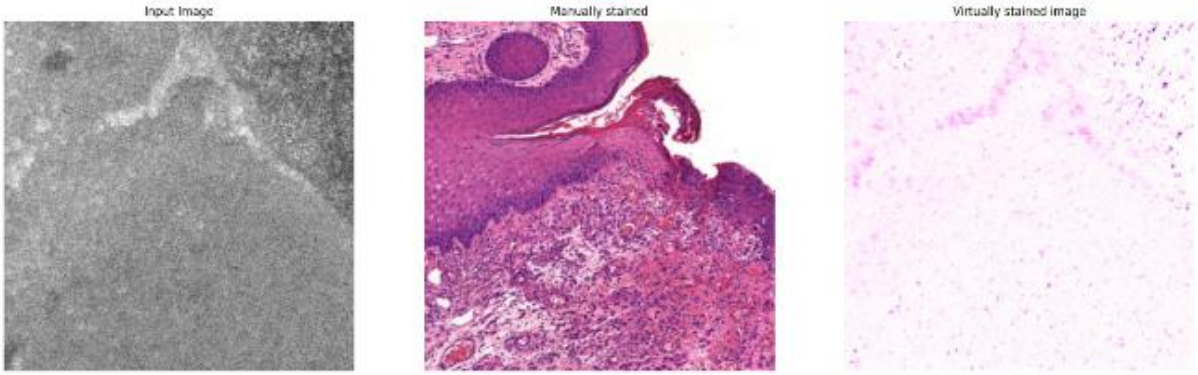
CycleGAN with U-Net approach the ResNet connections in the CycleGAN architecture were replaced with U-Net connections.

Results and Discussion

In our case, transfer learning strategy in virtual staining tasks was particularly relevant for veterinary oncology, where access to labeled training data is limited and manual histological staining is time-consuming and resource-intensive.

Figure 1

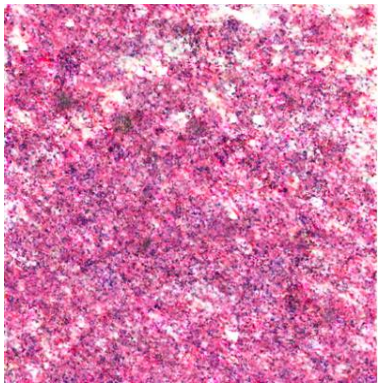
Soft tissue sarcoma from dog - virtually stained with Pix2Pix dense transfer learning OCT



Results in Figure 1 showed that since OCT and brightfield images contain entirely different types of structural and spectral features, the neural network could interpret only the isolated pink dots representing the maxima. Training from scratch unfortunately did not produce positive results — the output of the model did not yield interpretable images, see 'Figure 2'.

Figure 2

STS virtually stained with Pix2Pix dense OCT



In our previous work with autofluorescence and H&E samples, classic Pix2Pix model with no prior customization performed poorly (Dupļevska et al., 2024). Similar results can be observed in Figure 3.

Since the input and reference images differ significantly in this case and are not exactly a paired set, the CycleGAN architecture was used. Using CycleGAN with ResNet the VS image began to display contours and cell edges, and resembled the structure of OCT sample, see 'Figure 4'.

Figure 3

STS virtually stained with Pix2Pix U-net OCT

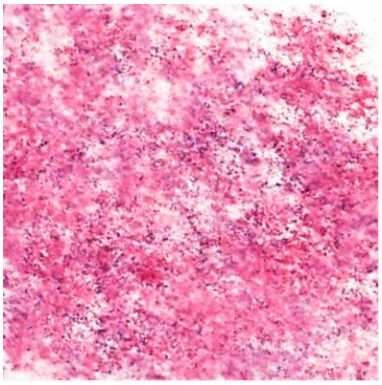
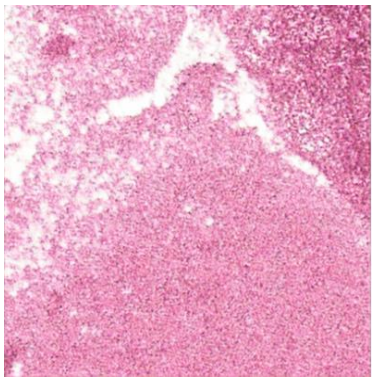


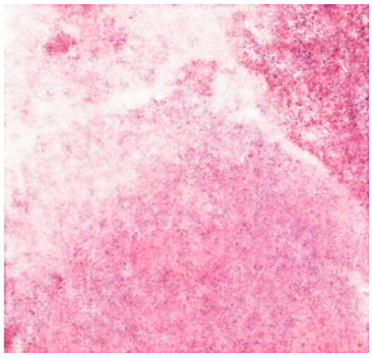
Figure 4

STS virtually stained with CycleGAN with ResNet



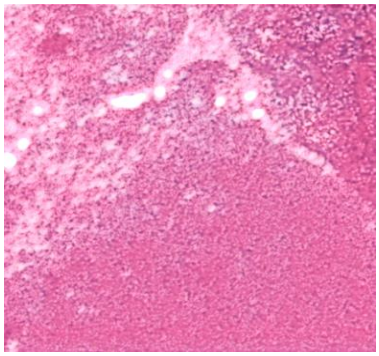
In CycleGAN with U-Net approach, the result was worse than in CycleGAN with ResNet because virtually stained image lost some structural details, Figure 5.

Figure 5
STS virtually stained with CycleGAN with U-net OCT



Dense U-Net architecture without ResNet or U-Net blocks did not improve after CycleGAN with U-net was applied. In Figure 6, the virtually stained image did not achieve higher quality compared to the previous models.

Figure 6
STS virtually stained with CycleGAN with Dense U-Net



While VS promises numerous advantages, including reduced resource consumption and increased efficiency, other approaches should be applied instead or together with OCT. Preliminary work is especially challenging when there is no prior research done with veterinary samples. In future work, we plan to improve the results with the help of a larger dataset. Currently, we used 51 tumor sample slides, but other applications in the literature indicate that Pix2Pix and CycleGAN require 300+ slides. In future, we plan to pair the data automatically using algorithms, rather than manually to test additional neural networks models, to improve acquisition time, to test different optical modalities, as well as to apply transfer learning by utilizing OCT/H&E datasets from open repositories or pre-existing modalities and to apply trained models.

Conclusions

1. Virtual staining may standardize veterinary histopathology as a rapid, label-free alternative to traditional methods, necessitating improvements in pilot OCT to H&E virtual staining results for clinical acceptance.
2. Accelerating model development necessitates dataset-specific tuning and preprocessing.
3. Additional research is imperative for training neural networks on virtually stained OCT images, particularly focusing on the OCT dataset.

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ASSESSMENT OF HISTOPATHOLOGY IN RABBITS EXPERIMENTALLY INFECTED WITH *TRYPANOSOMA EVANSI*

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Abstract
Trypanosoma evansi is a vector-borne protozoan parasite responsible for surra, a disease that affects a wide range of domestic and wild animals, causing severe health consequences and significant economic losses. This study aimed to investigate the histopathological effects of *T. evansi* infection in rabbits under controlled experimental conditions and assess the potential of rabbits as a suitable model for studying this disease. Sixteen rabbits were divided into infected and control groups. The infected group received an inoculation of *T. evansi* isolated from cattle. Clinical signs were monitored, and tissue samples from the liver, lungs, spleen, myocardium, and kidneys were collected for histopathological evaluation. Microscopic analysis revealed marked pathological changes in infected animals, including granular and fatty degeneration of hepatocytes, hyperemia, emphysema and exudative inflammation in the lungs, myocardial dystrophy, spleen hyperplasia, and degenerative changes in renal tissue. These alterations reflect systemic involvement, indicating the pathogenicity of *T. evansi* and its ability to affect multiple organ systems. The experimental model reproduced classical features of the disease, such as anemia, tissue edema, and hemorrhages, supporting the relevance of rabbits as a viable model for trypanosomiasis research. This study contributes to a better understanding of host-pathogen interactions and pathogenesis in surra. The results offer valuable insights for the development of diagnostic tools, treatment strategies, and vaccine research. Moreover, the established rabbit model may facilitate future investigations into the biology and virulence of *T. evansi* strains circulating in Kazakhstan and beyond.
Keywords: Trypanosomosis, *Trypanosoma evansi*, rabbits, histopathology.

Introduction

Trypanosomes are unicellular flagellated protozoa belonging to the family *Trypanosomatidae* and the genus *Trypanosoma* (Sobhy et al., 2017). The genus *Trypanosoma* comprises many species that cause diseases known as trypanosomoses in domestic and wild animals, as well as in humans (Mekata et al., 2013). Livestock trypanosomoses, caused by *Trypanosoma brucei*, *T. equiperdum*, and *T. evansi*, all of which belong to the subgenus *Trypanozoon*, have a significant socio-economic impact and limit animal productivity worldwide (Desquesnes et al., 2013).

Trypanosoma evansi is a protozoan parasite responsible for the disease known as surra, which affects various domestic and wild mammals. Discovered in 1880 by British veterinarian Griffith H. Evans in India, *T. evansi* was initially observed in horses suffering from surra. The parasite is characterized by a single flagellum running along its undulating membrane, facilitating movement. Unlike other trypanosomes transmitted by tsetse flies, *T. evansi* is primarily spread mechanically by blood-feeding insects such as horseflies (*Tabanidae*) and stable flies (*Stomoxys*). The parasite infects a wide range of hosts, including horses, camels, cattle, buffaloes, deer, elephants, and tigers. In South America, vampire bats and capybaras serve as reservoirs, contributing to the parasite's persistence in the environment (Sazmand & Joachim, 2017).

Trypanosoma evansi is mechanically transmitted by hematophagous insects (*Tabanidae* and *Stomoxydae*) and affects several tropical regions worldwide. This parasite causes the disease commonly known as 'Mal de Cadeiras' in Brazil and 'Derrengadera' in Venezuela (Desquesnes et al., 2013).

Although *T. evansi* is considered a hemoflagellate, it is a protozoan parasite that inhabits both intra- and extravascular fluids. One of the most intriguing aspects of *T. evansi* is its ability to periodically switch its major variant surface glycoprotein (VSG), leading to recurrent waves of parasitemia. These parasitemic waves have been observed in experimental infections with Brazilian *T. evansi* isolates (Aquino et al., 1999; Queiroz et al., 2000; Herrera et al., 2001).

The severity of *T. evansi* infections varies considerably across different geographical regions, depending on the virulence of the strain and the susceptibility of the host. Anemia is the primary consequence of infection. Consequently, it has been suggested that resistance to anemia, as well as the control of parasitemia, reflects the degree of host tolerance to infection (Trail et al., 1990). Affected animals may exhibit fever, general deterioration of health, and immunosuppression (Holland et al., 2001). Diagnosing *T. evansi* infection remains challenging due to the varied and non-specific clinical signs. In enzootic areas, natural hosts often present mild, chronic forms of the disease, further complicating diagnosis (Roberto et al., 1994).

Trypanosomosis in domestic animals is known to cause various pathological changes in vital visceral and reproductive organs. This study aimed to assess

the pathological changes in visceral organs of rabbits experimentally inoculated with *Trypanosoma evansi*.

Materials and Methods

Trypanosoma evansi isolate

For this research, a *T. evansi* isolate of cattle origin was propagated in guinea pigs at the laboratory of LLP 'Kazakh Scientific Research Veterinary Institute'.

Animal Studies

The study involved 16 clinically healthy adult rabbits (average weight 2–2.5 kg), which were randomly assigned into two groups (n = 8 per group):

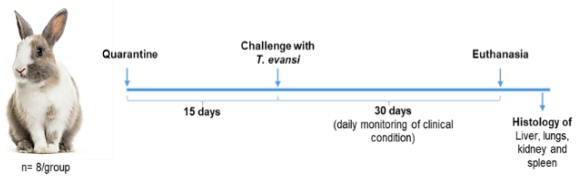
- Group I (Experimental group): Rabbits were inoculated with Trypanosoma evansi on day 0.
- Group II (Control group): Rabbits were not infected.

Before the experiment, all animals underwent a 15-day quarantine period to ensure they were free from clinical signs of disease. After challenge with *T. evansi*, rabbits in the experimental group were observed for 30 days, with daily monitoring of clinical condition. On day 30 post-challenge, all animals were humanely euthanized for sample collection and pathological assessment.

The experimental timeline and group distribution are shown in Figure 1.

Figure 1

Experimental design and animal grouping



Animal groups and Challenge

No.	Name	Challenge
1	Experimental	Inoculated with *T. evansi*
2	Control	Not infected

Histology Tests

The rabbits were euthanized by intraperitoneal administration of 10% chloral hydrate (Acros Organics, Geel, Belgium). Following necropsy, a macroscopic examination of internal organs was performed to assess the presence of lesions. Whole lungs, liver, kidneys, and spleen were fixed in 10% neutral formalin (Sigma, Taufkirchen, Germany) for histological examination (Figure 1). Tissue sections were prepared and stained with hematoxylin and eosin (Sigma, Taufkirchen, Germany).

Ethics statement

The study was conducted by national and international animal handling laws and recommendations. The study protocol was approved by the Local Bioethics Commission of Kazakh Scientific Research Veterinary Institute LLP (Protocol №10, dated 28 September 2024).

Results and Discussion

Histological examination results

Liver. In most cases, hepatic lobules exhibited granular dystrophy (Figure 2a) at varying degrees of severity. The affected hepatocytes were enlarged and rounded, with poorly defined lobular boundaries. Eosinophilic granules were observed in the cytoplasm. The nuclei of these hepatocytes displayed morphological changes, including karyopyknosis and karyolysis.

In rare cases, granular and fatty dystrophies co-occurred in the middle region of the hepatic septa (Figure 2b). In some hepatocytes, nuclear dispersion and dissolution were observed. Blood congestion was noted in the cavities of the septa, central veins, and sinusoidal capillaries. The endothelial layers of many vessels appeared enlarged and swollen. In certain areas, the structural arrangement of hepatic cords was disrupted, particularly around the central vein Figure 2c.

Figure 2a

Granular liver dystrophy. Hematoxylin-eosin staining

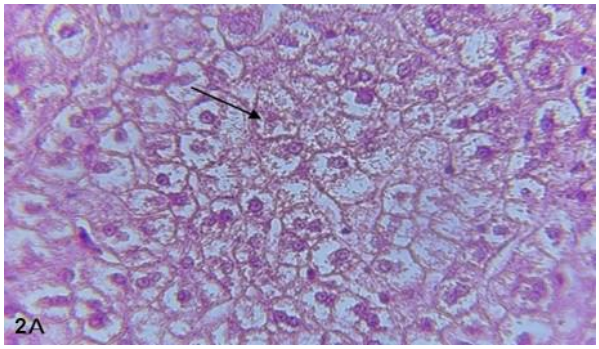


Figure 2b

Granular (a) and fatty (b) liver dystrophy. Hematoxylin-eosin staining

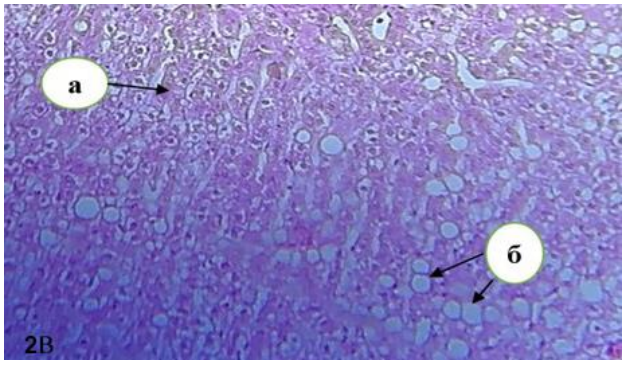
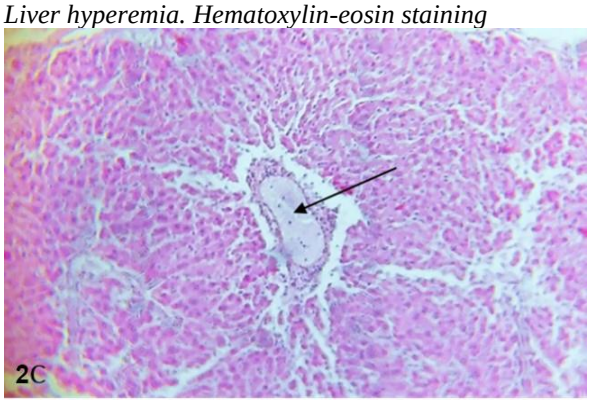


Figure 2c
Liver hyperemia. Hematoxylin-eosin staining



Lungs. Microscopic changes in the lungs were heterogeneous, with varying degrees of hyperemia, edema, emphysema, and atelectasis, which often overlapped. In large portions of the lung tissue, the capillary cavities within the interalveolar connective tissue were dilated and congested with blood, while the alveolar spaces contained eosinophilic fluid, which included erythrocytes, leukocytes, and alveocytes. Serous exudate accumulated around some bronchi. In certain areas, characteristic features of emphysema were observed (Figure 3a).

In emphysematous regions, alveolar cavities appeared expanded, with thinned and ruptured walls. The alveolar epithelium was stretched and attenuated, and blood vessels within the alveolar walls exhibited hemorrhagic changes. Focal areas of distal atelectasis and interalveolar septal thickening, due to cellular infiltration, were present against the background of acute alveolar emphysema. The blood vessels were moderately engorged, and in some areas, vascular walls were thickened with surrounding cellular infiltration. In certain vessels, plasma and cellular elements of the blood were separated. Additionally, many large and medium-sized bronchi appeared dilated without signs of inflammation or sclerosis (Figure 3b).

Figure 3a
Pulmonary emphysema. Hematoxylin-eosin staining

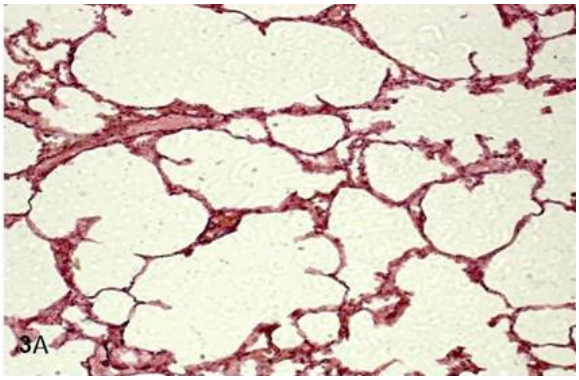
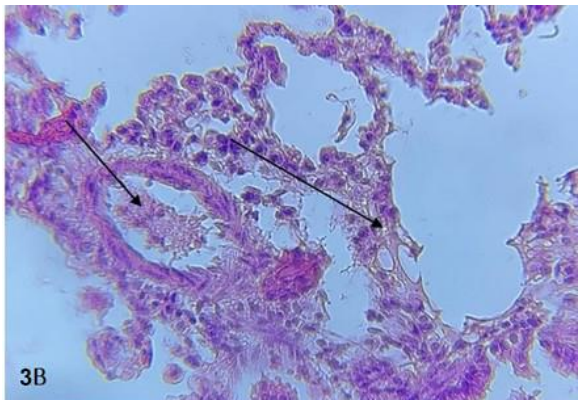
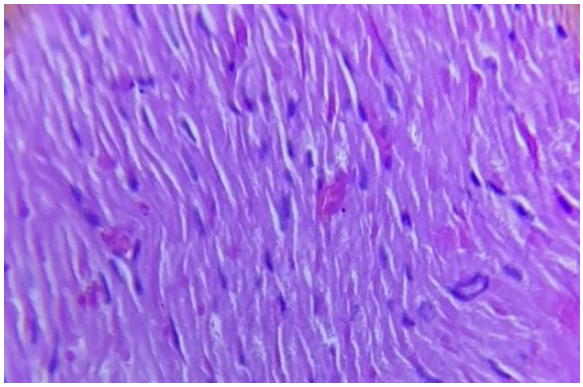


Figure 3b
Exudative inflammation of the lungs. Pulmonary vessels filled with blood. Hematoxylin-eosin staining



Myocardium. Numerous muscle fibers appeared swollen, with some exhibiting indistinct cross-striations and granular material accumulation in the cytoplasm. The nuclei were enlarged, intensely stained with hematoxylin, and displayed peripheral convexity. Between the muscle fibers, areas of swelling, occasional hemorrhagic foci, and scattered reticular infiltrates were observed. The endothelial cells of the vessel walls were enlarged and swollen. In rare cases, focal fragmentation of muscle fibers was noted (Figure 4).

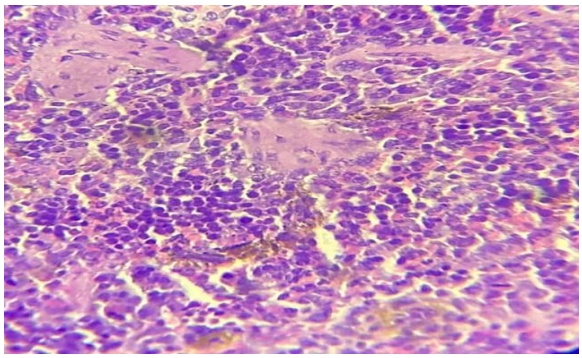
Figure 4
Myocardial dystrophy. Hematoxylin-eosin staining



Spleen. In all cases, the splenic pulp was congested with blood, with dilated vascular cavities. In some capillaries, erythrocytes were densely packed, forming a homogeneous mass. The follicles remained intact and in a normal state. Some trabeculae appeared swollen and thickened (Figure 5).

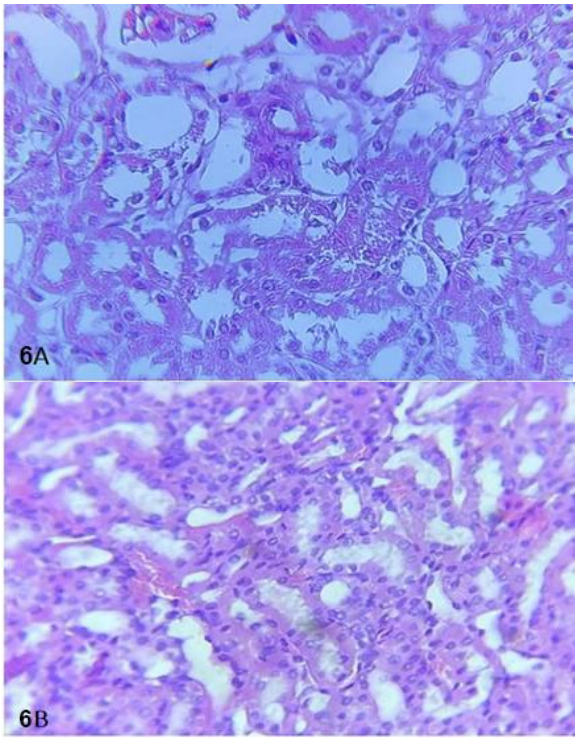
Kidneys. The vascular cavity was dilated and filled with blood, with erythrocytes undergoing hemolysis, resulting in a uniform size and the formation of a homogeneous mass. Some glomerular vessels were enlarged, the capillaries were engorged with blood, and a yellowish watery exudate accumulated in the capsule cavity.

Figure 5
Spleen hyperplasia. Hematoxylin-eosin staining



The nephrocytes lining the convoluted tubule walls appeared swollen, with well-defined boundaries. The cytoplasm was darkened and contained small eosinophilic granules stained red. The tubular lumen was narrowed, and in some cases, nephrocytes detached from the basement membrane, floating freely within the tubule lumen. The nuclei of nephrocytes exhibited karyopyknosis and karyolysis. In the juxtamedullary region of the kidneys, small foci of hemorrhage were frequently observed. The nuclei of some cuboidal epithelial cells lining the vertically oriented tubules were in a pyknotic state (Figure 6).

Figure 6
A - Granular and fatty degeneration of the kidney
B - Hematoxylin and eosin staining



Invasive diseases of animals, particularly trypanosomiases (surra and dourine), are characterized by debilitating symptoms such as intermittent fever, anemia, jaundice, hemoglobinuria, dysfunctions of the digestive, cardiovascular, nervous, and motor systems, paresis and paralysis of individual motor nerves, decreased productivity, severe emaciation leading to cachexia, and a high mortality rate. The prevalence of trypanosomiases ranges from 15% to 50% (Sabanshiev, 1993; Shabdarbayeva et al., 2014).

Trypanosomes are a distinct group of unicellular organisms, first discovered by Gruby in the blood of frogs. In 1880, the English veterinary surgeon Evans established that the causative agent of a widespread animal disease in India at the time, known as ‘surra’, was a trypanosome, later named *Trypanosoma evansi*. In 1894, Bruce demonstrated that the causative agent of the African animal disease ‘nagana’ was *Trypanosoma brucei*. Today, numerous species of trypanosomes are known to infect mammals, fish, birds, reptiles, and amphibians.

Among pathogenic trypanosome species, two parasites are found in the Republic of Kazakhstan: *Trypanosoma equiperdum*, the causative agent of dourine in horses, and *Trypanosoma evansi*, the causative agent of surra in animals. This has been confirmed through serological studies of camel and horse blood sera across the country (Sabanshiev, 1993; Shabdarbayeva et al., 2014). The urgency of combating trypanosomiases is due to the fact that this infection hinders the development of horse and camel breeding in Kazakhstan. As a vast Central Asian country with a long-standing tradition of using horses and camels for agriculture, transportation, food production, and cultural identity, where these practices are deeply embedded in the historical, cultural, and economic landscape, trypanosomiasis remains a significant problem.

In animals infected with trypanosomiasis (surra and dourine), symptoms include emaciation, anemia, remittent fever, edema in the chest area, limbs, and genital organs, as well as watery discharge from the eyes and nose. The disease lasts from 1.5 to 2 months, sometimes extending to 4–6 months, with some animals succumbing to the infection. Post-mortem examination reveals anemia of the mucous membranes, gelatinous infiltration of subcutaneous tissue, hemorrhages on serous and mucous membranes, in the kidneys, and in the urinary bladder, along with significant enlargement of lymph nodes and the spleen. Diagnosis is based on detecting the pathogen through microscopy of a crushed drop of peripheral blood or a lymph node aspirate. If initial results are negative, a bioassay is conducted using mice, rats, rabbits, guinea pigs, or dogs. In suspected cases, the blood serum of animals is tested using the complement fixation test (CFT) and X-ray fluorescence analysis (XRF).

Trypanosoma evansi, the causative agent of surra in camels, is also the etiological agent of dourine, which primarily affects horses (Gizaw, 2017). Unlike other trypanosomal infections, equine trypanosomiasis is not transmitted by insect vectors but exclusively by the sexual route (Desquesnes, 2013). Among pathogenic trypanosomes, *Trypanosoma evansi* has the broadest host range and the widest geographic distribution (Radwanska, 2018). *Trypanosoma evansi* is observed in domestic and wild animals in acute, subacute, and chronic forms, depending on the virulence of the strain and host-parasite interactions. Susceptible hosts include horses, camels, donkeys, mules, llamas, dogs, cats, cattle, and buffaloes (Desquesnes et al., 2016). In laboratory conditions, experimental infection has been successfully induced in dogs, rabbits, rats, and mice (Perrone et al., 2018).

Biswas et al. (2001) described *Trypanosoma evansi* as highly pathogenic to laboratory animals (mice, rats, and rabbits). The parasite utilizes glucose and oxygen for its growth and reproduction, leading to the depletion of these metabolites, which causes degenerative changes in the host. Further disease progression is associated either with toxins released by the parasite or with immunological reactions (Bal et al., 2012).

Our histological studies revealed hyperemia, edema, emphysema, and varying degrees of atelectasis in the lungs of infected rabbits, findings similar to those reported by Chandra et al. (1999) and Ngeranwa et al. (1993). In contrast, our histological examination of the liver in infected rabbits showed that affected hepatocytes were enlarged, had a rounded shape, and exhibited poorly defined lobular boundaries. Studies by Uche and Jones (1992) identified fatty degeneration followed by hepatocyte necrosis as a common cytological finding associated with *T. evansi* infection in rabbits (Uche & Jones, 1992).

Histopathological lesions caused by trypanosomiasis were also studied in the myocardium, spleen, and kidneys of infected rabbits, where varying degrees of dystrophy were observed. Although the pathology of the disease caused by different species of *Trypanosoma* in domestic and laboratory animals is well known, the knowledge gained from studying the histopathology of rabbits experimentally infected with animal trypanosomiasis could serve as a starting point for identifying key features of the infection's progression and the properties of the isolate found in our country. Additionally, these findings could be valuable in testing new drugs. The acquired knowledge will expand research capabilities to counteract emerging *Trypanosoma* isolates, making it a significant step toward future advancements.

Conclusions

Based on the results of this study, the following key conclusions can be drawn:

1. Rabbits are a suitable experimental model for studying animal trypanosomiasis caused by *Trypanosoma evansi.* The infection reliably reproduces the clinical and pathological features of the disease observed in natural hosts.
2. Histopathological examination revealed characteristic lesions in multiple organs, including granular and fatty degeneration of hepatocytes in the liver, emphysema and exudative inflammation in the lungs, myocardial dystrophy, hyperplasia of the spleen, and degenerative changes in the kidneys. These findings confirm the systemic nature of the infection.
3. The experimental infection model allows detailed observation of disease progression, tissue damage, and organ involvement, thereby providing a basis for evaluating the pathogenicity of different *T. evansi* strains.
4. The data support the use of rabbits in biological testing, especially in cases where traditional microscopic diagnostics yield inconclusive results despite the presence of clinical signs.
5. This research contributes to the broader understanding of trypanosomiasis pathogenesis and highlights the need for further studies to explore therapeutic and preventive strategies, including drug efficacy trials and vaccine development.

The findings are particularly relevant for Kazakhstan, where *T. evansi* is endemic and threatens the productivity and health of horses, camels, and other livestock species.

In summary, this study not only confirms the pathological potential of *T. evansi* in a controlled setting but also establishes a practical and reproducible platform for future research on surra and related trypanosomal diseases.

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MICROBIOLOGICAL SAFETY OF MEAT AND MEAT PRODUCTS AT THE RETAIL MARKET IN LATVIA

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Abstract
Microorganisms significantly affect the quality and safety of meat and meat products; therefore, detection of microbiological contamination is important to assess the safety of retailed products. The present study was aimed to detect microbiological contamination of raw meats and processed meat products purchased from supermarkets and farmers' markets during 2024-2025 in Latvia. Raw meat included poultry, beef, and pork, but meat products were smoked ham, smoked and boiled sausages, pâté, cutlets, and meat balls. Samples were investigated according to the International Organization of Standardization (ISO) methodology and detected microorganisms and microbial groups were the total microbial count (TVC), *Enterobacteriaceae, E. coli, Salmonella spp., Listeria* spp. and *Yersinia* spp. All purchased meat products had acceptable microbiological quality in terms of TVC, *Enterobacteriaceae* and E. coli. The highest TVC levels were recorded in raw meat samples, while the highest concentrations of *Enterobacteriaceae* were found in raw meat obtained from farmers' markets, supermarkets and retail stores. The highest levels of E. coli were found in raw meat and processed meat. Differences in microbial contamination of meat and meat product could be related to the processing and hygienic practices at the retail level. Higher microbial contamination rates for raw products at the farmer market could be explained with difficulties to provide an adequate level of hygiene at the farmer markets in comparison with supermarkets.
Keywords: food safety, food products, semi-finished products, contamination risk, microbiological contamination.

Introduction

A wide range of meat and meat products are available at supermarkets and farmers markets. These products are essential for human nutrition, as they provide essential microelements, vitamins, proteins, and other beneficial compounds for consumers' health and wellbeing. Therefore, ensuring the highest quality and safety standards for meat and meat products at the retail level is important for public health protection. To facilitate the offer of high-quality meat products at the market, food businesses work closely with farmers, regulatory authorities, and other stakeholders to provide safe food for consumption throughout the entire food chain. Food safety is a global concern that requires continuous innovation to mitigate the risks posed by pathogenic microorganisms. Foodborne pathogens remain a primary food safety issue within the European Union from farm to table strategy.

Meat is particularly susceptible to microbial growth (Sun et al., 2022), and the processing of meat products does not significantly reduce the number of microorganisms which are present if hygienic requirements are not satisfactory or processing do not target inhibition of microbial growth in foods. Since meat and meat products are rich in nutrients, microorganisms are able to colonize and proliferate rapidly making those products highly perishable. The high levels of proteins, vitamins, and minerals, combined with a nearly neutral pH, create an ideal environment for the rapid growth of various microorganisms (Fudali et al., 2021; Panea et al., 2020; Szymański et al., 2023).

The microbiota of the final product can be originated from the meat itself, as well as from spices, other ingredients, the environment, equipment, and personnel during processing. All these factors contribute to the product's microbiological quality. A lack of standardized production processes and poor manufacturing hygiene can result in microbiological contamination (Sachindra et al., 2005). The bacteria present in meat and meat products may include foodborne pathogens, opportunistic microorganisms, or commensals, which can act as reservoirs for antibiotic resistance genes or other virulence factors. Food products of animal origin are a significant source of foodborne illnesses may harbour pathogens capable of causing outbreaks and fatalities due to direct transmission from animals during primary processing steps. Foodborne zoonoses can be detected only with appropriate microbiological methods, hence interventions to eliminate these pathogens from food-producing animals or other food products could be ineffective if specific properties of pathogens are not targeted (Heredia & García, 2018). The microbiological quality of food, including meat and meat products, is crucial for consumer protection. Each producer is responsible for safety of their products placed at the retail market. The hygienic requirements for production of food for retail purposes must adhere to food legislation, specifically Regulation (EC) No. 852/2004 and Regulation (EC) No. 853/2004 which set detailed hygiene requirements for food of animal origin (European Parliament & Council, 2004).

Research indicates that meat products can be a source of pathogenic microorganisms. Studies on quality and safety aspects of meat products worldwide have identified the presence of *Listeria monocytogenes*, *Campylobacter* spp., *Salmonella* spp., coagulase-positive staphylococci, and *Escherichia coli* in meat and meat products (Halagarda & Wójciak, 2022). For instance, in Turkish sausage 'sucuk' contamination with *Listeria monocytogenes* was identified in 11.6% of tested samples (Colak et al., 2007). This pathogen

has also been isolated from smoked fermented Portuguese sausages ʻalheiraʼ, (Ferreira et al., 2006) and from ʻbiltongʼ - a popular African delicacy (Naidoo & Lindsay, 2010). Additionally, in the Lithuanian offal product ʻEars Language Rollʼ, which was available on the British market, *L. monocytogenes* levels reached 2.64 log CFU/g, exceeding the microbiological criteria set by the European Union (Gormley et al., 2010). Furthermore, the traditional Brazilian product ʻSarapatelʼ exhibited the presence of anaerobes, spore-forming bacilli, and pathogens, with *Staphylococcus aureus* levels exceeding 2.7 log CFU/g (Brasil et al., 2014). In traditional Spanish pork sausages, *Salmonella* spp. were discovered in ʻBotilloʼ and ʻAndrollaʼ sausage, while *E. coli* was detected in ʻBotilloʼ (Garcia et al., 2007; de Queiroz et al., 2013). *Staphylococcus aureus* was also isolated from another Brazilian offal-based product named ʻBuchada caprinaʼ (de Queiroz et al., 2013). The traditional Nigerian beef product ʻkilishiʼ contained both *S. aureus* and *E. coli* (Raji, 2006). Additionally, *Listeria* spp. were found in all tested samples of traditional Greek sausage (Drosinos et al., 2005).

According to the European Food Safety Authority (EFSA), foodborne zoonoses continue to pose significant public health concerns within the European Union, with salmonellosis remaining the most frequent cause of foodborne outbreaks. The highest prevalence of *Salmonella* in meat and meat products was observed in fresh poultry meat (12.6%), mechanically separated meat (MSM) (12.4%), poultry-based meat products intended for cooking (5.4%), and raw meat products, excluding those in which the production process or composition eliminates the risk of *Salmonella* contamination (0.87%). In addition, *Listeria monocytogenes* was detected in 90% of ready-to-eat meat and meat products (European Food Safety Authority & European Centre for Disease Prevention and Control, 2021).

According to Poland's Chief Sanitary Inspectorate, the national food safety authority, the most frequently reported microbiological hazard in 2022 was *Salmonella*, predominantly in poultry meat and related products (191 notifications), as well as in non-poultry meat and meat products (5 notifications). Notably, the number of *Salmonella* notifications in poultry meat and its derivatives showed a decreasing trend, dropping from 273 cases in 2020 to 263 in 2021, and further to 191 in 2022 (Chief Sanitary Inspectorate, 2022).

Meat and meat products may contain microbiological contamination and become contaminated with pathogenic microorganisms of public health significance; hence the aim of the present study was to detect microbiological contamination of meat and meat products available at the retail market in Latvia.

Materials and Methods

Collection of samples

The study was conducted from October, 2024 to February, 2025 in the region of Zemgale, Latvia. Samples of meat and meat products were collected from various retail outlets, including four supermarket chains, as well as butcher shops and farmer market in Jelgava. A total of 73 samples were selected for analysis, including cold-smoked products (n=7), hot-smoked products (n=9), pâtés (n=8), raw meat (n=18), boiled meat products (n=13), semi-finished products (n=7), boiled-smoked products (n=6), and dry-cured products (n=4).

The majority of the selected products (60 samples) was produced locally or imported by various companies and private entrepreneurs from Lithuania (8 samples), Poland (3 samples), and Estonia (2 samples). Of out these, 32 samples were packaged in protective packaging, such as vacuum or polymer packaging with hermetic sealing. All products were purchased from retail outlets within their shelf-life period.

For the remaining 41 products sold by weight, the customer assistant weighed them into a single-use, food-grade plastic bag at the customer's request. Among those samples, 21 were purchased from supermarkets. Additionally, 20 samples were obtained from grocery and farmers markets. Before purchasing, the adherence to shelf-life, storage temperature and storage condition were checked.

All the samples were transported to the laboratory according to storage conditions indicated on the product package or according to labels were available at the retail outlets for customers. The microbiological investigations were initiated immediately after delivering of products to the laboratory.

The research was conducted at the laboratories of the Institute of Food Hygiene and Environmental Health at the Faculty of Veterinary Medicine of Latvia University of Life Sciences and Technologies. The meat product samples were analysed for total microbial counts (TVC), as well as for the presence of hygiene indicators (*Enterobacteriaceae* and *Escherichia coli*) and pathogens (*Salmonella* spp., *L. monocytogenes*, *S. aureus* and *Y. enterocolitica*).

Preparation of samples and microbiological investigations

Detection of quantitative microbiological contamination

For microbiological analysis, the tested meat products were prepared according to ISO 6887-2:2017 (ISO, 2017a). A 10 g portion of each product sample was placed in 90 mL of sterile buffered peptone water (BPW; Biolife Italiana Srl, Italy) and homogenized for 1 minute. The initial suspension was then used to prepare decimal dilutions in BPW. Plate Count Agar (PCA) was used for the enumeration of the TVC in accordance with ISO 4833-1:2013 (ISO, 2013). A 1 mL aliquot of the diluted suspension was inoculated onto Plate Count Agar (PCA) and incubated at 30 °C for 72 hours. For the detection of *Enterobacteriaceae*, the sample suspension was plated onto Violet Red Bile Glucose (VRBG) agar and incubated at 37 °C for 24 hours, in accordance with ISO 21528-2:2017 (ISO, 2017b). Typical colonies of violet red colour with

diameter of 1-3 mm were considered as *Enterobacteriaceae*.

Escherichia coli was identified following the ISO 16649-1:2018 (ISO, 2018). A loopful of the diluted sample was streaked onto Chromogenic Coliform Agar (CCA) and incubated at 36 ±2 °C for 24 hours. Blue or purple colonies were considered presumptive *E. coli*, while pink colonies were recorded as other coliforms.

The isolation and identification of *Staphylococcus aureus* were performed according to ISO 6888-3:2003 (ISO, 2003). Ten-fold serial dilutions of the sample suspension were inoculated onto Baird-Parker agar (Biolife, Italy) and incubated aerobically at 37 ±1 °C for 18 to 24 hours. Colonies presumptive for *S. aureus* were identified by their characteristic appearance: black center surrounded by clear haloes.

Qualitative detection of foodborne pathogens

The presence of *Yersinia* spp. in meat and meat products was assessed using both direct plating and cold enrichment methods, following ISO 10273:2017 (ISO, 2017c). Samples were prepared in Peptone Mannitol Bile Salt Broth (PMB), and the sample suspensions were inoculated onto Cefsulodin-Irgasan-Novobiocin (CIN) agar. For direct plating, a 10 µL of the inoculated PMB suspension was spread onto the surface of CIN agar and incubated aerobically at 30 °C for 24–48 hours. For cold enrichment, PMB suspensions were incubated at 4 °C for one, two, and three weeks. After each enrichment interval, CIN agar plates were inoculated. If no presumptive colonies were observed after the first or second week, a 0.25% KOH alkaline treatment was applied to reduce background microbiota. Colonies exhibiting small dark red centers surrounded by clear, colorless zones on CIN agar were considered as presumptive for *Yersinia*. Preliminary confirmatory tests included screeding for urease activity using Christensen's urea agar.

Listeria monocytogenes was detected in accordance with ISO 11290-1:2017-07 guidelines (ISO, 2017d), which include pre-enrichment, selective enrichment, and plating onto selective agar media. For pre-enrichment, 25 g of the sample was transferred into Half-Fraser Broth (Oxoid, UK) and incubated at 30 °C for 24 hours. Subsequently, 0.1 mL of the pre-enriched culture was transferred into 9 ml of Fraser Broth (Oxoid, UK) and incubated at 37°C for 48 hours. Samples that turned black after incubation (indicator of esculin hydrolysis) were considered presumptive for Listeria. These samples were streaked onto selective agars: ALOA (Agar Listeria according to Ottaviani and Agosti; Biolife, Italy) and PALCAM Agar (Biolife, Italy) followed by incubation at 37 °C for 24–48 hours. Colonies of typical morphology for Listeria were subcultured onto Columbia Blood Agar to assess β-haemolysis for further confirmation.

The presence of *Salmonella* spp. was determined according to ISO 6579-1:2017 guidelines (ISO, 2017e). Initially, samples were pre-enriched in buffered peptone water at 37 °C for 18–24 hours. Following pre-enrichment, the sample suspensions were selectively enriched in Müller-Kauffmann Tetrathionate-Novobiocin (MKTTn) broth (Oxoid, UK) at 37 °C for 24 hours.

After enrichment, aliquots were streaked onto Xylose Lysine Deoxycholate (XLD) agar and incubated at 37 °C for 24 hours. Colonies with typical Salmonella morphology were selected for further identification. Confirmation of microbial species was conducted using matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF MS; Vitek MS, Biomerieux, Marcy l'Etoile, France).

Data analysis

The microbiological results were expressed in log CFU/g. For microbiological contamination with the TVC, *Enterobacteriaceae* and *E. coli*, the mean and standard deviation were calculated.

Results and Discussion

The enumeration of aerobic mesophilic micro-organisms in meats is considered as one of the key microbiological indicators of its quality and hygiene. The presence of those microorganisms in high counts reflects favorable conditions for microbial growth and proliferation in a product (Kebede & Getu, 2023). In the present study, TVC, *E. coli*, and *Enterobacteriaceae* were detected in categories of tested meat products. Microbial counts varied depending on the type of product and the manufacturer. The highest levels of bacterial contamination were observed in raw meat samples, where TVC reached 5.5 ± 0.46 log CFU/g. In contrast, the lowest levels were recorded in dry-cured products with TVC values of 3.7 ± 0.5 log CFU/g.

A high number of aerobic colonies (5–6 log CFU/g) may indicate that food is potentially hazardous due to violations during storage, processing, or hygiene practices. Although TVC is not a direct food safety indicator, it plays an important role in assessing the hygienic conditions under which food is produced, processed, and stored (Chukuezi, 2010).

Based on our findings, the average TVC in raw meat was of 5.5 ± 0.46 log CFU/g, which is the upper limit of the acceptable range. However, considering the standard deviation, it is likely that some samples exceeded the 6.0 log CFU/g threshold, suggesting that the regulatory or HACCP-based microbial contamination limits may have been partially exceeded. This highlights the need for improved monitoring of storage conditions and hygiene during raw meat processing.

The highest *E. coli* levels were observed in raw meat (0.7 ± 0.7 log CFU/g) and semi-finished products (0.4 ± 0.5 log CFU/g). The lowest levels were found in hot-smoked products (0.07 ± 0.21 log CFU/g), whereas *E. coli* was not detected in dry-cured products and pâtés.

The average values and standard deviations indicate a high variability of contamination between samples. Although the levels of *E. coli* were not elevated, its presence indicate fecal contamination, which may result from violations of hygiene during production,

packaging or retail. Contributing factors may include handling meat with bare hands, lack of protective clothing, or contact with money during service, all of which can significantly increase the risk of contamination of meat products (Grace et al., 2019).

Regarding *Enterobacteriaceae*, the highest concentration was found in raw meat (1.9 ± 0.8 log CFU/g), while the lowest was detected in hot-smoked products (0.1 ± 0.31 log CFU/g). The results are summarized in Table 1.

Table 1
Microbiological contamination of meat and meat products

Product Type	***No. of samples***	***Microbiological criteria***		
		TVC	***Escherichia coli***	***Enterobacteriaceae***
		Mean log CFU/g (mean ± SD)		
Cold smoked products	7	5.14 ± 0.39	0.2 ± 0.2	1.2 ± 0.4
Dry-cured products	4	3.7 ± 0.5	0	0.4 ± 0.7
Hot smoked products	9	4.8 ± 0.7	0.07 ± 0.21	0.1 ± 0.31
Cooked-smoked products	6	5.0 ± 0.35	0.2 ± 0.4	0.7 ± 0.7
Cooked sausages	13	4.1 ± 1.8	0.2 ± 0.4	0.5 ± 0.8
Raw meat	18	5.5 ± 0.46	0.7 ± 0.7	1.9 ± 0.8
Semi-finished products	7	4.6 ± 1.9	0.4 ± 0.5	1.1 ± 0.9
Pâtés	8	5.4 ± 0.28	0	0.9 ± 0.4
Total	73			

The microbiological analysis of meat products to detect the presence of pathogenic microorganisms yielded the following results. Among the 73 tested samples, no *Salmonella spp.* was detected, which complies with the requirements set forth in Commission Regulation (EC) No 2073/2005, indicating that the sanitary condition of the examined products is satisfactory (European Commission, 2005). However, certain samples tested positive for other pathogens, namely *Yersinia enterocolitica* (16 % of the samples), *Staphylococcus aureus* (12 %), and *Listeria monocytogenes* (6 %). Across all retail outlets examined, the highest contamination rates were found in raw meats and semi-finished products.

Despite the presence of these pathogens, their levels did not exceed the permissible limits established by European legislation (European Commission, 2005) in most cases. The results are presented in Table 2.

Table 2
Foodborne Pathogens in Meat and Meat Products

Product Type	***No. of Samples***	***Foodborne pathogen***		
		Staphylococcus aureus	***Yersinia enterocolitica***	***Listeria monocytogenes***
		No. of positive samples (%)		
Cold smoked products	7	0 (0)	0 (0)	0 (0)
Dry-cured products	4	0 (0)	1 (25)	1 (25)
Hot smoked products	9	1 (11)	0 (0)	0 (0)
Cooked-smoked products	6	1 (17)	2 (33.3)	1 (17)
Cooked sausages	13	0 (0)	0 (0)	0 (0)
Raw meat	18	4 (22)	2 (11.1)	1 (5.6)
Semi-finished products	7	2 (29)	4 (57.1)	0 (0)
Pâtés	8	1 (14)	0 (0)	0 (0)
Total	73	12%	16%	6%

A microbiological assessment of various meat and meat products collected from different retail sources revealed notable variations in contamination levels depending on the type of product and type of retail outlet. The analysis targeted key pathogenic microorganisms (*S. aureus*, *Y. enterocolitica*, *L. monocytogenes*), as well as general hygiene indicators such as total viable counts (TVC), *E. coli*, and *Enterobacteriaceae*.

Among the tested categories, semi-finished products obtained from supermarkets exhibited the highest levels of pathogenic contamination, with *S. aureus* and *Y. enterocolitica* detected in 28.5% and 42.8% of samples, respectively. Raw meat samples also showed

a concerning level of microbial presence in all types of retail outlets. In supermarkets, *Y. enterocolitica* was found in 16.6% of raw meat samples, while the prevalence of 5.5% for *S. aureus*, *Y. enterocolitica*, and *L. monocytogenes* were identified for both retail stores and farmer markets for raw meat. Cooked-smoked products from supermarkets were similarly contaminated by all three pathogens (16.6%). In contrast, no pathogenic bacteria were detected in cooked sausages or cold smoked products from any outlet type.

Dry-cured products purchased from supermarkets were contaminated with *Y. enterocolitica* and *L. monocytogenes* (25% for each pathogen) while 25% of pâtés samples from supermarkets contained *S. aureus*. Regarding general microbiological indicators, the highest TVC counts were recorded in raw meat from farmer markets (6.4 ± 1.97 log CFU/g), followed by supermarket samples (5.4 ± 0.38 log CFU/g) and retail stores (5.8 ± 0.2 log CFU/g). Raw meat also exhibited the highest levels of *E. coli* and *Enterobacteriaceae*, with concentrations reaching 0.8 ± 0.6 and 3.1 ± 1.4 log CFU/g, respectively, particularly in samples purchased from retail stores and farmers' markets. Cooked sausages and pâtés demonstrated significantly lower total viable counts (TVC) compared to raw meat and semi-finished products, indicating better microbiological stability. In contrast, dry-cured and hot-smoked products showed reduced levels of hygiene indicator bacteria, such as *Enterobacteriaceae* and *Escherichia coli*, especially in samples obtained from supermarkets, suggesting better compliance with storage and handling standards. The findings of the present underscore the importance of retail outlet type because it may influence microbial quality and safety of meat products. Microbial contamination was associated with semi-finished and raw meat products, pointing to the need for more stringent hygiene monitoring and processing control for these product categories.

The present study results demonstrated that contamination levels varied significantly depending on the product type, storage conditions, and the place of purchase.

The highest levels of microbiological contamination were observed in samples of raw meat and semi-finished products purchased from farmer markets. In those samples increased TVC, *E. coli*, and *Enterobacteriaceae* were found, indicating poor hygiene practices, lack of temperature control, and unsanitary handling conditions.

Similar findings were reported by (De Oliveira et al., 2011), who documented high contamination levels in meat products sold at traditional markets, largely due to the absence of packaging and inadequate sanitary conditions.

In contrast, products purchased from supermarkets generally met microbiological safety requirements. However, several cases of contamination were found in semi-finished products, suggesting that issues may originate from the production level, rather than the retail environment.

Retail stores exhibited moderate contamination levels, particularly in terms of TVC and *E. coli*, highlighting the need for improved storage and hygiene control.

Furthermore, the presence of foodborne pathogens such as *S. aureus*, *Y. enterocolitica* and *L. monocytogenes* was confirmed from 5.5% to 16.6% of tested samples, mainly in raw meat and semi-finished products.

These results are consistent with the observations of (Buncic & Sofos, 2015), who emphasized that meat remains a key reservoir of foodborne pathogens, especially when hygiene is compromised.

Conclusions

1. The findings of this study underline the importance of a comprehensive and preventive approach to microbiological safety across all stages of the food chain - from production to final consumption.
2. Strengthening implementation of HACCP-based procedures, standardizing storage conditions, and training of personnel remain essential strategies for reducing foodborne risks.

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RECOVERY OF NEWCASTLE DISEASE VIRUS STOCKS FOR M, F AND HN GENE AMPLIFICATION FOR FUTURE CLONING PURPOSE

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Abstract

This article presents the results of the work to refresh and optimize the cultivation of the Newcastle disease virus (NDV) La-Sota strain (AV-0330) in embryonated chicken eggs to obtain high-quality viral material suitable for gene cloning and the development of vector constructs. One of the main objectives was to determine the optimal infective dose and passage level that would ensure maximum virus yield while maintaining embryo viability. The virus was cultured in 10-day-old embryos, and infectious and hemagglutinating activity was assessed at doses ranging from 10 to 1.000,000 EID_{50}. Titers were calculated using the Reed–Muench method. Molecular identification was performed by RT-PCR using custom-designed primers specific to the M, F, and HN genes, each containing restriction sites for downstream cloning. The results demonstrated that optimal replication occurred at doses of 1,000–10,000 EID_{50}, with infectious activity reaching 9.4±0.06 log_{10} EID_{50}/mL, hemagglutination titers up to 1:256 and no embryo mortality. Serial passaging up to the seventh generation showed a stable increase in infectivity starting from the fifth passage. All virus-containing suspensions remained microbiologically sterile. Amplification of the M, F, and HN genes yielded specific fragments of the expected lengths, confirming the integrity of the viral RNA and the suitability of the material for molecular cloning. Thus, the optimized cultivation of the La-Sota NDV strain and the application of validated primer systems provide a reliable foundation for generating recombinant constructs and confirm the potential of NDV as a platform for vaccine development in both veterinary medicine and biomedicine.

Keywords: Newcastle disease virus, vector, primers, chicken embryos, genes.

Introduction

Newcastle disease virus (NDV), also known as *Avian orthoavulavirus 1* (AOAV-1), belongs to the *Paramyxoviridae* family, subfamily *Avulavirinae*, whose members cause diseases of varying severity in birds (Rima, 2019). NDV infects more than 240 species of domestic and wild birds and is an enveloped virus with a negative-sense, single-stranded RNA genome. Its non-segmented genome, approximately 15,000 nucleotides in length, is divided by conserved intergenic regions into six genes arranged in the order 3'-NP–P–M–F–HN–L–5'. These genes encode eight viral proteins, including the main structural components of the virion (Alexander, 2000; Fauquet, 2005).

From a phylogenetic perspective, NDV is divided into two evolutionarily distinct classes. Class I includes a single genotype, mainly comprising low-pathogenic isolates obtained from wild and domesticated birds (Czegledi, 2006; Treshchalina, 2023). Class II comprises 21 genotypes, encompassing a wide range of strains with varying virulence levels, and is distributed globally (Dimitrov, 2019; Treshchalina, 2023). This class represents the most genetically diverse and rapidly evolving group of NDV.

Among poultry, particularly chickens, NDV remains one of the most serious infectious threats, with mortality rates reaching up to 100% when infected with highly pathogenic strains. Based on their virulence in chickens, NDV isolates are classified into lentogenic (low pathogenic), mesogenic (moderate pathogenicity), and velogenic (highly pathogenic) pathotypes (Frolov et al., 2021). While most apathogenic isolates from wild birds pose minimal risk to domestic poultry, the potential for mutations that increase virulence remains a significant concern.

The most cost-effective strategies to prevent the spread of infectious diseases include early pathogen detection, alert systems, and, critically, vaccination. Timely prevention of infectious and particularly dangerous diseases forms the foundation of national veterinary security. The development of next-generation prophylactic agents based on recombinant proteins is expected to enhance the epizootic safety of Kazakhstan. Vaccine development technologies utilizing viral vectors to deliver target antigens represent a modern approach to immunization.

Compared with other viral vectors, NDV offers several advantages. As the type species of the *Avian orthoavulavirus 1* group, NDV possesses a non-segmented negative-strand RNA genome that supports the insertion of foreign genes (up to ~5 kbp), which can be stably and highly expressed. Moreover, NDV is an acutely replicating cytoplasmic virus with an encapsidated genome, minimizing risks of recombination and persistence in host tissues. It replicates efficiently at high titers in cell cultures, making it a promising vector platform for vaccines targeting both animal and human pathogens.

Therefore, the aim of this study was to refresh and cultivate the NDV La-Sota strain in chicken embryos to obtain active virus-containing material for subsequent experimental use, specifically for cloning the M, F, and HN genes of Newcastle disease virus.

Materials and Methods

Newcastle Disease Virus

The Newcastle disease virus (NDV) isolate La-Sota (AV-0330) from the collection of the RSE National Veterinary Reference Center was used in this study.

Infection of Embryonated chicken eggs (ECEs)

Infection was carried out by injecting the virus into the allantoic cavity of 10-day-old developing chicken embryos. Inoculated embryos were incubated at 37 °C for 72 hours.

Evaluation of Infectious Activity

The biological activity of the viral material was assessed by titration on 10-day-old chicken embryos using a standard method. Viral titers were calculated using the Reed–Muench method and expressed in $\log_{10}$ EID_{50}/cm^3. Following each passage, the presence of hemagglutinins in the allantoic fluid was determined by the micromethod of the hemagglutination reaction (HAR) using a 1% suspension of chicken erythrocytes (King, 1991).

Statistical analysis of the obtained data was conducted using GraphPad Prism 8. The results were analyzed using the Student's t-test and considered statistically significant at $p < 0.05$ (Ashmarin, 1975).

Primer Design

Primers were designed based on reference gene sequences from the NCBI GenBank database using OligoAnalyzer and Primer-BLAST software. Restriction enzyme recognition sites were incorporated into the primer sequences to facilitate downstream cloning into expression vectors.

RNA Extraction and Reverse Transcription Polymerase Chain Reaction (RT-PCR)

Viral RNA was extracted from the allantoic fluid using the QIAamp Viral RNA Mini Kit (Qiagen, Germany). RT-PCR was performed using a one-step reaction mixture containing Taq DNA polymerase and reverse transcriptase, 5X reverse transcription buffer with magnesium chloride, dNTPs, specific oligonucleotide primers, and RNase-free water. The reaction mixture was pre-incubated at 50°C for 30 minutes for cDNA synthesis, followed by heating at 95 °C for 15 minutes to inactivate the reverse transcriptase and activate the DNA polymerase. Amplification was carried out for 40 cycles under the following thermal profile: denaturation at 95 °C for 10 seconds, primer annealing at 55 °C for 20 seconds, and elongation at 72 °C for 1 minute.

PCR products were analyzed by electrophoresis in 1% agarose gel stained with ethidium bromide and visualized using a gel documentation system.

Results and Discussion

In the present study, one of the cultivation parameters that we optimized experimentally was the infectious dose of virus used for embryonated chicken eggs (ECEs). This parameter is critical for achieving effective production of complete viral particles. As shown in Table 1, all tested doses (10, 100, 1,000, 10,000, 100,000 and 1.000,000 EID_{50} per ECE) contributed to viral accumulation - both in terms of infectious titers (ranging from 7.1 ± 0.22 to 8.95 ± 0.18 $\log_{10}$ EID_{50}/mL) and hemagglutinating activity (ranging from 1:8 to 1:512) - under otherwise consistent cultivation conditions.

However, the use of minimal doses (10 and 100 EID_{50}) resulted in significantly lower hemagglutinating activity compared to doses ≥1,000 EID_{50} ($P < 0.0001$ to 0.01), while the highest dose (1.000,000 EID_{50}) yielded reduced infectious titers compared to doses ≤100,000 EID_{50} ($P < 0.0001$ to 0.02). Based on these findings, doses of 1,000 to 10,000 EID_{50} were selected as optimal for infection of ECEs, as they provided consistently high infectious titers across all tested strains (strain-to-strain variation, $P > 0.99$ to 0.13), and hemagglutination titers that were comparable to or not significantly different from those achieved at higher doses ($P = 0.99$ to 0.24).

Subsequent assessments focused on quantifying viral accumulation relative to the infective dose, with the objective of maximizing virus yield. All experiments were conducted under standardized conditions: incubation at 37 ± 0.5 °C with 10-day-old chicken embryos and a relative humidity of $55 \pm 5\%$.

The results of infectious and hemagglutinating activity measurements across the tested doses are presented in Table 1.

Table 1

Study of the level of virus accumulation at different doses of infection

Infective dose, EID_{50}	***Number of dead / total chickenembryos in experiment***	***Hemagglutinating activity***	***Infectious activity, $log_{10}EID_{50}/mL$***
~10	0/20	1:64	8.7 ± 0.11^{ab}
~100	0/20	1:128	9.2 ± 0.08^{bc}
~1000	0/20	1:128	8.9 ± 0.2^{a}
~10,000	0/20	1:256	9.4 ± 0.06^{c}
~100,000	2/20	1:256	9.1 ± 0.24^{ab}
~1.000,000	0/20	1:256	9.3 ± 0.14^{c}

Note: Values are presented as mean ± standard deviation. a, b, c indicates statistically significant differences between groups ($p < 0.05$) according to one-way ANOVA followed by Tukey's multiple comparisons test. Groups not sharing the same letter differ significantly.

The results presented in Table 1 demonstrate that infection of ECEs with varying doses of the virus (ranging from ~10 to ~1.000,000 EID_{50}) resulted in a low embryo mortality rate, even at the highest inoculation levels, indicating the low virulence of the NDV La-Sota strain during embryonic incubation. Hemagglutinating activity remained stable across all doses, ranging from 1:64 to 1:256, suggesting preservation of the virus's antigenic properties regardless of infection dose.

Notably, the highest viral accumulation was observed at a dose of 10,000 EID_{50}, with an infectious titer of 9.4 ± 0.06 $\log_{10}EID_{50}$/mL.

Statistical analysis using one-way ANOVA revealed significant differences in viral titers between groups ($p = 0.0005$). Post hoc comparisons using Tukey's test identified that viral accumulation at 10,000 and 1.000,000 EID_{50} doses was significantly higher than in several lower-dose groups ($p < 0.05$). Superscript letters in the table indicate statistically distinct groups; values not sharing the same letter differ significantly.

Viral material from the NDV La-Sota strain was further propagated through seven successive passages in 10-day-old chicken embryos (Figure 1). The collected virus-containing suspensions (VCS) were subjected to quality control assessments, including evaluation of hemagglutinating activity, infectious activity, and microbiological sterility. The quality control results are summarized in Figure 1.

Figure 1

Dynamics of infectious activity and hemagglutination titer of NDV-La Sota strain across serial passages in embryonated chicken eggs. Blue bars represent the infectious activity of the NDV-La Sota strain (log_{10} EID_{50}/mL). The orange line corresponds to the hemagglutination titer (HAR), expressed as the reciprocal of the last dilution showing complete agglutination (1:256 or 1:512). Statistical significance was assessed by one-way ANOVA followed by Tukey's post hoc test. p-values above the bars indicate significant differences between selected groups ($p < 0.05$)

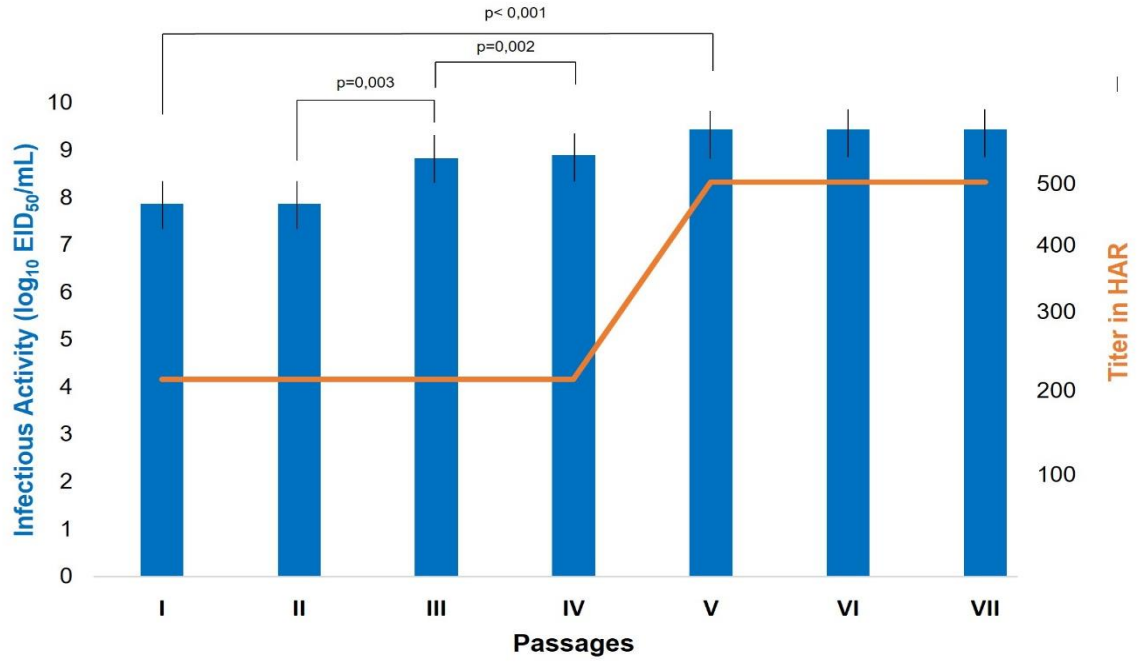

Figure 1 shows the data on the quality of virus-containing suspensions (VCS) obtained during the serial passaging of the NDV La-Sota strain in 10-day-old chicken embryos. Over the course of seven consecutive passages, the virus titer determined by the hemagglutination reaction increased from 1:256 (passages I-IV) to 1:512 (passages V-VII), indicating progressive viral accumulation and adaptation to the embryonic environment. This trend was paralleled by an increase in infectious activity, which reached 9.45 ± 0.37 $\log_{10}$ EID_{50}/mL by passages V-VII. Notably, beginning with the fifth passage, all virus-containing samples remained microbiologically sterile, confirming adherence to aseptic conditions during virus propagation.

These findings confirm that the NDV La-Sota strain exhibits stable replication and infectious activity in embryonated egg systems, supporting its suitability for downstream applications such as vaccine production. The observed increase in both hemagglutinating and infectious titers with successive passages highlights the efficiency of viral adaptation and the potential for accumulating high-titer, biologically safe material as early as the fifth passage.

For the molecular identification of the refreshed Newcastle disease virus strains inoculated into chicken embryos, polymerase chain reaction (PCR) was employed using previously developed strain-specific primer systems. These primers targeted key viral genes – M (matrix), F (fusion), and HN (hemagglutinin-neuraminidase) – which are crucial for viral replication, pathogenicity, and immunogenicity (Ikramkulova et al., 2025). PCR amplification was performed using in-house designed primer pairs specific to the M (1095 bp), F (1566 bp), and HN (1751 bp) genes (Table 2), successfully confirming the presence of the viral RNA in the embryo-derived material.

Table 2
Structure of primers for amplification of the M, F, and HN genes of NDV

Gene	***Primer***	***Primer sequence***	***Number of nucleotides***
M	M_F_Nde	ATCATATGGACTCATCTAGGACAATT	26
	M_R_Ecor	CGAATTCTTTCTTAAAAGGATTGTA	25
	M_F_Nde	GGATCATATGGACTCATCTAGGACAATTGGG	31
	M_R_Not	CGCGGCCGCTTTCTTAAAAGGATTGTA	27
F	F_F_Nde	GTCATATGATTGATGGCAGGCCTCTTG	27
	F_R_Not	TGCGGCCGCCATTTTTGTAGTG	22
NH	NH_F_Nde	ATCATATGGACCGCGCCGTTAGC	23
	NH_R1_Not	AGCGGCCGCGCCAGACCT	18
	NH_R2_Ecor	TCGAATTCGCCAGACCTGGCTT	22

The primers were designed with high specificity to the target regions of the respective M, F, and HN genes, ensuring both sensitivity and accuracy in PCR diagnostics. Additionally, restriction enzyme recognition sites, like NdeI, EcoRI, and NotI, were incorporated into the primers to facilitate downstream molecular cloning, including applications in recombinant vaccine development and in vitro protein expression. As shown in Table 3, the primer lengths ranged from 18 to 31 nucleotides, in accordance with generally accepted standards for efficient amplification. The restriction sites were strategically positioned at the 5' ends of the primers, allowing for efficient enzymatic processing and seamless insertion into cloning vectors without disrupting the reading frame.

Thus, the developed primer systems serve as versatile molecular tools suitable for both the detection of Newcastle disease virus (NDV) and the generation of genetic constructs for fundamental and applied research, particularly in the development of modern prophylactic approaches.

PCR using the designed primers for the M, F, and HN genes demonstrated high amplification efficiency. Distinct amplicons of 1095 bp, 1566 bp, and 1751 bp, respectively, were visualized on electropherograms and matched the expected product sizes. No amplification was observed in the negative control, confirming the specificity of the primers and the absence of contamination.

These results validate the high specificity and practical utility of the developed primer systems for subsequent molecular cloning and NDV-related research.

Newcastle disease virus (NDV) is a highly contagious orthoavulavirus that affects a broad range of bird species and causes significant economic losses in the poultry industry (Alexander, 2000; Samal, 2011). Due to their low virulence and ability to induce a robust immune response without pronounced clinical symptoms, lentogenic NDV strains such as La-Sota and B1 have been successfully employed for over 70 years in the production of live attenuated vaccines (Samal, 2020; Kim & Samal, 2016).

Avirulent NDV strains are considered highly safe, replicate efficiently in vivo, and elicit strong immune responses. Unlike adenovirus-, herpesvirus-, and poxvirus-based vectors, NDV encodes only seven proteins, reducing antigenic competition between the vector components and the expressed foreign antigens. The virus replicates in the cytoplasm, does not integrate into the host genome, and exhibits a low frequency of recombination. Its modular genome structure facilitates genetic manipulation. Furthermore, the intranasal route of infection induces both mucosal and systemic immunity. The wide variety of available NDV strains supports its use as a vaccine vector, including for the development of DIVA (Differentiating Infected from Vaccinated Animals) vaccines (Kim & Samal, 2016).

Lentogenic strains such as LaSota and B1 are highly attenuated and do not cause disease in domestic or wild birds, making them unique among live vaccines. In contrast, most currently used live virus vaccines for humans and animals are not naturally attenuated (Samal, 2020).

The safety and immunogenicity of NDV-vectored vaccines have been extensively studied in non-human primates, which serve as a relevant preclinical model due to their anatomical and phylogenetic similarity to humans (DiNapoli et al., 2007a, 2007b; Bukreyev &

Collins, 2008; DiNapoli et al., 2010; Khattar et al., 2013; Bukreyev et al., 2005). In one study, African green and rhesus macaques were inoculated intranasally and intratracheally with lentogenic (LaSota) or mesogenic (Beaudette C) NDV strains. No clinical signs of disease were observed, and virus isolation from throat and tracheal swabs was minimal. Post-mortem analyses detected limited viral replication in the upper respiratory tract and lungs, while no virus was found in the blood or other organs (Bukreyev et al., 2005).

In another study, African green monkeys were immunized via the respiratory tract with NDV expressing the S glycoprotein of SARS-CoV. The vaccinated monkeys developed strong neutralizing antibodies against SARS-CoV. Following high-dose SARS-CoV challenge, viral titers in the lungs of vaccinated animals were significantly reduced compared to those in unvaccinated controls (DiNapoli, 2007). These findings indicate that NDV is highly attenuated in primates, similar to humans, and its replication is largely confined to the respiratory tract.

There are rare reports of NDV infection in humans, typically among poultry workers and laboratory personnel (Capua & Alexander, 2004). In such cases, symptoms are generally mild and include conjunctivitis, laryngitis, or flu-like illness, resolving spontaneously within 1–2 days (Nelson et al., 1952; Lippmann, 1952). A serological study in India revealed that 38% of poultry workers were seropositive for NDV, compared to less than 4% of the general population, suggesting that most infections in occupationally exposed individuals are asymptomatic (Charan et al., 1981). Similarly, a U.S. study found 29% seropositivity among poultry workers (Miller & Yates, 1971), further supporting this observation. Importantly, no evidence of human-to-human transmission of NDV has been reported (Charan et al., 1981).

In this study, we successfully reactivated the NDV La-Sota strain in embryonated chicken embryos, enabling the production of reproductively active viral material. Analysis of cultivation parameters demonstrated that inoculation doses of 1,000–10,000 EID_{50} resulted in maximal virus accumulation, with infectious titers reaching up to 9.4 ± 0.06 $\log_{10}$ EID_{50}/mL and hemagglutinating activity up to 1:256. These values were comparable to those obtained with higher doses. Importantly, embryo mortality remained at zero even at the highest inoculation doses, confirming the retention of the avirulent properties of the La-Sota strain and supporting its continued suitability for experimental and production purposes.

Furthermore, serial passaging over seven generations revealed a consistent increase in both infectious and hemagglutinating activity, with complete microbiological sterility achieved from passage V onward. This indicates effective viral adaptation to the embryonic system and supports the feasibility of standardizing the production of virus-containing material.

To confirm the presence of viral RNA and assess the suitability of the resulting material for molecular cloning, reverse transcription followed by PCR was performed using custom-designed primers targeting the M, F, and HN genes (Ikramkulova et al., 2025). The resulting amplicons matched expected fragment sizes and were clearly visualized on agarose gels, confirming the efficiency of the primer systems. The inclusion of restriction enzyme recognition sites in the primer design facilitates direct cloning of PCR products into expression vectors without additional modification, streamlining the construction of recombinant systems.

In conclusion, this study confirmed the high stability, safety, and adaptability of the NDV La-Sota strain under embryonic cultivation conditions and demonstrated its potential as a robust platform for vector development. The generated viral material and validated molecular tools may be effectively utilized for the development of recombinant vaccines targeting a wide range of pathogens in both veterinary and biomedical contexts.

Conclusions

1. The cultivation conditions of the Newcastle disease virus (La-Sota strain, AV-0330) in chicken embryos were successfully optimized, enabling the production of highly active and sterile viral material suitable for molecular and biotechnological applications.
2. Optimal infection parameters, including virus dose and incubation conditions, were established. These conditions ensured consistent accumulation of infectious and hemagglutinating activity starting from the fifth passage, supporting standardization of virus propagation.
3. Specific primer systems targeting the M, F, and HN genes were developed and effectively applied, allowing for highly specific and sensitive detection of the virus using RT-PCR.

The results obtained provide a foundation for the development of universal antigen delivery systems and the construction of genetically engineered platforms applicable in both veterinary and human medicine.

Thus, this study offers promising prospects for further advancement in viral biotechnology and vector-based vaccine development using Newcastle disease virus as a platform.

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THE ROLE OF NATIONAL AGRICULTURAL ADVISORY SERVICES FOR INTRODUCING DIGITAL FARMING TO SMALL FARMERS: A REVIEW

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Abstract
The pursuit of sustainability in agriculture, being a key focus in the Common Agricultural Policy (CAP) of the European commission, has resulted in numerous initiatives being launched to speed up the modern farmer's transition to sustainable farming practices. However, the use of digitalization in agriculture, despite being able to address many sustainability challenges, is still not resonating with small farmers, leading to their low adoption of digital farming practices. Bulgaria and Romania – two of the EU countries where small farmers dominate the agricultural landscape – are among the EU countries with least digitalization in farming, and this is particularly valid for small farms. The goal of this paper is to explore the potential of the National Agricultural Advisory Services (NAAS) in Bulgaria and Romania in encouraging the small farmers' adoption digitalization via the support with consulting and application preparation for European Union (EU)-funded projects. Drawing on literature review and previous surveys related to the efficiency of the NAAS of Bulgaria and Romania and the consulting needs of the farmers in the two countries, the paper makes conclusions on the potential of those services to successfully promote the use of digital technologies by small farmers. The analysis reveals that if the NAAS is able to efficiently reach the farmers and respond to their consulting needs, they can influence the farmer's decision to make an investment in digital agriculture solutions via EU-funded programs. Considering the role of example for the wider adoption of digitalization among small farmers, the study concludes that NAAS consultations can play a major role for the increased adoption of digital technologies among the small farmers in poorer EU countries like Bulgaria and Romania.
Keywords: digitalization in farming, national agricultural advisory services, small farmers, Bulgaria, Romania.

Introduction

With digital technologies entering and transforming every sphere of life, the wider adoption of digitalization in agriculture has long been awaited, in the view of the pressing issues with growing world population, climate change challenges and resulting food security issues.

The term 'digitalization in agriculture' refers to the process of integrating advanced digital technologies like Artificial Intelligence, big data, robotics, unmanned aviation systems, sensors, and communication networks, all connected through the Internet of Things into the farm production system (Lioutas et al., 2021). Digital technologies have the potential to increase efficiency, improve the predictability and sustainability of farms and ensure less dependency on the scarce supply on the agricultural labour market (Gebresenbet et al., 2023). Technologies also make the agricultural sector more attractive, particularly to the younger generation (Borda et al., 2023) which has to take over the responsibility for ensuring the food supply of nowadays, albeit in challenging times. Finally, technologies like precision farming can reduce the negative environmental impact of agriculture, ensuring that resources such as water, fertilizers, and pesticides are applied precisely and mitigating the negative impacts on soil health, water quality, and biodiversity (Getahun et al., 2024).

Due to the numerous benefits of digitalization in farming, it is a key priority for the EU agricultural sector, with digitalization being embedded in the achievement of 10 key objectives of CAP 2023-27 (European Commission, 2025).

Digital technologies, however, can be expensive to adopt and integrate into the farming processes. This is particularly valid for the farmers defined as 'small' in poorer EU countries like Bulgaria and Romania.

The agricultural sector is comprised of different types of farmers, with one of the criteria being the size of the farmer. There is no universally accepted definition of a small farm and farm size can be assessed using farm's structural size, economic size, labour force and farms' market participation. EUROSTAT and the Food and Agriculture Organization (FAO) define small farms as those with an agricultural area of less than 5 hectares (ha), but this threshold can vary geographically (Guiomar et al., 2018).

Almost two-thirds of the EU's farms were less than 5 ha in size in 2020. Bulgaria and Romania are two countries in the EU with a significant percentage of small farmers, Romania being the leader in small farmers among all EU countries (Eurostat, 2023).

The economic effect of small farms is considerably less significant compared to larger farms; they are not as competitive as the big farmers in terms of access to labour and market. The importance of those farms lies in their ability to offer diverse varieties of agricultural produce, including traditional ones, to maintain the livelihood and existence of the rural communities (European parliament, 2022).

The EU objectives in the latest CAP are underwired by digital tools, and the aim for increased digitalization for small farms, is evident in the increased importance of digitalization and environmental criteria for receiving EU funds by small farms. However, the lower economic potential of the small farmers in the EU makes them less able to afford to invest in the advancements of technologies to become more sustainable and efficient (Rijswijk et al., 2021). In Bulgaria, the small farmers do not have enough assets, their business is considered high risk and hence, they

have low access to banking loans (Koteva & Fidanska, 2018). The same is valid for Romania - credit institutions place most farmers in the high-risk category (Mihai & Toderiţă, 2013) resulting in few loans given.

Thus, small farmers in Bulgaria and Romania count on EU-funded and government-funded programs to grow their business and finance new technologies. Hence, EU-funded programs can become the mechanism driving the adoption of digitalization in small farms.

Studies of the Bulgarian and Romanian NAAS, however, show that the small farmers in those two countries need consulting support to be able to take advantage of the EU-funded programs.

The purpose of the present review is to study the role that EU funded programs can play in the small farmers' decisions for investment in digital innovations. It aims to review the specifics of the European funding for small farmers in Bulgaria that can motivate small farmers to invest in digitalization via EU-funded programs. Next, it seeks to review the results reported by the NAAS of Bulgaria, as well as surveys on the farmers' opinion on the consulting institutions in two countries, in order to identify how the public agricultural consulting service can efficiently reach the farmers, increase the success of its services and influence the small farmers' decision to introduce digital technologies in their farms.

Materials and Methods

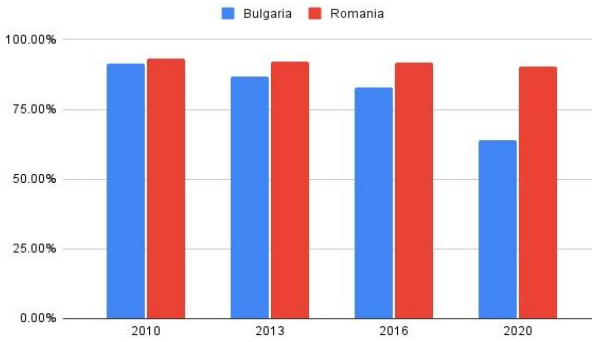
In the article, review of statistical data from various national and statistical portals has been done in order to identify indicators of the agricultural sector in Bulgaria and Romania confirming the importance of small farmers for the agricultural sector. Classical research methods such as analysis of results from previous surveys were used to identify the expectations of the farmers towards the consulting services and the characteristics of the NAAS of Bulgaria and Romania that can increase the success of the agricultural consulting service. Review has been done on the information available publicly on the website of the NAAS of Bulgaria 2019-2024 in the form of annual reports and announcements in order to collect information of the results they achieved in that period. Descriptive statistical analysis methods were used to present data from Eurostat and information on the specifics and results of Bulgarian and Romanian NAAS.

Results and Discussion

Small farmers dominate the agricultural landscape in Bulgaria and Romania. Between 2010 and 2020, farms of 5 ha or less in these two countries hold a significant share of the total number of farm holdings 'Figure 1'. In the aforementioned period, the share of small farmers in Romania persisted above 90%. In Bulgaria small farmers somewhat diminished but still accounted for about two-thirds of all farmers (Eurostat, 2023, latest date available is as of 2020).

Figure 1

Small farms in Bulgaria and Romania as % from the total number of farms, 2010-2020



Small farmers in all EU countries have EU funding programs accessible to them that aim to encourage the sustainability and modernisation of the farms. In poorer EU countries like Bulgaria and Romania, these funding programs could be the only option for the farmer to afford investment in assets, including digital technologies. However, small farmers require extra government support to take advantage of EU-funded programs. Applying for a subsidy from the EU-funded programs requires meeting eligibility criteria, preparing a business plan for achieving specific targets, and tailoring the business plan in order to maximize the points earned based on the project criteria (National Agricultural Advisory Service, 2025). This means that the application for funding programs for small farmers requires specific knowledge, including meeting the administrative criteria. Additionally, a business plan is not something small farmers are preparing as part of their daily activities, considering that in Romania, for example, 99.1% of small farmers do not even have a legal personality (Stoica, 2023).

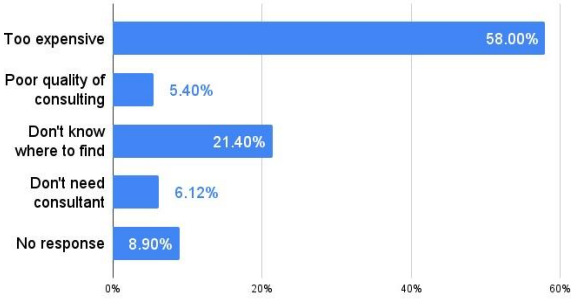
Further to the above, small farmers have little or no budget to spend with consultants preparing projects for the EU funding calls. This was confirmed by a survey of Bulgarian NAAS performed in the first years after it was selected as a single provider of advisory services by Ministry of Agriculture and Food in the context of the Rural Development Programme 2007-2013, measure 143 'Provision of agriculture advice and consultancy in agriculture in Bulgaria and Romania'. The survey (National Agricultural Advice Service, 2014) which included a total of 1,733 farmers, 76.6% being small farmers cultivating up to 5 ha of land, showed that 58% of the interviewed farmers do not use consulting services because they are expensive. 21.4% of the surveyed farmers do not know where to find consulting services 'Figure 2'. This confirmed the necessity for free public agricultural consultancy by Bulgarian NAAS.

McBride & Daberkow (2003) conclude that it is personal contacts, including informal contacts with relatives and peers and formal contacts with institutionalised sources, such as organisations and

consultants that have greater effectiveness compared to impersonal sources in affecting users' perceptions regarding the usefulness and ease of use of an innovation. This implies that formal contacts with organisations and consultants, like agricultural consultants from NAAS, can potentially influence the farmer's decision to use innovations on their farm. It also shows that if part of the small farmers is supported to adopt and start using digital technologies efficiently, then they could refer the solutions used to their close peers' network and increase the widespread adoption among the general small farmer community.

Figure 2

Reasons why farmers in Bulgaria are not using consultancy services



With regard to the specific consulting topics needed by the small farmers, Bulgarian NAAS survey confirmed that consulting needs are mostly related to accessing EU funding. 90% of the survey respondents said finding information about the farmer funding programs as well as applying for them would create difficulties for them. The same consulting needs, albeit from a later survey performed in 2022 and including 310 Romanian farmers and 50 actors directly involved in the agricultural knowledge and innovation system in Romania, showed that the state advisory system is in demand especially in the area of accessing subsidies and European funds (Meirosu et al., 2023).

Free consulting related to EU funded programs and delivered by the Bulgarian and the Romanian National Agricultural Advisory Services is thus needed, and it is mostly related to support with EU-funded programs. Given the specific deadlines for the application periods, it poses demands for sufficient consulting personnel serving small farmers.

The Bulgarian NAAS has 27 regional offices and 28 mobile municipal offices in the country, with the latter created at the end of 2022. Bulgarian NAAS provides free specialized consulting services and prepares business plans for all measures of the Thematic subprogram for the development of small farms (EU CAP network, 2023; National Agricultural Advisory Service, 2025)

The Romanian public advisory system consists of 479 advisors working under the 41 County Agricultural Directorates (DAJs), working in the offices of the county seats of the DAJs (approx. 200 advisors) and at the local level through the local centres (approx. 7-9 municipalities in each county belonging to the local centre have agricultural advisors; a total of 279 advisors are distributed across all local centres). (Meirosu et al., 2023).

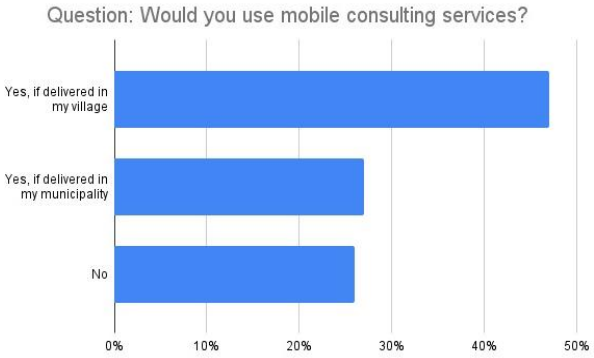
Comparing the National Agricultural Services of Bulgaria and Romania, we can see that they offer free advisory service via numerous offices and personnel. The efficiency of the public advisory system, measured in terms of its ability to reach farmers and make them use the advisory services, depends on the ability of the advisors to deliver consulting services close to the farmer.

In Romania, 92% of the farmers prefer to access advisory services in person. Both farmers and experts see a need to strengthen a regional network of physical offices where farmers can access a wide range of information, advice and services on a 'one-stop shop' basis (Meirosu et al., 2023).

The survey of Bulgarian NAAS showed that 74% of farmers would use mobile consulting services, with 47% preferring mobile services in their city or village and 27% willing to use consulting from a mobile office that comes to their municipal centre 'Figure 3'.

Figure 3

Willingness of Bulgarian farmers to use mobile consultancy services



The two surveys show that farmers need consulting in person, on-site or near their farms. A regional network of physical offices where farmers can access agricultural advice and information is required, but mobile services visiting the farmers on site are highly needed.

In November 2021, the Bulgarian NAAS received a budget for setting up mobile units and as seen in 'Figure 4', in 2023 when the units were already functional, the total consultations delivered by NAAS surpassed the consultations delivered in any year from 2019 to 2022, with the mobile office consultations scoring the largest increase. Compared to 2022, the total consultations in 2023 increased significantly with 33.7% (National Agricultural Advisory Service, 2025) which showed the positive response by the farmers.

In-person consultations and on-site visits are however time-consuming due to the travel required, often in poor-infrastructure rural areas and thus are tightly related to the availability of advisory personnel. Table

1 below compares the availability of agricultural advisors in Romania and Bulgaria as of 2023. It shows that the number of farmers that one advisor in Romanian NAAS should serve is about 5.3 times more than the farmers an advisor in Bulgarian NAAS should serve (Meiroșu et al., 2023; National Agricultural Advisory Service, 2025).

But even the number of farmers to be served by 1 Bulgarian NAAS advisor is high. Experience elsewhere in Europe has shown that coverage of between 1 and 1.5 full time equivalents (FTE) of professional expertise is required to adequately serve 100 farmers – i.e., one consultant can efficiently advise between 65 and 100 farmers (Stefanescu et al., 2013).

Figure 4

Consultations delivered by Bulgarian NAAS

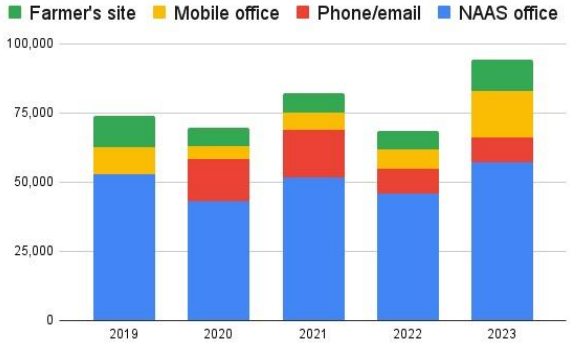


Table 1

NAAS of Bulgaria and Romania - advisors in 2023

Country	*Number of farmers*	*Agricultural advisors*	*Farmers per 1 advisor*
Bulgaria	132,742	117	1,135
Romania	2.887,000	479	6,027

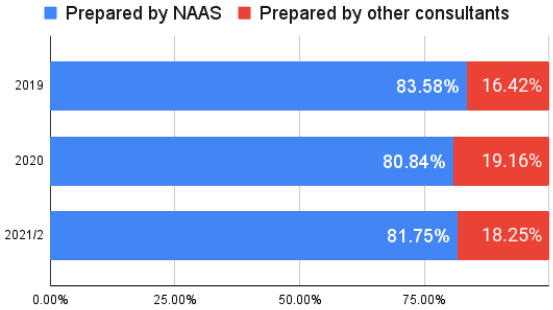
The deficiency of public advisors in Romania available to consult the farmers is reflected in the fact that the website of the Romanian Agency for Financing Rural Investments - an institution subordinated to the Ministry of Agriculture and Rural Development (MARD) that is responsible for the technical and financial implementation of the National Rural Development Program 2014 - 2020 (NRDP 2020) - lists the contacts of a large list of private consultants, along with region they cover and funding programs they consult on (AFIR, 2025).

The preparation of an application for an EU-funded Bulgarian small farmer program requires evaluation of the appropriateness of the farm and defining a number of administrative characteristics for it, like the standard production output of the farmer, creation of a business plan and making sure the plan includes the components appropriate to the farm that would give extra points to its application. Thus, we can consider the number of EU-funded applications submitted by the NAAS as an indicator on longer and more in-deep collaboration with the farmer rather than an indicator of one-time consulting service done. Between 2019 and 2022, Bulgarian NAAS prepared a total of 3,452 project applications only on sub-measure 6.3 'Start-up' aid for the development of small farms. Those applications were more than 80% of all applications submitted 'Figure 5'. This shows that Bulgarian NAAS is succeeding in establishing in-depth cooperation with many small farmers.

The recent funding programs for small farmers, per Bulgaria's CAP strategic plan (CAPSP) for agriculture and rural development 2023-2027, include criteria of investment in assets contributing to digitalization, offsetting climate change and environmental impact in all funding programs for small farmers (State Fund Agriculture, 2025).

Figure 5

Project applications for sub-measure 6.3 for very small farmers in Bulgaria, 2019-2022



As seen in Table 2, such an investment contributes between 18.52% and 28.85% of the maximum points in the application, emphasizing the significance of this criteria. The usage of digital technologies in farming can be used to combat climate change and protect the environment, as already stated above, and hence digital solutions can be used to match these criteria.

Table 2

Bulgarian EU-funded programs for small farmers 2024: Points for digitalization, climate change or environmental protection assets

Funding program	*Points*	*% from max points*
Young farmers	10	18.52%
Very small farmers	15	28.85%
New farmers	8	20.00%

Additionally, a fixed minimum part of such an investment is required to be done from the first funding received, as seen in Table 3, thus encouraging the farmer to use the purchased asset to achieve the results entitling him/her to get the second 50% of the funding (State Fund Agriculture, 2025).

Table 3
Bulgarian EU-funded programs for small farmers 2024: Investment in digitalization, climate change or environmental protection assets

Funding program	***Minimum to be invested***
Young farmers	€7,000. 35+ % from first payment
Very small farmers	€1,750
New farmers	€2,250

Given the importance of the digital criteria in the three funding programs for small farmers in Bulgaria, the consultants would need to be aware of the available digital solutions on the market that can fit the specifics and budgets of the small farmers applying for funding. This makes the training of the NAAS consultants critical in order to positively influence the adoption of digital tools.

It could be additionally researched how each NAAS can ensure that all consultants have relevant knowledge of digital tools and can recommend the best tool for every farmer. The steps that the Bulgarian NAAS has taken, as seen in their annual budgets, is sending printed materials, conducting webinars and on-site seminars for its consultants. However, the role of the consultant's background and his motivation to perform highly and meet the needs of the farmer can be factors affecting the efficiency of NAAS in promoting the appropriate digitalization tools and those can be the subject of further analysis.

A further complexity lies in the fact that NAAS, being a state-funded institution, cannot officially promote and recommend commercial digital solutions. This hinders the collaboration, like on-site demonstrations and trainings with commercial providers of digital solutions and thus, consultants can only recommend general approaches/solutions for digitalization of the small farm, leaving the final provider selection in the hands of the farmer. A step in this direction has been made by the Romanian Rural Investments Financing Agency AFIR which maintains a third-party Price Reference Database (PRD) on its website.

'Through the Price Reference Database, the Rural Investments Financing Agency (AFIR) facilitates access for applicants to the European fund information while also simplifying the procurement procedure. Thus, the products that can be found in this Database are directly available for purchase for private beneficiaries without going through any other procurement procedure' (AFIR, 2025).

The PRD of AFIR gives a choice of verified solutions, categorized per the respective EU funding programs and enables the taking of a more informed decision by the funding applicant or by the consultants on the funding programs. The Bulgarian NAAS does not have such a database of digital solutions.

Even though Bulgarian and Romanian public agricultural advisory services cannot directly recommend digital solutions suppliers, it is clear that they can influence the farmers to include digital solutions in their business plan in order to maximize on funding application points. Even if the decision on selecting a digital solution is left in the hands of the farmer, the consultant plays a major role in communicating the importance of digital solutions for winning the EU funding, in raising interest and provoking action by the farmer towards researching available digital solutions, considering the potential benefit from each and making his choice. Such a first step, even though provoked by the need to access EU funding, can equip the farmer with his first digital farming tools, letting him see the benefits from digitalization in farming and potentially resulting in sharing his experience and the larger adoption of digital solutions among the small farmers community.

Conclusions

The following can be concluded from the research results:

1. Small farmers in poorer EU countries like Bulgaria and Romania cannot afford consultancy services and would rather use public, free agricultural consulting.
2. Consulting by NAAS is not efficient and used if there are insufficient human resources to deliver consulting in person, close to the farmer's location.
3. Mobile offices and consultations delivered in or close to the farmer's village at specific times of the day are more likely to be used by the farmers and hence the success of reaching the farmer would be higher.
4. Free agricultural consulting for EU-funded projects can open the door to the first steps in digitalization in farming.
5. The criteria for digitalization or reduction of environmental impact on small farmer EU-funded projects is likely to push consultants into increasing their own and the farmer's awareness on digital tools for agriculture so that appropriate tools fitting the budget requirements can be proposed for the business plan in pursuit of maximized points.

Acknowledgements

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THE INFLUENCE OF GREENHOUSE INTEGRATED PHOTOVOLTAICS ON MICROCLIMATE

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Abstract
The utilization of photovoltaics (PVs) has proven to be a remarkably effective solution in a diverse range of domestic and industrial contexts. The integration of roof surfaces with PV systems has facilitated the generation of clean, renewable electricity, thereby addressing critical concerns regarding energy sustainability and environmental impact. Photovoltaic greenhouses constitute hybrid systems, integrating photovoltaic technology with conventional agricultural practices within a single space. Furthermore, this particular type of greenhouse retains all the characteristics of a conventional greenhouse, whilst simultaneously offering the possibility of electricity production. The purpose of this study is to evaluate the impact of the shading caused by photovoltaic panels on the microclimate, with specific reference to air temperature and relative humidity. The experiment was conducted in two similar greenhouses. Bifacial photovoltaics were installed on the entire roof surface of one greenhouse, while the other greenhouse, which was uniformly shaded by a polycarbonate sheet, served as a control greenhouse. The results illustrate that, despite the negligible immediate effect of photovoltaics, a comparison with findings from other scientific studies clearly indicates that photovoltaics can contribute to the improvement of greenhouse microclimate, including in the Nordic countries of the Baltic States. Moreover, it has been demonstrated that photovoltaic technology has the capacity to serve not only as a source of energy but also as a constructive element in greenhouse systems.
Keywords: photovoltaics, microclimate, greenhouse, humidity, shading.

Introduction

Greenhouse cultivation is a contemporary agricultural technology that provides an optimal microclimate conducive to the growth of crops. Such a climate is characterized by specific factors such as relative humidity, lighting, and ambient air temperature, which are collectively or separately influential on the cultivation of specific crops and the timing of their yield. The application of this technology is especially relevant in contexts involving out-of-season cultivation (Lu et al., 2020). Consequently, agrivoltaic systems have come to the fore as a potential solution to mitigate the competing demands on land usage that arise from the deployment of photovoltaic (PV) technology and agricultural activities (Fernández et al., 2022). Moreover, greenhouses are typically constructed in areas characterized by ample sunlight exposure. This is due to the necessity of sunlight for the process of photosynthesis in plants. Consequently, such locales are inherently conducive to the generation of photovoltaic energy (Zhao et al., 2021).

One such area of interest is the development of urban areas through the establishment of urban gardens. This approach could be demonstrated to enhance the quality of sustainable urban environments and promote food self-sufficiency. Furthermore, it could help increase independence from electricity prices and power outages by utilizing the same area.

Photovoltaic energy can thus be considered as renewable, sustainable, clean and available. It is evident that the utilization of this energy is on the rise. In addition, it is both the most widely used and the most widespread form of energy in the world. Consequently, the utilization of photovoltaic energy within greenhouses constitutes a pivotal objective in achieving sustainable greenhouse crop production (Kadowaki et al., 2012).

A range of climatic parameters are known to characterize the microclimate of a greenhouse, with the set of these factors differing significantly from external conditions. Such factors, which may be categorized as temperature, relative humidity, carbon dioxide (CO_2) concentration and solar radiation, play a pivotal role in shaping the unique environmental conditions within a greenhouse. Each of these parameters exhibits a strong correlation with both external weather conditions and the unique characteristics of the greenhouse (Ezzaeri et al., 2018). As posited by numerous authors, the integration of photovoltaic panels into a greenhouse structure has been demonstrated to result in a decline in both interior light intensity and air temperature (Gorjian et al., 2021; Friman-Peretz et al., 2020).

It is also noteworthy to observe the presence of other conclusions. The author of the study draws attention to the fact that the temperature levels within both greenhouses are almost identical, with only slightly elevated temperatures recorded in the reference greenhouse (Trypanagnostopoulos et al., 2017).

The objective of the present study is to evaluate the impact of shading caused by photovoltaic panels on the microclimate in region of Baltic States. The present evaluation is concerned with ascertaining the extent to which the local climate of the region exerts an influence on the microclimate of the greenhouse under photovoltaic technology. To this end, the evaluation considers air temperature and relative humidity.

Research indicates that the photovoltaic module's surface temperature exhibited an average increase of 8 °C compared to the internal air temperature of the greenhouse. Additionally, the difference between the module temperature and the ambient temperature was recorded as 14 °C. It is noteworthy that the maximum and minimum temperatures of the photovoltaics

recorded were 48.3 °C and 23 °C, respectively, while for the greenhouse operated under natural ventilation, the recorded maximum and minimum temperatures were 38 °C and 23.3 °C, correspondingly. The findings demonstrated the efficacy of integrating photovoltaic technology in the external structure of the greenhouse in mitigating the issue of overheating in the summer months (Hassanien et al., 2018). Consequently, it can be deduced that there are numerous options for the placement of solar panels on greenhouse roofs. The results indicate that there are significant temperature fluctuations in other regions; however, it should be noted that these fluctuations may vary from region to region.

Shading greenhouses have been found to be an efficacious method of achieving an optimum environment for crop growth and enhancement of crop productivity and quality in regions characterized by high temperatures and solar irradiance. The implementation of shading results in a significant reduction in air temperature within the greenhouse, typically by 5–10 °C compared to the ambient outdoor temperature. Concurrently, it leads to an enhancement in relative humidity by approximately 15–20%. As a consequence of the aforementioned, it is evident that the implementation of shading in a greenhouse results in a significant reduction in solar radiation when compared with solar radiation in a greenhouse without shading. Indeed, the reduction in solar radiation is reported to be between 30–50% (Ahemd et al., 2016).

The studies have revealed significant variations in relative humidity, which were predominantly detected at midday. The range of day relative humidity differences between the photovoltaic and control sections was found to be between 2–9%. Furthermore, relative humidity levels in both the photovoltaic shaded and control sections were found to be higher than the ambient relative humidity levels. The elevated relative humidity observed in the control section was attributed to the elevated irradiance levels, which subsequently led to increased transpiration within that particular section (Waller et al., 2021).

The application of selective filtration of light has also been demonstrated to be an effective strategy for the regulation of temperature within a greenhouse setting. The predominant heating component of light is infrared. The greenhouse can be rendered more insulated from external temperature fluctuations by reflecting the aforementioned light component. The optimal temperature range for the majority of greenhouse vegetable plants is between 20–25 °C during the day and 14–18 °C at night. In climates where temperatures are lower than 4 °C, particularly during winter, the use of heating systems becomes imperative to elevate the greenhouse's internal temperature (Ahemd et al., 2016).

Materials and Methods

The experiments were carried out within two adjacent greenhouses. These greenhouses were located at the experimental site of the Institute of Agricultural Resources and Economics in Priekuli (57.3137778 N; 25.338472222222222 E). The greenhouse was divided into two sections. Each greenhouse compartment occupies a surface area of 4 m^2, with a maximum height of 2.2 m, and wall heights of 1.5 m. The construction of both greenhouses comprises a galvanized steel profile frame, with a 4 mm thick cellular polycarbonate cover. Each greenhouse is equipped with doors at the ends, accompanied by automatically controlled window openings according to the indoor temperature.

One of the two greenhouses has been equipped with solar panels on its roof, thus ensuring complete coverage of the roof area. The configuration of these photovoltaic panels was oriented in an east-west direction, while the second greenhouse was designated as a control. The experiment was conducted using four 1765 mm long and 1043 mm wide photovoltaic panels – Figure 1, with the relevant parameters documented in Table 1.

Figure 1

Photovoltaic covered greenhouse

An investigation into the climatic parameters of the greenhouse was conducted during the fall season. However, the current research has been conducted over a single measurement period, specifically from 8 September 8.17 a.m. to 12 September 9.17 p.m. in 2024. The primary variables, including temperature and humidity, were measured and recorded on a data logger at hourly intervals, fixed at a height of 1.5 meter to the side wall. The Testo 174H data logger was utilized in conjunction with a temperature

measurement range of -20 to +70 °C, with an accuracy of ±0.5 °C (-20 to +70 °C), and a humidity measurement range of 0 to 100% RH, with an accuracy of ±3% RH (2 to 98% RH).

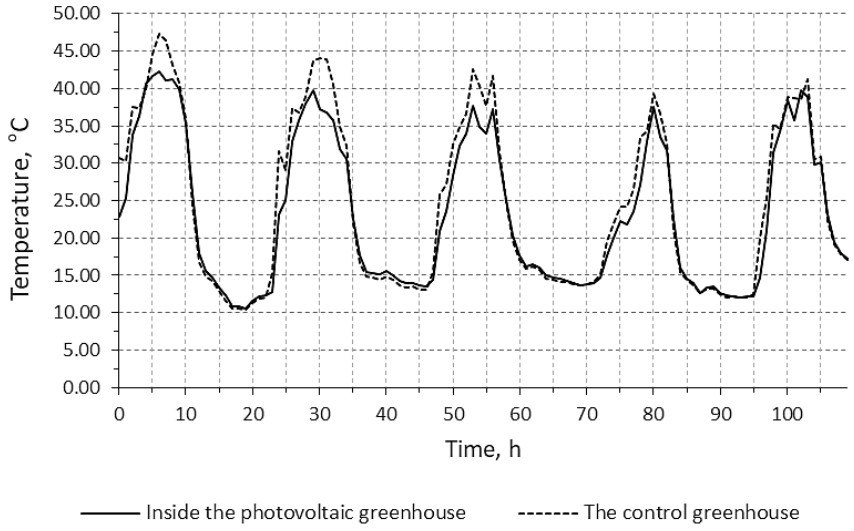
Table 1
Characteristics of the photovoltaic panels

Name	***B60/6–370W$_p$***
Peak power (P_{max})	370 W
Open Circuit Voltage (V_{oc})	42.2 V
Short circuit Current (I_{cc})	11.25 A
Voltage	36.9 V
Current (I_{mp})	10.03 A
Solar cell	Bifacial M6, 9BB
Dimensions	1765×1043×5 mm
Weight	22 kg

Furthermore, the distribution of internal climatic parameters in both greenhouses was measured concurrently at a designated hour, thereby ensuring the acquisition of data over a specified period, encompassing external conditions such as clouds that may have influenced the climate in both greenhouses concurrently.
Measurements of air temperature and relative humidity were taken at the equivalent point in both the photovoltaic greenhouse and the control greenhouse.

Results and Discussion
As illustrated in Figure 2, the air temperature fluctuations inside both greenhouses are presented in the form of a time graph. The data were collected over a period of five days, commencing on the 8th and concluding on the 12th of September 2024. The results indicate that the temperature fluctuations were particularly pronounced during the day, with a decline observed during nocturnal periods. The observed difference in maximum temperatures between the two greenhouses can be attributed to the combined effects of the greenhouse effect and the thermal properties of the cover.

Figure 2
Evolution of air temperature



In fact, the lowest temperature recorded in the photovoltaic greenhouse was between 10.6 °C and 13.7 °C, while the highest temperature varied between 37.5 °C and 42.2 °C. In the control greenhouse, minimum temperatures ranged from 10.4 °C to 13.7 °C, with maximum temperatures varying from 39.3 °C to 47.3 °C. The maximum observed difference in temperature between the two greenhouses was 8.5 °C.
The data gathered from the measurements indicate that during daylight hours, the air temperature within the greenhouse equipped with solar panels is lower compared to the control greenhouse. Conversely, at night, the trend is reverse, with incline in temperature observed within the solar paneled greenhouse. In the control greenhouse, a slight decline in temperature is observed. The disparity in temperature between the two greenhouses is minimal. The maximum disparity in temperature is observed to occur precisely during the day, around noon.
The varying degrees of shading, ranging from 0% to 78%, exhibited by the photovoltaic panels, along with the measured temperature range within the interior of the structure during the period of peak temperature, and on days characterized by clear skies, have been determined to fall within the optimal ranges for the cultivation of major vegetable species and this observation may be attributed to the configuration of the photovoltaic panels and their respective tilt angles (Marucci & Cappuccini, 2016). It has been demonstrated that shading has a beneficial effect on the microclimate of greenhouses. Indeed, it has been shown to enhance the cooling effect and reduce the energy required for cooling by up to 20%.

Furthermore, it has been demonstrated that shading can reduce irrigation by up to 25% (Ahemd et al., 2016).

The indoor air temperatures measured in the photovoltaic greenhouse were found to be within an acceptable range during nocturnal periods, however, during daylight hours, the temperatures were found to be elevated. In order to address this issue, it is recommended that the aperture on the side of the structure should be increased, with a view to maximizing the natural ventilation rate. The internal air temperature in the photovoltaic greenhouse was found to be lower than that of the control greenhouse during the measurement period, suggesting that the photovoltaic panels placed on the roof of the greenhouse act as shading screens (Ezzaeri et al., 2018).

The temperature within the two greenhouses exhibited a near sinusoidal trajectory. During the summer months, the disparity in air temperature between the shaded and unshaded greenhouses was more pronounced. The unshaded greenhouse recorded a 8% increase in temperature compared to the shaded greenhouse (Ezzaeri et al., 2020).

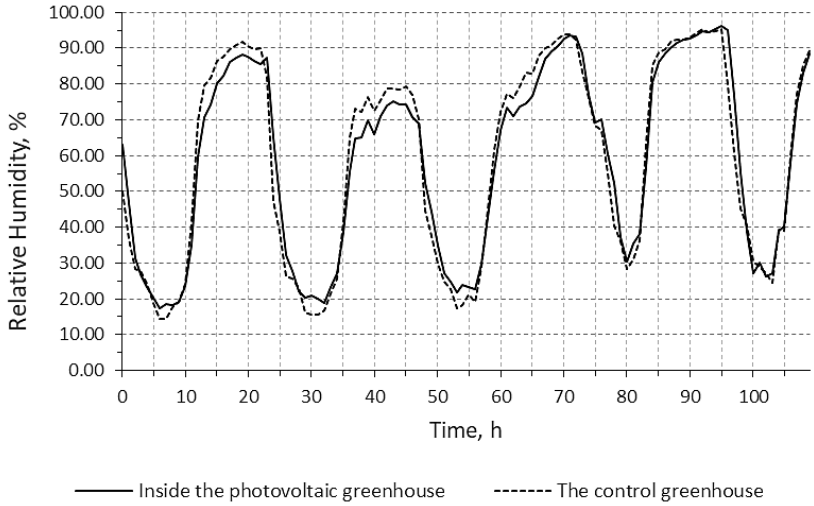
In the context of reduced temperature levels, the energy output of photovoltaic panels is advantageous with respect to air temperature management within the greenhouse environment. This is due to by combining these panels with a charging station at night or during colder period electricity utilized for the purposes of heating the structure, thereby ensuring thermal comfort.

However, it is important to acknowledge that temperature must also be considered when assessing the impact on solar panels, since temperature is a crucial factor affecting photovoltaic cell and panel performance, along with irradiance (Cotfas et al., 2018), but the present article is not concerned with a more detailed discussion of this issue.

As illustrated in Figure 3, the hourly variations in air relative humidity within the photovoltaic and control greenhouses were monitored over the period from 8 to 12 September 2024.

Figure 3

Evolution of Relative humidity



As demonstrated in Figure 3, the variation in air relative humidity exhibits a quasi-periodic pattern, analogous to the observed quasiperiodic variation in temperature. The increase in relative humidity is indicative of a decrease in air temperature. Furthermore, the study observed that during daytime hours, relative humidity decreased to its minimum levels, while at nighttime, it increased to almost maximum levels (100% in external environments).

The values of the relative humidity recorded within the photovoltaic greenhouse ranged from 17.5% to 93.6%, while within the control greenhouse, these values ranged from 14.3% to 93.9%. The maximum discrepancy observed in the air relative humidity between the two greenhouses was 17.6%.

In addition, a comparison of the air humidity data reveals that the air humidity remains marginally lower at night in the greenhouse covered with solar panels. Conversely, during the day, the air humidity is observed to be higher in the greenhouse covered with solar panels than in the control greenhouse. The most significant disparities in measurements are evident precisely at night.

As demonstrated in other studies, the findings indicate that the range of relative humidity within the photovoltaic greenhouse, measuring from 60% to 90%, is conducive to a broad spectrum of crop growth (Marucci & Cappuccini, 2016) and research findings indicated a lower mean daily relative humidity in the control zone when compared with the zone equipped with the photovoltaic panels. This discrepancy can be attributed to the characteristics of the photovoltaic panels utilized in the study (Ureña-Sánchez et al., 2012). Lower relative humidity is unsuitable for cultivation resulting in the closure of the stomata and restricts plant environment gas exchanges thus immediately impacting

photosynthesis as well as many physiological processes. Moreover, a too moist air fosters the development of fungal diseases and poor pollination of flowers. The excess or lack of moisture will strongly influence the crop productivity (Ezzaeri et al., 2018).

Conclusions

1. Although the effect caused by photovoltaics was not significant, a comparison of our findings with those from other studies clearly indicates that photovoltaics can help ameliorate the greenhouse microclimate, including in the Nordic countries of the Baltic States.
2. It has been established that this material has the capacity to serve as a constructive element, whilst simultaneously functioning as an energy source. Beyond this, the positive impact extends to the microclimate, whilst concurrently engendering a sustainable environment.
3. Future studies should concentrate on the following aspects: the amount of energy produced, the impact of solar radiation, and the microclimate within the greenhouse during plant growth. Furthermore, there is a need for further research on microclimate in different seasons. One of the objectives of this research is to determine whether integrating a photovoltaic cell can improve yields.

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EXPERIMENTAL INVESTIGATION OF COMPOSITE ACTION OF THIN LAYERED FIBER REINFORCED SANDWICH PANEL WITH SHEAR CONNECTORS

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Abstract
The construction industry faces growing pressure to create sustainable, cost-effective building solutions while ensuring structural performance. Traditional precast concrete sandwich panels often use excessive materials due to conservative design approaches and typical reinforcement methods. This research investigates the structural behaviour of innovative thin-layered sandwich walls (SW) manufactured using steel fibre reinforced concrete (SFRC) with integrated shear connectors. The experimental program examines 6 almost full-scale SW specimens measuring 1900×1000×270 mm, consisting of two SFRC bearing layers and an insulation core. The panels incorporate PD210 shear connectors and steel fibre reinforcement at a dosage of 30 and 50 kg m^{-3}. Concrete with strength class C40/50 was used for the bearing layers, with an intermediate layer of TENAPORS EPS 150 insulation. The study evaluates the composite action between layers and the effectiveness of shear connection systems under load. It involves full-scale specimen testing to assess bending behaviour and composite action efficiency, focusing on deformation characteristics and shear connector performance. The goal is to provide insight into the structural effectiveness of thin-layer SFRC sandwich panels for potential use as load-bearing components in building envelopes. The experimental tests showed a weak composite action of the SW specimens, which was determined based on the load–deflection behaviour and strains measured on each surface of the wythes. A parallel study investigates the performance of these walls under eccentric compression. The study evaluates the necessity of composite action, suggesting that thin layer wall structures can support significant axial loads even without it.
Keywords: fibre reinforced concrete, experimental study, four-point bending, level of layer composite action.

Introduction

In today's world, where the construction industry is focused on reducing carbon emissions generated during the construction process, we are compelled to seek more efficient solutions that minimize the consumption of building materials.

Three-layer panels are frequently used in building construction. Traditionally, concrete is reinforced with steel bars. In low-rise buildings, the thickness of these panels often exceed load-bearing capacity requirements. Conventional reinforcement must be provided with minimal thicknesses of concrete cover following current building codes EN 1992 (CEN, 2024). The thickness of the panels could be reduced by replacing conventional reinforcement bars with an alternative that does not require such a large thickness of concrete cover.

Many authors have demonstrated in their studies how concrete reinforced with fibres can be used in load-bearing structures, reducing the inefficient use of cross-section. (Naaman, 2003; Katzer & Domski, 2012). Steel fibre reinforced concrete (SFRC) can be used to produce rather thin concrete wythes ensuring sufficient ductility and load bearing capacity for single-storey buildings (Barros et al., 2007; Lameiras et al., 2021).

Skadins et al. (2023) in their numerical analysis of three-layer thin-walled fibre reinforced concrete panel showed that the load-bearing capacity of panels with 60 mm thick wythes exceeded the design loads of a single-storey family house for around 100 times. This demonstrates the significant potential for optimizing these structural elements.

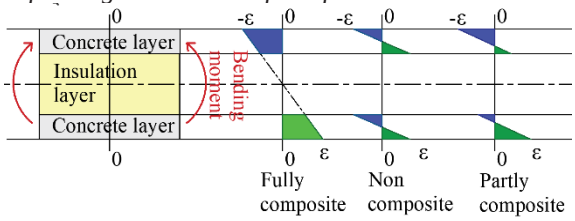
In this research endeavour, we build upon our previous analytical study by incorporating experimental methodologies to investigate the findings further. This continuation aims to validate our initial hypotheses through hands-on experimentation, providing a more comprehensive understanding of the subject. Recent studies have shown changing views on precast concrete sandwich panel behaviour. Anand and Singhal (2023) highlighted the important role of shear connection systems while noting that new research questions whether full composite behaviour is always needed or cost-effective. This viewpoint is confirmed by the previous study Skadins et al. (2023), which shows that thin-layer wall structures can withstand significant loads even without full composite action.

If slender elements are subjected to compressive load, they can buckle before reaching the resistance of the cross-section. The thinner walls are, the smaller load is needed for them to buckle. A solution to this problem is the use of composite cross-section or so-called sandwich type walls (SW). The outer layers or wythes of such walls are made of concrete, while the inner layer is for thermal insulation purposes. If the composite action of such a wall's layers is obtained, the moment of inertia as well as the radius of gyration is increased significantly and thus the critical buckling load.

Shear connectors can provide composite or non-composite, but usually semi-composite, action between the outer layers of a panel (Benayoune et al., 2008). Typical strain profiles for the different composite and non-composite cases were described in many articles (Pessiki & Mlynarczyk, 2003; Flansbjer et al., 2018; Anand & Singhal, 2023; O'Hegarty et al., 2019) and are displayed in Figure 1. In the composite behaviour of the panel, both outer layers of the panel jointly resist bending, which is observed in the strain

diagram as a continuous line connecting the compressive strain on the upper panel surface with the tensile strain on the lower panel surface through a zero point at the panel centre of gravity. This can be achieved by ensuring full shear force transfer from the upper layer to the lower one.
In the case of non-composite behaviour, each layer resisted bending independently. This is observed as 2 separate strain diagrams with neutral axes passing through the centre of gravity of each layer.

Figure 1
Illustration of strain profiles in a fraction of a sandwich wall (SW) subjected to pure bending depending on the level of composite action



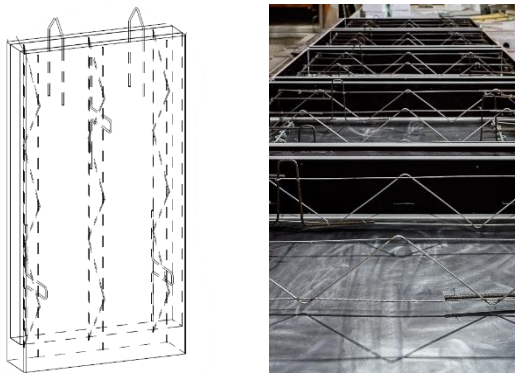
However, according to the previous numerical study (Skadins et al., 2023), the composite action is not always favourable. Indeed, the SW with non-composite section reached the same load bearing capacity as the ones with the composite section. Due to the composite behaviour, the temperatures caused by solar radiation can result in unfavourable lateral deformations and cracking. Thus, to prevent thin wythes from buckling, it is more important to connect them with an adjacent and unloaded wythe than to try to introduce very expensive shear connectors.
To verify the validity of the conclusions based on the numerical analysis, an experimental study of large size thin-layer SW is conducted. The study consists of two parts dealing with the evaluation of the composite action and with the load bearing capacity under compression. The aim of this study is to present the evaluation of the level of composite action of such walls obtained by experimental loading if steel lattice girders are used as the shear connectors. The results presented in this paper are going to be used in further evaluation of necessity of complex shear connectors to ensure sufficient load bearing capacity of thin layer SW.

Materials and Methods

Two series (SW1 and SW2) of full scale thin-layer sandwich wall specimens were tested in the four-point bending test setup. All specimens were fabricated at the production plant of MB BETONS group in Liepaja, Latvia. Each series consisted of three identical specimens having two different contents of fibre. The specimens represent a wall of a single-storey building, consisting of two self-compacting steel fibre reinforced concrete (SFRSCC) outer layers or wythes that are connected at the bottom of the wall and an insulation layer in between. The SW specimens were 1.0 m wide, 1.9 m tall with overall thickness of 270 mm. A 3D representation of the panels is given in Figure 2(a). Each panel was reinforced with three Peikko PD 210 single-lattice girders equipped with loops at each end to prevent cracking during lifting and transportation, several lifting loops (see Figure 2(b)), and steel fibres randomly distributed in the concrete. Two different fibre dosages were used in this study – of 30 kg m^{-3} for SW1 series panels and 50 kg m^{-3} for SW2. The PD 210 single-lattice girders were used as shear connectors between the wythes of the panels.

Figure 2
SW test specimen: (a) 3D visualization, (b) reinforcement of the specimen before casting

(a) (b)



Composite action of the specimens was evaluated by measuring mid-span deflection of the panels and strains on both sides of each layer.
Self-compacting concrete of grade C40/50 was used. Hooked end steel fibres with diameter 0.5 mm, length 35 mm and nominal tensile strength of 960–1350 MPa were used. The shear connectors were made of 5 mm steel (500 and 600 MPa) and stainless steel (520–720 MPa) wires. The loops were made of ribbed steel reinforcement bars (grade B500) embedded for lifting and transportation purposes.
Material properties of SFRSCC used in the specimens were obtained by testing standard 150 mm cubes under compression according to standard EN 12390-3 (CEN, 2019) and prisms in the three-point bending according to standard EN 14651 (CEN, 2022). There were three cube specimens tested per each series. The mean compressive strength f_{cm} was 83.26 and 73.85 MPa with the coefficient of variation (CoV) 1.5% and 4.2% for SW1 and SW2, respectively. There were ten prisms with dimensions of 150×150×600 mm used in each series to measure the post-cracking flexural tensile strength at crack mouth opening distance (CMOD) 0.5 and 2.5 mm, respectively. The mean flexural tensile strength f_{R1} (at 0.5 mm) was 3.13 and 6.44 MPa (CoV = 10.4 and 12.2%), and fR3 (at 2.5 mm) was 2.60 and 5.93MPa (CoV = 15.2 and 14.2%) for series SW30 and SW50, respectively. The mean modulus of elasticity calculated from the mean cylindrical compressive

strength according to EN 1992-1-1 (CEN, 2024) was 38510 and 37000MPa for series SW1 and SW2, respectively. Material properties were obtained for specimens at concrete age of 75 to 80 days and is shown in Table 1. SW panels were tested at concrete age of 260 to 380 days.

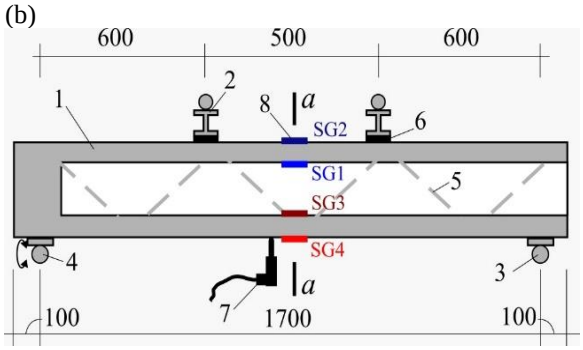
Table 1
Material properties of the test series

Series name	Number of SW specimens	Concrete strength, MPa	Fibre content, kg m^{-3}	f_{R1}, MPa	f_{R3}, MPa
SW1	3	83.26	30	3.13	2.60
SW2	3	73.85	50	6.44	5.93

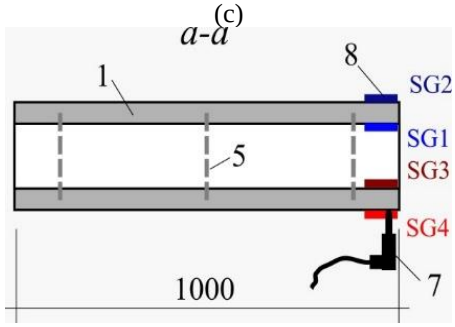
The experimental program includes loading of full-scale SW specimens to assess bending behaviour and the level of composite action. Key parameters monitored include load–deflection behaviour and strains on all the surfaces of the wythes. Composite action of the specimens was evaluated based on the measuring mid-span deflection and the strains.
To measure strains in both top and bottom concrete layers, four HBM linear strain gauges with base length 20 mm and gauge factor 2.19 were used. They were placed as shown in Figure 3(b) in the direction of the length of the panel and in Figure 3(c) in a cross section through the middle of the panel.

Figure 3
Sandwich panel test setup:
(a) image of SW in the loading frame,
(b), (c) schematic representation (1 – sandwich wall specimen, 2 – steel beam for load distribution with roller, 3 – roller support, 4 – double acting roller support, 5 – shear connector, 6 – rubber, 7 – displacement transducer, 8 – strain gauges with labels SG1–SG4)
(a)

(b)



(c)



Methods to evaluate the level of composite action
The level of composite action of the panels was evaluated by two approaches. First, the obtained strain pattern was compared to the theoretical strain distributions in case of fully composite and non-composite sections. Second approach was to find a moment of inertia from the load–deflection behaviour and compare to the moments of inertia of fully composite and non-composite cross-sections.
In the first approach, plain strain hypothesis is assumed and the depth of the neutral axis x_i is calculated from the strains on both sides of a layer according to equations (1).

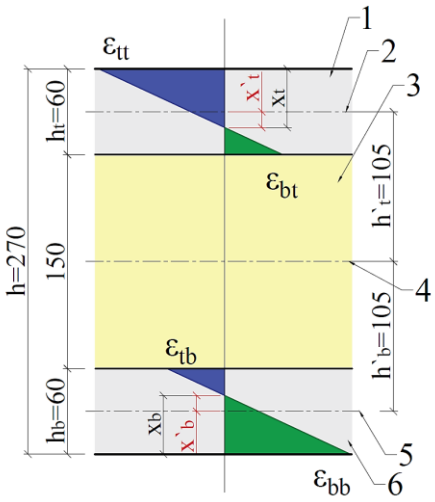
$$x_i = \frac{h_i}{|\varepsilon_{it}| + |\varepsilon_{ib}|} \cdot |\varepsilon_{it}| \quad (1)$$

where h_i is the thickness of the top or bottom layer, ε_{it} and ε_{ib} are strains measured on the top and bottom surface of the considered layer. Graphical representation of the designations used in equations (1) to (3) is given in Figure 4. The index i should be replaced by t or b depending on the layer under consideration.

The reference to the fully-composite and non-composite sections is made by relating the experimentally measured neutral axis to the axes of fully composite and non-composite sections with a distance $x`_i$ according to the equation (2).

$$x`_i = \frac{x_i - h_i}{2} \quad (2)$$

Figure 4
Graphic arrangement of symbols used in equations (1) to (3) (1-top concrete layer, 2- fully non composite panel top layer neutral axis, 3-insulation layer, 4- fully composite panel neutral axis, 5- fully non composite panel bottom layer neutral axis, 6- bottom concrete layer)



The level of composite action can be determined using the equation (3), giving value between 0 and 100%, where 0 stand for non-composite and 100% – for fully composite.

$$k_\varepsilon = \frac{x`_i}{h`_i} \cdot 100\% \quad (3)$$

where $h`_i$ is the distance between neutral axes in case of fully composite and non-composite sections.
In the second approach, deflection δ of the SW panels with the span and cross-section identical to the test specimens with fully composite and non-composite sections are calculated by equation (4). This calculation includes the applied load P, the distance a from the support to the load application point, the panel span L, and the modulus of elasticity E determined from compressive strength.

$$\delta = \frac{\frac{P}{2} \cdot a \cdot (3L^2 - 4a^2)}{24EI} \quad (4)$$

The experimental moment of inertia can be derived from equation (4) by substituting the deflection δ with the deflection obtained experimentally. Then, the level of composite action is evaluated by comparing the experimental moment of inertia with the ones of fully composite and non-composite sections.
The moment of inertia for a fully composite panel I_c is calculated by equation (5) and for non-composite action I_{nc} by equation (6).

$$I_c = \frac{b \cdot {h_t}^3}{12} + A_t \cdot {h`_t}^2 + \frac{b \cdot {h_b}^3}{12} + A_b \cdot {h`_b}^2 \quad (5)$$

$$I_{nc} = \frac{b \cdot {h_t}^3}{12} + \frac{b \cdot {h_b}^3}{12} \quad (6)$$

In this paper, the composite action percentage, $k(\%)$, is calculated based on the measured deflection δ during bending tests by equation (7), following the method outlined by (Pessiki & Mlynarczyk, 2003).

$$k(\%) = \frac{I_{exp} - I_{nc}}{I_c - I_{nc}} \quad (7)$$

Results and Discussion

Strain analysis

Strains on four surfaces of the tested specimens registered during loading are given in Figure 5. All the specimens were subjected to cyclic loading except for SW1.1 that was used to determine load levels for the cycles. In all cases with cyclic loading, the first cycle shows some nonlinearities, after which all other cycles seem to follow a consistent path. Magnitudes of the strains vary from -300 microns on the top surface up to 150 microns on the bottom surface. The variation of the strains among different surfaces differs from specimen to specimen. For some specimens (SW1.2, SW2.1, SW2.2) a sudden drop of strains of the lower wythe during the firs cycle can be observed. That can be explained with appearance of a crack, after which large part of the deformations are accumulated in the crack and lower levels of strains remain in the bottom wythe. In the case of specimens SW1.3 and SW2.3 no such drop of strains is visible; consequently, the levels of strains in both wythes remain mutually similar. The strain diagrams along a section going through the strain gauges (at midspan) are compared among the specimens in Figure 6. The comparison is made before the first cycle at the moment indicated with a black dashed line in Figure 5 to avoid the influence of a crack.
Based on the measured strains, the neutral axis location and the level of composite action were calculated for each specimen, as shown in Table 2. In all the cases, there are both compression and tension side on both wythes, having a neutral axis within the thickness of the wythe. In the top wythe, the compressive strains are larger than the tensile strains, while in the bottom wythe the tensile strains are governing.
Experimental composite action (k_ε) for sample, SW1 varies from 8.7% to 17.6% and from 8.2% to 14.7% for SW2. These values indicate that the tested SW walls show a weak composite action even at the very beginning of the loading before cracking starts.

Load-deflection behaviour

The load–deflection behaviour is compared among the specimens together with the theoretical lines in the case of fully composite and non-composite section in Figures 7 and 8.

Figure 5
Strains measured on the test specimens during the cyclic loading

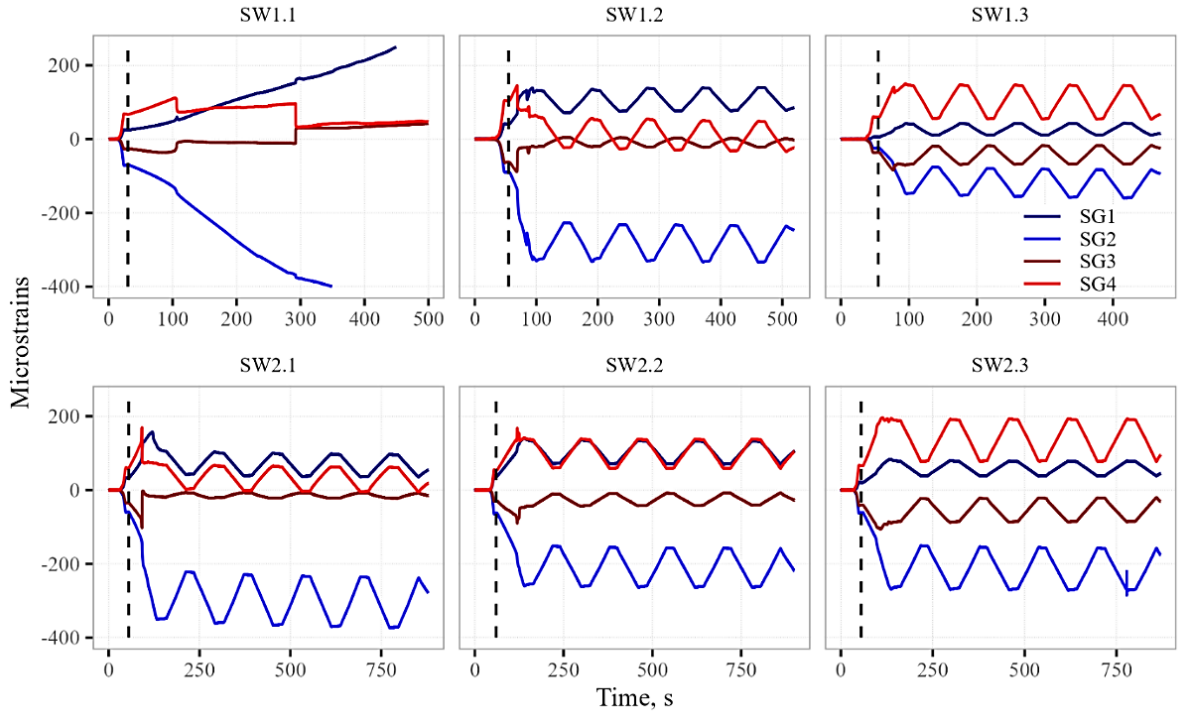


Figure 6
Strain diagrams at the middle section of the specimens before cracking

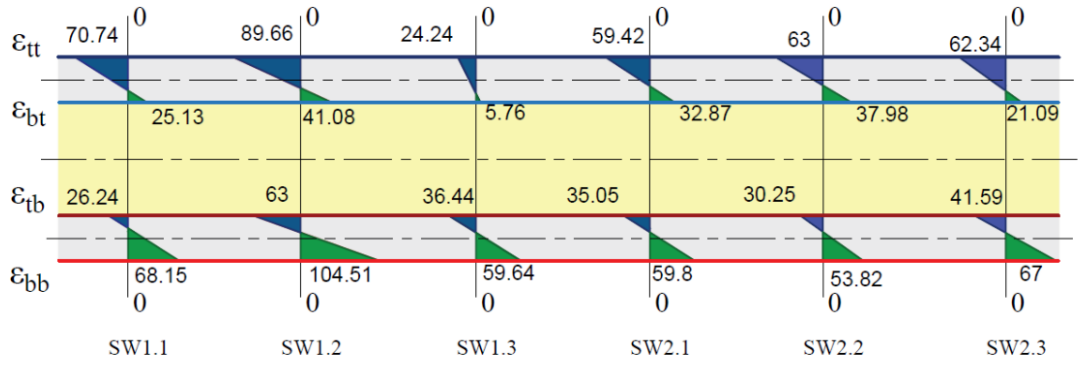
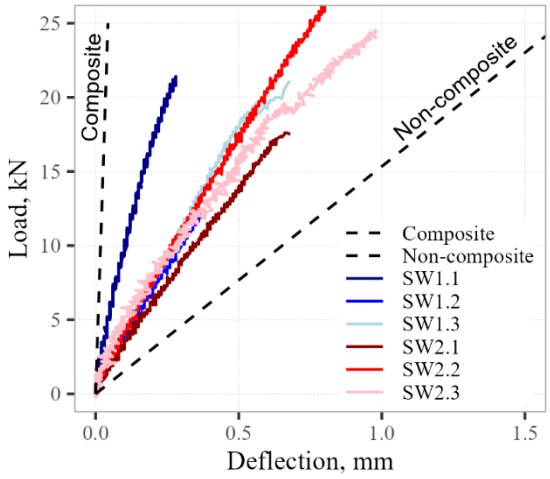


Table 2
Neutral axis location and composite action percentage for tested specimens

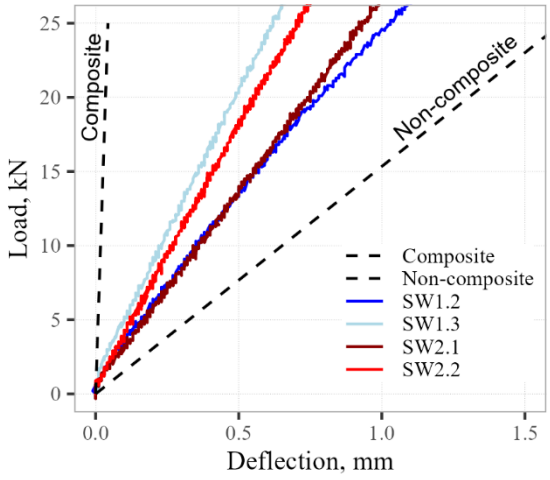
Specimen		ε_{tt}	ε_{bt}	ε_{tb}	ε_{bb}	x_t (mm)	x_b (mm)	$x`_t$ (mm)	$x`_b$ (mm)	$k_{\varepsilon t}$(%)	$k_{\varepsilon b}$(%)
Fibre content 30 kg m^{-3}	SW1.1	70.74	25.13	26.24	68.15	44.27	43.32	14.27	-9.18	13.6	8.7
	SW1.2	89.66	41.08	63.00	104.51	41.15	37.43	11.15	-15.07	10.6	14.3
	SW1.3	24.24	5.76	36.44	59.64	48.48	37.24	18.48	-15.26	17.6	14.5
Fibre content 50 kg m^{-3}	SW2.1	59.42	32.87	35.05	59.64	38.63	37.79	8.63	-14.71	8.2	14
	SW2.2	63.00	37.98	20.25	53.82	37.43	38.41	7.43	-14.09	7.1	13.4
	SW2.3	62.34	21.09	41.59	67.00	44.83	37.02	14.83	-15.48	14.1	14.7

Figure 7
Experimentally obtained load–deflection diagrams up to the first cracks compared to theoretical limits of fully composite and non-composite cross-sections



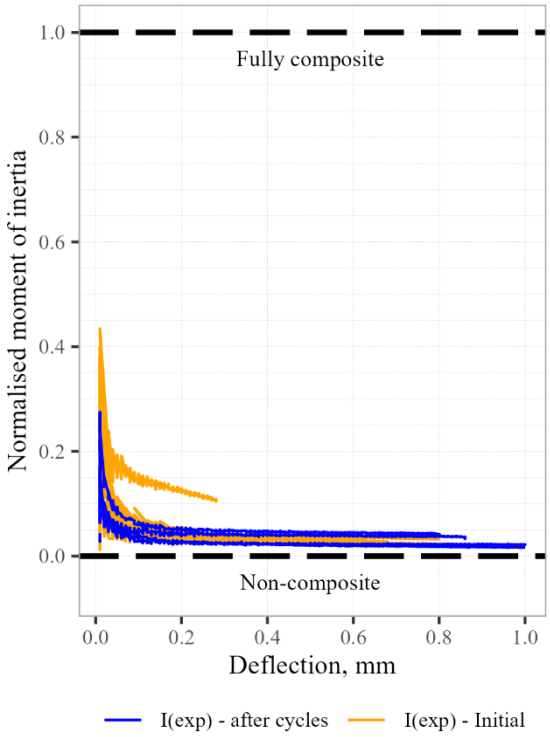
In Figure 7, the range up to the appearance of the first crack is plotted, representing the initial stiffness of the specimens.
In Figure 8, the loading data during the last cycle are shown setting their starting point to zero. The theoretical limits are calculated according to equation (4). The figures show that all experimental deflection curves lie between the boundary lines of non-composite and composite action, indicating semi-composite behaviour action.

Figure 8
Experimentally obtained load–deflection diagrams in the range of the last loading cycle compared to theoretical limits of fully composite and non-composite cross-sections



The derived values of the moment of inertia from the equation (4) for both the initial loading stage and during the last loading cycle in normalised form according to equation (7) are given in Figure 9. At the deflections up to 0.2 mm, the normalised moment of inertia representing the level of composite action drops from 40% to 5% (upper bound) during the initial loading and from 28% to 5% (upper bound) during the last cycle. Over this point, the composite action of the test specimens both at the initial loading and during the last cycle were in the range of 2% to 5%.

Figure 9
Level of composite action based on the moment of inertia



The study agrees with O'Hegarty et al. (2019, 2020) in demonstrating that shear connectors offer only limited interlayer interaction, and achieving full composite performance in sandwich panels continues to be a challenge. This finding aligns with reviews by Amran et al. (2022), who observed that connection quality is crucial for panel performance. Our findings confirm that linking the layers effectively remains challenging. This study also supports the theory proposed by Pessiki & Mlynarczyk (2003) that the degree of composite action exhibited by a panel may vary throughout the panel's loading history.

Conclusions

This paper represents an experimental study of thin-layer steel fibre reinforced concrete (SFRC) sandwich walls (SW) subjected to flexural loading with the aim to evaluate its composite action. The main conclusions are the following:

1. Truss-type shear connectors made of 5 mm steel wires ensure a weak composite action between sandwich panel wythes.
2. SW panels with different dosages of steel fibres showed similar level of composite action, suggesting that the amount of fibres does not affect it significantly.
3. The level of composite action at the initial loading

stage was in the range of 7% to 18% based on the analysis of strains on all the surfaces of the wythes.
4. The level of composite action is in the range of 2% to 5% based on the analysis of deflection and moment of inertia of the cross-section.
5. This study is part of a research project where a thin layer SFRC SW is investigated experimentally under different loading conditions. The findings presented in this paper are going to be discussed with the results of load bearing capacity under eccentric compression suggesting that thin layer wall structures are capable to withstand significant axial loads even without composite action.

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INFLUENCE OF STEEL FIBRES ON SELF-COMPACTING CONCRETE BEAMS WITH LONGITUDINAL REINFORCEMENT FAILING IN SHEAR

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Abstract
Fibre-reinforced concrete, if properly designed, can be a very efficient construction material. However, there are challenges to using them in load-bearing structures due to the high dispersion of strength properties. Therefore, structural design methods need to be calibrated with experimental data. This research aims to investigate factors that influence the shear capacity of steel fibre-reinforced concrete (SFRC) beams with conventional longitudinal reinforcement (Hybrid reinforcement). An experimental test program of 30 large beam specimens, 96 prism specimens, 45 cores, and 15 cubes was conducted. Beams were tested in a three-point bending configuration resulting in a shear failure. Additionally, the crack propagation and crack width were examined. Two types of fibres were used with diameter of 0.5 mm and length of 50 mm and 35 mm. The fibres at volume fractions of 40 kg m^{-3} and 80 kg m^{-3} were tested and compared with the specimens that were without steel fibres. Tools like a digital image correlation (DIC) were employed to monitor the crack propagation, and a web plot designer was utilized to analyse the fibre count. The results demonstrate that the fibres contributed up to 120% for the increase of shear capacity with fibre dosage of 40 kg/m^3, and up to 220% when the dosage was 80 kg m^{-3}. Beams with long fibres (50 mm) showed more abrupt failure caused by rupture of fibres. The results of the current study reveal that there are phenomena that cannot be captured based on the standard prism tests. These results are going to be used to calibrate numerical models in nonlinear models in non-linear finite element analysis software in future studies.
Keywords: experimental tests, hybrid reinforcement, self-compacting concrete, shear capacity, steel fibre reinforced concrete.

Introduction

Concrete by nature is a very brittle material due to its low tensile strength. That is true also for concrete structures subjected to shear stresses because, in most cases, the shear capacity is governed by tensile strength. However, tensile and shear stresses can be resisted by several forms of reinforcement. Compared to conventional steel-reinforcement, fibres of various materials can be utilized as the primary reinforcement or as a supplement. For structural purposes, steel fibre reinforced concrete (SFRC) is the most commonly used. Besides other advantages, steel fibres enhance shear strength and moderate crack formation; they can resist brittle failure (Cohen & Aoude, 2012).

It is well established that SFRC is efficient to increase shear capacity of beams (Baston et al., 1972; Swamy & Bahia, 1985; Narayanan & Darwish, 1987; Kwak et al., 2002; Sahoo & Sharma, 2014). However, there is still a challenge to predict the capacity and post-peak behaviour of reinforced SFRC beams subjected to shear. The shear phenomena is complicated and challenging even in conventional reinforced concrete beams due to the many affecting parameters like concrete strength, shear span to depth ratio, amount of longitudinal reinforcement, aggregate size, size of the cross-section, and others. With the use of SFRC, several other parameters are introduced, which increase the complexity of the prediction.

There are several methods to estimate the effect of the SFRC beams subjected to shear given in standards and technical literature (European Committee for Standardization, 2023; Fédération internationale du béton, 2013). Many approaches and models are being proposed by researchers to predict the shear behaviour (Kwak et al., 2002; Sahoo & Sharma, 2014; Shahnewaz & Alam, 2014; Minelli & Plizzari, 2010). Slater et al. (2012) used linear and non-linear regression analysis on the previous experimental date to developed a shear strength prediction model for beams. Kim et al. (2012) used the smeared crack model and truss model and developed a shear behaviour model for SFRC beams by applying material constitutive equations and by modifying conditions for strain compatibility and force equilibrium. Finite element method (FEM) is being widely utilized by numerous researchers because it allows for nonlinear material properties to be defined, which is important in case of SFRC (Zhang et al., 2020; Skadins & Cervenka, 2024). Two main groups of FEM nonlinear analysis software can be distinguished based on the methods of analysis: smeared crack method (Rashid, 1968; Červenka & Gerstle, 1971) and discrete crack method (Saouma, 1981; Lee et al., 2016).

However, the problem to predict the shear behaviour of SFRC beams is well illustrated in the results of the blind competition organised by fib TG 2.4.1 – Modelling of Fibre Reinforced Concrete Structures. Almost all of the participants overestimated the load bearing capacity and the stiffness of the beams tested in the competition significantly (Barros et al., 2020). Many analyses predicted that the failure will be caused by bending moment suggesting that the shear capacity was even higher. The problem may not be in the nonlinear analysis software but in the input parameters that are defined for SFRC.

The aim of the study is to use a series of experimental tests of SFRC beams reinforced with conventional longitudinal rebars without shear links subjected to shear failure and evaluate the parameters affecting shear capacity. The results of this study are going to be used to evaluate the predictions given by nonlinear analysis using finite element method in future studies.

Materials and Methods

The influence of fibres on the shear capacity of beams is evaluated by conducting an experimental test program. There were ten series of 2.0 m long beams manufactured to be tested in three-point bending. The series were designed to evaluate the influence of shear span to depth ratio, fibre content and the length of fibres.

Specimens

The shape of the beams was designed with two heights, where the part with the bigger height was reinforced with shear links, while the other part with smaller height had no shear reinforcement except for the steel fibres. It was expected that the shear failure occurs in this part. The geometry and the reinforcement layout are given in Figure 1.

The heights of the beams (shear side/other side) were 300/500 mm and 400/600 mm, and the width of the beams was 150 mm. The beams were made of five types of materials, which are described below. Altogether there were 30 beam specimens grouped in ten series with three specimens in each series. The description of the beam series is given in Table 1.

The specimens were reinforced with longitudinal rebars on top (2Ø20 mm) and bottom (4Ø20 mm) to prevent them from failing due to bending moment. The top reinforcement was tied with horizontal links to minimize the risk of buckling due compressive stresses. The shear links (Ø10, @100 mm) were provided only on one part of the span to prevent it from failure and diagonal cracking. Nominal concrete cover of the longitudinal reinforcement was 30 mm.

Figure 1

Beams specimens used in experimental programme with dimensions and reinforcement layout

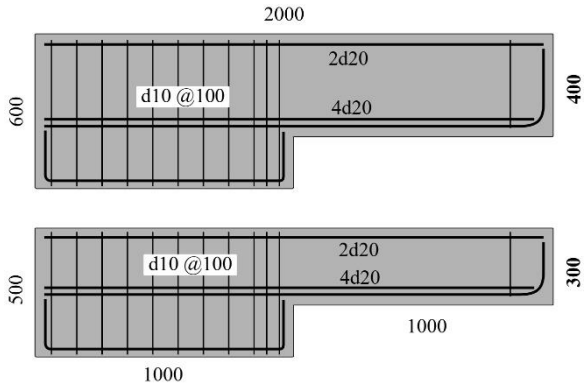


Table 1

Description of beam samples

Series name	*Material label*	*Number of specimens*	*Depth, mm*	*Fibre dosage, kg/m³*	*Fibre length, mm*	*Fibre diameter, mm*
FRC-3-4-300	FRC-3-4	3	300	40	35	0.5
FRC-3-8-300	FRC-3-8	3	300	80	35	0.5
FRC-5-4-300	FRC-5-4	3	300	40	50	0.75
FRC-5-8-300	FRC-5-8	3	300	80	50	0.75
FRC-3-4-400	FRC-3-4	3	400	40	35	0.5
FRC-3-8-400	FRC-3-8	3	400	80	35	0.5
FRC-5-4-400	FRC-5-4	3	400	40	50	0.75
FRC-5-8-400	FRC-5-8	3	400	80	50	0.75
PC-300	PC300	3	300	NA	NA	NA
PC-400	PC400	3	400	NA	NA	NA

Materials

Five different materials were used in this study. Four of them were different mixes of self-compacting SFRC (SFRSCC). The difference was obtained by using fibres with two different lengths, and two different fibre dosages. There was plain self-compacting concrete (SCC) used for reference. The material labels used in this study (e.g. FRC-3-4 or PC) indicate type of concrete, length of fibres, and fibre dosage. Two labels are used for material: FRC and PC referring to SFRSCC and SCC, respectively. The first number in the material label (3 or 5) refers to the length of the fibres 35 mm or 50 mm, respectively. The last number (4 or 8) refers to the fibre dosage 40 or 80 kg m^{-3}, respectively. The dispersion of fibres was evenly distributed along the cross section of the specimens, with no segregation identified, as it is a self-compacting concrete, see Figure 7.

The SSC mix was made of 280 kg m^{-3} of cement (42.5R), sand (0–4 mm) 727 kg m^{-3}, gravel (2–8 mm) 885 kg m^{-3}, limestone flour 84 kg m^{-3}, fly ash 98 kg m^{-3} and a chemical additive 1.2% of the mass of cement. The water cement ratio was 0.65. The slump-flow class used in this study was SF2 according to the standard EN 206 (European Committee for Standardization, 2021). Material properties of SFRSCC used in the beams were obtained by laboratory tests. For each material, four cubes (edge size of 150 mm) were used to obtain compressive strength according to the standard EN 12390 (European Committee for Standardization, 2019). The mean value of the concrete strength varies from 67.03 MPa to 85.35 MPa

with the coefficient of variation (CoV) 1.0 to 3.0%. The cubes were tested at concrete age of 75 days.

Post-cracking flexural tensile strength was determined by notched prisms (150×150×600 mm) under three-point bending tests according to the standard EN 14651 (European Committee for Standardization, 2007). There were 24 specimens for each material tested. Load versus crack mouth opening displacement (CMOD) diagrams of the prisms are given in Figure 2. The residual strength values f_{R1} and f_{R3} at CMOD 0.5 mm and 2.5 mm were in range 5.57–10.34 MPa and 4.77–9.87 MPa, respectively, with CoV 13.2–18.3%. Detailed description of the materials is given in Table 2. The prisms were tested at concrete age of 120 to 132 days.

All the test specimens were manufactured in a concrete plant in middle of January 2022. After casting, they were covered with plastic sheet. All the cubes and prisms were wrapped in plastic film, see Figure 3. The specimens were brought to the laboratory in the end of January and stored in the room conditions till testing. The beam specimens were watered and covered with a plastic sheet, see Figure 4. The tests of the beams were performed during the period from 500 to 900 days.

After the test of the beam specimens, cores were taken from the uncracked and unreinforced regions of the test beams. Actual concrete compressive strength of each beam was obtained by three cores. The results of the strength are given in Figure 5.

The strength of the beams obtained from the extracted cores is very similar to the strength obtained from the cubes. The beams with fibre dosage of 40 kg m^{-3} have higher strength (around 82 MPa) if compared to the beams with fibre dosage of 80 kg m^{-3} (around 72 MPa). The strength of the beams with plain concrete was smaller – around 69 MPa.

Figure 2
Load–CMOD diagrams of notched prisms

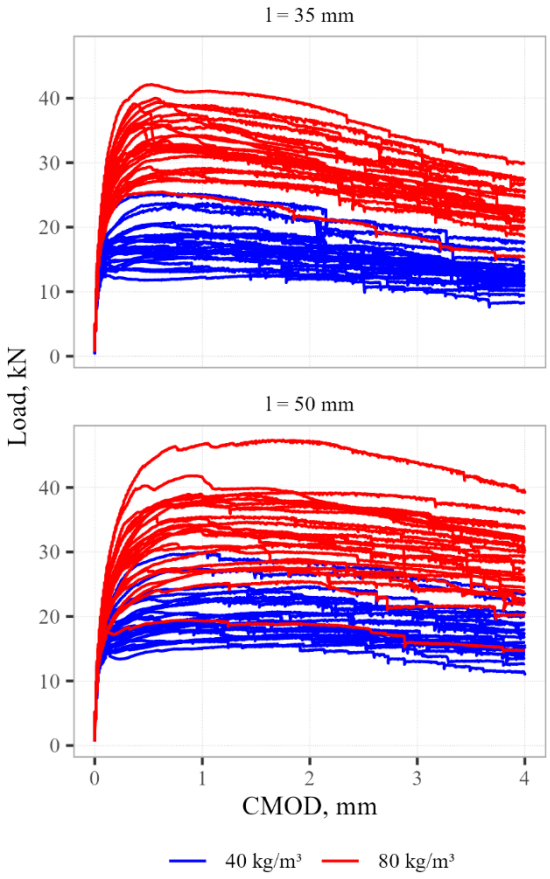


Table 2
Material properties

Material label	f_{cm}, *MPa*	*Coef. of variation (CoV, %)*	f_{R1}, *MPa*	*CoV, %*	f_{R3}, *MPa*	*CoV, %*
FRC-3-4	83.26	2.97	5.57	18	4.77	15.33
FRC-3-8	69.76	2.08	10.34	13.74	8.82	13.23
FRC-5-4	85.35	2.07	6.11	18.23	6.02	17.20
FRC-5-8	77.73	1.55	9.85	18.16	9.87	18.32
PC	67.03	0.99	0	0	0	0

Test setup

The beams were simply supported and set through a three-point bending configuration during the shear test. Form+Test hydraulic test frame Alpha 10-3000 with Zwick Roel load cell with capacity of 600 kN (Class 1) was used. The test setup is shown in Figure. The load was applied at the mid-span by controlling piston displacement at a speed of 0.5 mm/min. The load was transmitted through a spherical steel loading hinge and the beam were supported on rollers at both ends to have free rotation. The test configuration was aimed to result in shear cracking and eventual shear failure. Mid-span deflection relative to a horizontal steel bar fixed to the beam at the supports was recorded using a Linear Variable Displacement Transducer (LVDT) up to 10 mm as shown in Figure 6(b).

In addition, a Digital Image Correlation (DIC) system was utilized to capture vertical displacements and crack evolution. A stochastic black-on-white scattered pattern was added to the surface of the shear span of the beam for the DIC, see Figure 6(a).

Figure 3
Curing of concrete specimens wrapped in plastic film

Figure 4
Beam specimens watered and covered with plastic sheet

Figure 5
Concrete strength determined by cores extracted from test beams after the tests

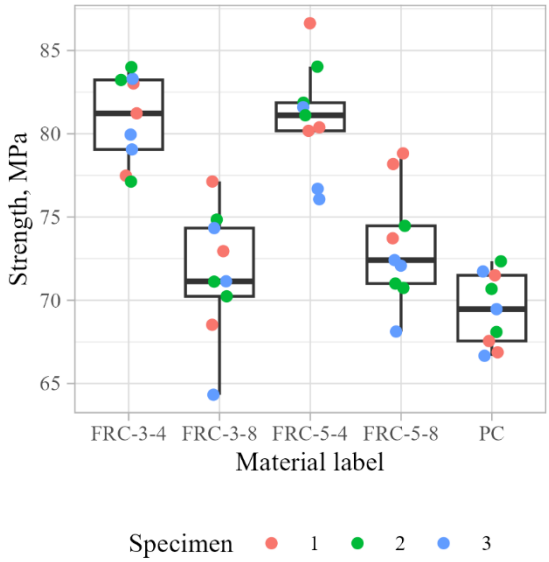
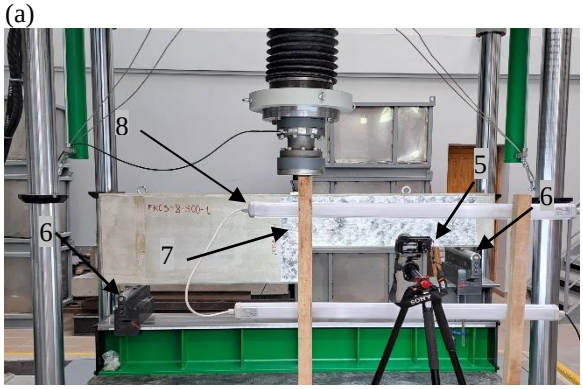


Figure 6
Experimental Test setup: front view (a) and back view (b). (1 – Steel bar, a reference for deflection; 2 – Linear variable differential transformer (LVDT); 3 – Hinge; 4 – Load cell; 5 – Digital camera; 6 – Rollers supports; 7 – painted speckles for Digital image correlation method (DIC); 8 – LED lights)

(a)



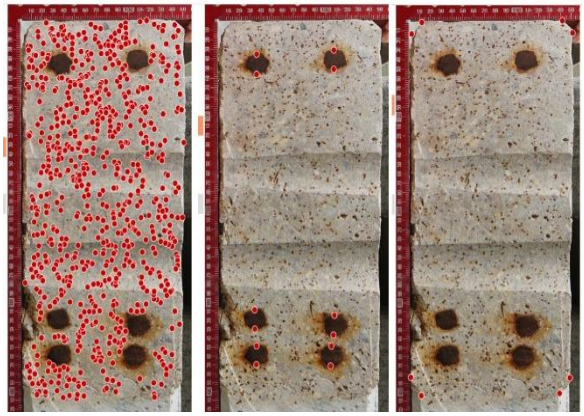
(b)

A high-resolution digital mirrorless cameras Sony α6400 equipped with SAMYANG AF 12 mm F/2.0 lenses, was placed at 1 m distance from the specimen. The images were taken with time interval of 5 seconds during the test of each beam. LED lights were used to ensure consistent light intensity during the test. The images were processed using Zeiss Correlate software.

Fibre counting

In order to evaluate the influence of fibres more precisely, a manual fibre counting procedure was applied. The beams were cut at the middle of the span – perpendicular to the beam's longitudinal axis. The surface was treated with hydrochloric acid to increase the contrast of the fibres. High-resolution images of the cut surfaces together with 90-degree ruler were taken. The geometry of the images was corrected using image manipulation software. Coordinates of every fibre and longitudinal rebars relative to the lower left corner of each section were determined using the WebPlot Digitizer (Rohatgi, 2024) tool as shown in Figure 7.

Figure 7
Fibre counting procedure using WebPlot Digitizer (the red dots show positions of the measured points on the cross-section: fibres, rebars and edges of the cross-section)



Results and Discussion

All of the tested beams failed due to shear in the part with the smaller depth of the beam. The typical failure mode characterised by a group of inclined cracks captured by DIC is given in Figure 8.

The effect of fibre dosage, length of the fibres, and the depth of the beam is evaluated in the load versus deflection diagrams plotted in the Figure 9. The mean values of the maximum load together with the efficiency if compared to the beams made of plain concrete are given in Table 3.

Table 3
Experimentally obtained mean values of maximum load of the beam series

Series name	$F_{max,mean}$, *kN*	*CoV*	*Efficiency*
FRC-3-4-300	248.64	15.7%	177%
FRC-3-8-300	404.92	7.3%	288%
FRC-5-4-300	228.71	3.0%	163%
FRC-5-8-300	329.90	4.1%	234%
PC-300	140.68	12.3%	100%
FRC-3-4-400	312.81	20.6%	166%
FRC-3-8-400	431.44	8.9%	229%
FRC-5-4-400	353.17	10.9%	188%
FRC-5-8-400	533.88	12.0%	283%
PC-400	188.33	27.7%	100%

The efficiency is calculated by dividing the maximum load of a beam with the maximum load of the beam without fibres and of the same height. According to these results, the efficiency of the fibres is in range 163–188% when the dosage was 40 kg m^{-3} and 229–288% when the dosage was 80 kg/m^3. Figure 9 shows that fibre amount has higher influence on the stiffness of the beams if compared to concrete compressive strength – the beams with higher fibre dosage (80 kg m^{-3}) had lower compressive strength, see Figure 5, but the stiffness of these beams is higher.

Figure 8
Typical failure mode of the beam specimens captured by DIC

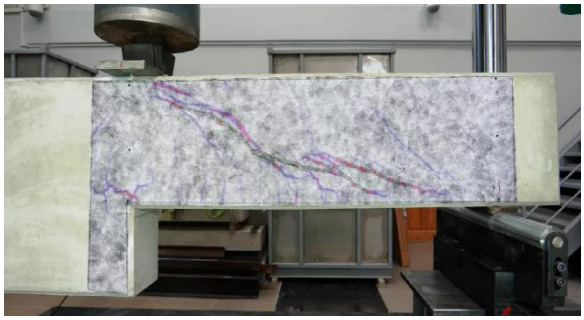
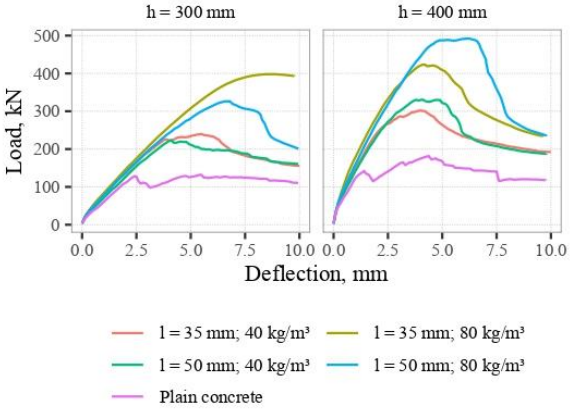


Figure 9
Average load versus deflection diagrams



However, beams with 50 mm long fibres exhibited higher abrupt breakdowns due to fibre rupture. This type of rupture was not observed for beams with fibre length of 35 mm. It should be noted that the tests with the notched prisms did not show any similar rupture of the fibres, see Figure 2. That means that SFRC in structures can behave differently than in the prisms tested according to the standard EN 14651 (European Committee for Standardization, 2001). It can be justified by the reduced amount of fibres aligned with the direction of the tensile stresses in the beams' failure zone. If the fibre length exceeds a critical length, the force to pull them out of the concrete matrix is higher than it is necessary to reach the tensile strength of the fibres, leading to an abrupt failure of the beam. In the prisms, where the fibres have a tendency to align with tensile stresses, the abrupt failure is not visible.

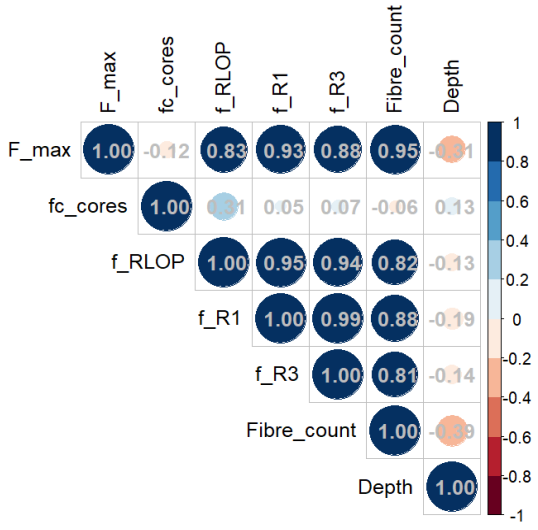
It complies with the findings by Skadins & Červenka (2024) that the residual tensile properties (tensile

function) should be reduced to have correct predictions of the shear behaviour of SFRC beams without shear links. The experimental study reveals that the length of the fibres can play a significant role. In case of long fibres, the tensile diagram should be reduced to take account for an abrupt failure in shear.

The influence of the different parameters considered in this study is analysed by means of correlation coefficient. Matrices of the coefficients between the parameters like maximum load, concrete compressive strength obtained from the cores, residual flexural tensile strength at different CMOD values, fibre count, and depth is given in Figures 10 and Figure 11 for beams with height of 300 mm and 400 mm, respectively. The study concludes that fibre dosage and residual flexural strengths at various CMOD values (f_{R1}, f_{R3}, f_{RLOP}) are the most crucial parameters in enhancing the beam maximum load capacity (F_{max}). However, the compressive strength obtained from the extracted cores has very small impact on the shear capacity (F_{max}).

Figure 10

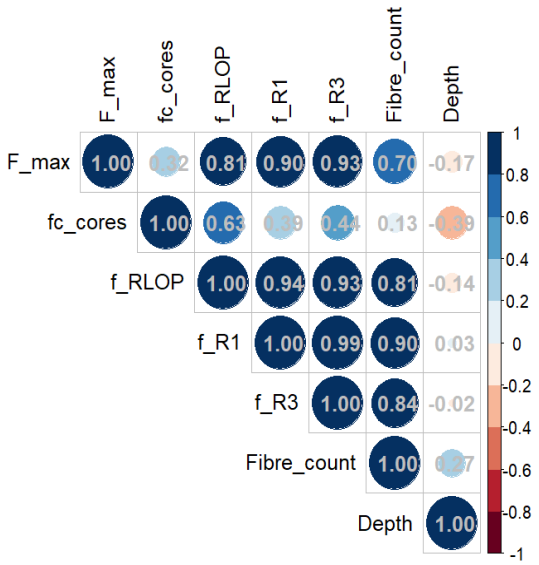
Matrix of correlation coefficient between the considered parameters in case of the beams with height of 300 mm



Obviously, there is an influence of the depth of the beam on the shear capacity if beams with height of 300 mm are compared to the same type of beams with height of 400 mm. However, in this case it is small if compared to the effect of fibres. In the Figures 10 and 11, the depth parameter is measured from images as the average depth of the two layers of tensile rebars using WebPlot Digitizer. As it can be seen from the figures, the actual position of the rebars has no significant influence on the load bearing capacity of the beams.

Figure 11

Matrix of correlation coefficient between the considered parameters in case of the beams with height of 400 mm



Conclusions

An extensive experimental study of self-compacting steel fibre reinforced concrete (SFRSCC) beams with conventional longitudinal reinforcement and without shear reinforcement is carried out. The influence of several factors on the shear capacity is analysed. The following main conclusions can be drawn:

1. Shear capacity of the tested beams are strongly related to the presence of fibres and the corresponding residual tensile strength of SFRSSC.
2. If compared to the beams made of plain concrete, the efficiency of SFRSCC on the shear capacity is in range 163–188% with fibre dosage of 40 kg m^{-3} and 229–288% with fibre dosage of 80 kg m^{-3}.
3. Fibre amount has higher influence on the stiffness of the beams if compared to concrete compressive strength.
4. The experimental study reveals that the length of the fibres can play a significant role. The failure of the beams with longer fibres (50 mm) are characterised as abrupt due to the rupture of the fibres. This was not the case for the beams with fibres of length 35 mm.

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EVALUATION OF MATERIAL PROPERTIES OF STEEL FIBRE-REINFORCED CONCRETE FULL-SCALE ELEVATED SLABS

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Abstract
The paper examines the methods used to determine the mechanical properties of steel fibre-reinforced concrete (SFRC) slabs. The proper design of SFRC properties is fundamental to ensuring safe and sustainable building structures. Along with compressive strength, tensile strength and residual tensile strength of SFRC are essential in structural analysis. In this study, the mechanical properties of two full-scale cast-in-situ SFRC and two steel fibre-reinforced self-stressing concrete (SFRSSC) slabs are investigated. To assess the compressive strength of the concrete, both cubes and cylinders were cast and tested. Modified conversion factors for non-standard specimens were proposed to adjust the strength of standard specimen's size and shape. The moulded specimens were compared with the results of the specimens extracted from the slabs. To determine concrete tensile strength, prism specimens were cast and tested according to the three-point bending test method described in EN 14651. The tensile strength of notched prism specimens derived from three-point bending tests shows results similar to those of four-point bending tests; therefore, it can be used to evaluate the uniaxial tensile strength of steel fibre reinforced concrete. The findings of this research offer a better understanding of how to evaluate concrete mechanical properties for safe fibre concrete structural design.
Keywords: steel fibre reinforced concrete (SFRC), residual tensile strength, three-point bending test, compressive strength.

Introduction

Steel fibre-reinforced concrete (SFRC) is increasingly used in various load-bearing structures. Recent improvements in the material composition have led to improved behaviour of the structures under loading conditions (He et al., 2008; Oslejs & Kravalis, 2014; Cepuritis et al., 2023). Several full-scale tests of floors on piles and elevated slabs demonstrate the capacity of the material if designed and built properly (Aidarov, 2021; Suta et al., 2024). SFRC reduces construction timelines and facilitates the cost-effective production of prefabricated components by integrating fibres during manufacturing, thereby eliminating the need for costly reinforcement (Look et al., 2021). With the increase of structural application of SFRC, it is very important to understand how basic material properties are affected and can be determined for use in numerical analysis of the structures.

Concrete mechanical properties such as compressive strength, tensile strength, and modulus of elasticity are much studied and well-known among scientists and material engineers and are well described in the design standards. Compressive strength can be obtained by different methods, including direct and indirect ones. Each method gives slightly different results that can be converted to the standard cylinder compressive strength necessary for the evaluation of the safety of building structures. One way to do this is to use conversion factors to adjust the strength obtained from non-standard specimens to match the strength of the standard specimen (*fib* Special Activity Group, 2013; European Committee for Standardization, 2022). The coefficient depends on the size and shape of the test specimen as well as the concrete strength (Sinaie et al., 2015). With the increase in variations in concrete technology and the use of additives and fibres of different sizes, these coefficients need to be re-evaluated.

Another important mechanical property used in structural design is uniaxial tensile strength. The most appropriate method is to load the specimens under direct tension (Look et al., 2021; De Smedt et al., 2022). However, it comes with several experimental difficulties; therefore, it is not practically used (*fib* Special Activity Group, 2013).

More popular are the methods where tensile strength can be determined indirectly from e.g. flexural tensile strength or splitting tensile strength. The flexural strength tensile strength of concrete is obtained mainly from 3-point and 4-point bending tests. It is noted that the 3-point bending test method gives about 13% higher values for flexural strength than the 4-point bending test method (European Committee for Standardization, 2019b).

Another method is to calculate tensile strength from the compressive strength of concrete specimens; however, this method neglects the influence of fibre orientation and formwork geometry on tensile strength (Fraile et al., 2024). Round panel tests according to ASTM C1550–02 may also be conducted to evaluate the properties of fibre-reinforced concrete. However, due to the larger specimen size (800mm in diameter), the tests are complex and time-consuming; therefore, it is not widely used, although it is known to provide more consistent results (Tan et al., 2021).

If SFRC is used in the design without the conventional reinforcement, it is important to use the appropriate tensile strength because it is one of the governing properties determining the sizes and, eventually, the costs of the structure.

The aims of the current study are to compare the experimental results of both compressive and tensile strength of SFRC obtained using various approaches and methods, as well as to evaluate how the flexural strength of unnotched beams correlates with the flexural tensile strength of notched beams, and whether it can be used to derive uniaxial tensile strength.

Materials and Methods

All the test specimens discussed in this paper are part of two full-scale tests of steel fibre-reinforced concrete (SFRC) and self-stressing steel fibre-reinforced concrete (SFRSSC) slabs conducted in Jelgava. During these experiments, four slabs (two in 2023 and two in 2024) were produced and tested. Materials SFRC-1 and SFRSSC-1 refer to the tests in 2023, while materials PC-2 (plain concrete), SFRC-2 and SFRSSC-2 refer to tests in 2024. In addition to the full-scale slabs, a battery of laboratory tests was performed to determine the various mechanical properties of the materials. All the samples were tested in the LBTU Structures Laboratory. Only samples tested at 28 days are covered in the present study. Six specimens were used in each sample. The concrete mix design was the same for all specimens of the same year except for the chemical components of self-stressing concrete. Hooked-end steel fibres (L=60 mm, d=0.9 mm) were added to the concrete mixture. The composition of materials is shown in Table 1.

Compressive strength f_c was determined according to the standard EN 12390-3 (European Committee for Standardization, 2019a) using three different types of moulded specimens: 100 mm cubes (C100), 150 mm cubes (C150), and cylinders with a diameter of 150 mm and a height of 300 mm (CY150). These specimens were cured in laboratory conditions fully emerged in water.

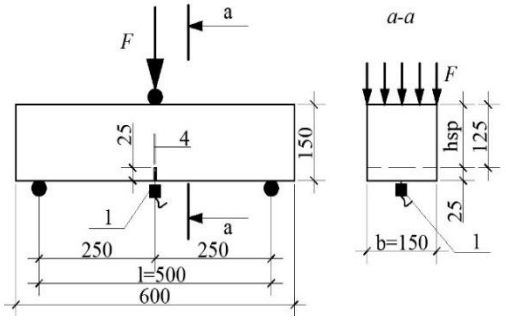
In addition, cores were drilled from the full-scale slabs with a diameter of 70 mm and a height of 150 mm (CO70) and cured under the same outdoor conditions as the full-scale slabs. The CO70 specimens were tested according to standard EN 12504-1 (European Committee for Standardization, 2021).

Uniaxial tensile strength f_{ctm} was derived using three methods: 1) from the characteristic compressive strength obtained from the cylinders (CY150), 2) from the strength at the limit of proportionality $f_{R,LOP}$ according to the standard EN 14651 (European Committee for Standardization, 2007) determined using 150×150×600 mm prisms in three- point bending tests, and 3) from the flexural tensile strength determined according to the standard EN 12390-5 using 150×150×600 mm prisms in four – point bending tests (both with and without fibres).

Figure 1 illustrates the three-point bending loading scheme of the prism. A Class 1 bending testing machine, Type Delta 5-300 (Form+Test), was used. The test was controlled by crack mouth opening displacement (CMOD). A PI-shape displacement transducer (PI-5-50, Tokyo Measuring Instrument Lab) with a gauge length of 50 mm was used to register CMOD.

Figure 1

Three-point bending scheme for prism specimens with a notch (1 – PI-shape displacement transducer)



The flexural strength in three-point bending $f_{ct,fl3}$ can be calculated by equation (1).

$$f_{ct.fl3} = \frac{3}{2} \cdot \frac{F_{LOP} \cdot l}{b \cdot h_{sp}^2}, \quad (1)$$

where F_{LOP} – maximum load in the range of CMOD up to 0.05 mm, as shown in Figure 3, l – the distance between supports, b – specimen width, h_{sp} – the distance between the tip of the notch and the top of the specimen.

Table 1

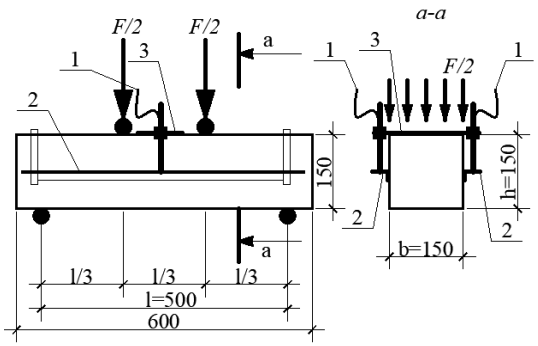
Concrete mix design

Material	***Amount, kg m^{-3}***				
	2023		***2024***		
	SFRC-1	***SFRSSC-1***	***PC-2***	***SFRC-2***	***SFRSSC-2***
CEM II/A-LL 52,5N	360		360		
Water	162		165		
Water/cement ratio (w/c)	0.45		0.47		
Sand	952*		783**		
Gravel	914***		300/791****		
Admixture (PrīmX Flow HRWRA)	3.60		3.24		
Steel fibres (L=60 mm, d=0.9 mm)	50			50	
Admixture (PrīmX DC)	-	40	-	-	40

*- grain size 0-8 mm, ** - grain size 0-4 mm; ***- grain size 5-16 mm; ****- grain size 2-8/8-16 mm.

The loading scheme in the four-point bending test is shown in Figure 2. deflections were measured using two LVDTs, which recorded the distance from the top surface of the prisms to the horizontal rod affixed to the specimens at the supports, positioned halfway up the specimen's height.

Figure 2
Four-point bending scheme for unnotched prism specimens (1 – linear variable differential transformer (LVDT), 2 – reference rod, 3 – plate attached to the specimen for fixing LVDTs)



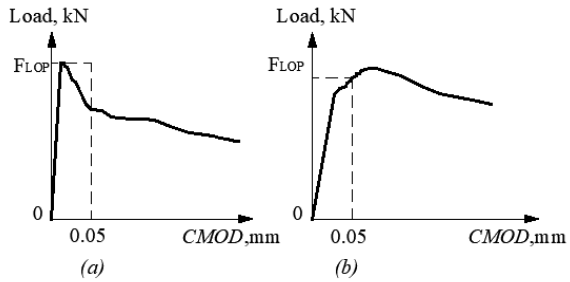
The tensile strength in four-point bending $f_{ct,fl4}$ can be calculated by equation (2).

$$f_{ct,fl4} = \frac{F \cdot l}{b \cdot h^2}, \quad (2)$$

where F – maximum load, l – distance between supports, h – specimen's height.

In the case, where this formula was applied to the results of unnotched SFRC or SFRSSC prisms, the maximum load F was determined according to the method shown in Figure 3, in the range of deflections up to 0.1 mm. In this range, the first crack had appeared and the first local peak was passed.

Figure 3
Load- CMOD diagram and FLOP for the prism (a) with a local peak and (b) without a local peak in the range of CMOD up to 0.05mm



Uniaxial tensile strength f_{ctm} is derived from the experimental results using three different approaches:
1) based on the characteristic value of compressive strength obtained from CY150 according to equation (3);
2) using the conversion factor α_f given in Model Code 2010 according to equations (4) and (5);
3) according to the equation (6) given in Eurocode 2 (European Committee for Standardization, 2023).

$$f_{ctm} = 0.3 \cdot f_{ck}^{2/3} \quad (3)$$

In equation (3), f_{ck} – characteristic concrete compressive strength, which in this study is calculated by subtracting 8 MPa from the mean compressive strength f_{cm} obtained experimentally from CY150.

$$f_{ctm} = \alpha_f \cdot f_{ctm.fl} \quad (4)$$

$$\alpha_f = \frac{0.06 \cdot h^{0.7}}{1 + 0.06 \cdot h^{0.7}} \quad (5)$$

$$f_{ctm} = \frac{f_{ctm.fl}}{1.6 - \frac{h}{1000}} \quad (6)$$

In the equations (4) to (6), $f_{ctm.fl}$ is flexural tensile strength $f_{ct,fl3}$ and $f_{ct,fl4}$ determined according to the equations (1) and (2), h – the height of the beam, which should be taken as h_{sp} for notched prisms.

Results and Discussion
Compressive strength
The results of the compression tests are given in Table 2.

Table 2
Concrete compressive strength f_{cm}

Sample	***SFRC-1***		***SFRSSC-1***	
	f_{cm}, MPa	***CoV, %***	***f_{cm}, MPa***	***CoV, %***
C100	44.88	3.39	54.96	4.00
C150	44.24	3.71	54.53	3.20
CO70	29.83	6.34	44.71	5.02
CY150	41.03	4.29	49.29	1.58
	SFRC-2		SFRSSC-2	
C150	56.55	2.91	60.32	2.60
CY150	50.49	3.91	53.61	3.65
	PC-2			
C100	62.57	3.18		

The compressive strength varies from 41.03 to 44.88 MPa for SFRC-1 and from 49.29 to 54.96 MPa for SFRSSC-1 if moulded specimens cured in laboratory conditions are tested. The strength of the corresponding extracted specimens is 29.83 MPa for SFRC-1 and 44.71 MPa for SFRSSC-1. The lower values of the extracted specimens can be justified by the lower air temperatures and fluctuating moisture content during the curing process. The compressive strength ranges from 50.49 to 56.55 MPa for SFRC-2 and from 53.61 to 60.32 MPa for SFRSSC-2. The compressive strength of plain concrete specimen PC-2 is 62.57 MPa, which is the highest result among all tested samples.
The relationships between the strength values obtained from the different specimen shapes and sizes are

represented in a matrix form in Table 3. The coefficients in Table 3 represent the mean values for each specimen shape and dimension.

Table 3
Conversation factors for different specimen sizes and shapes

	C100	C150	CO70	CY150
C100	1.00	0.99	0.74	0.91
C150	1.01	1.00	0.75	0.90
CO70	1.37	1.35	1.00	1.24
CY150	1.10	1.11	0.82	1.00

Latvian national standard LVS 156-1 suggests using a conversion factor of 0.95 to obtain standard 150 mm cube strength from smaller 100 mm cubes' strength. The main reason is that the smaller cubes have fewer initial imperfections. Therefore, their strength is higher than that obtained from larger specimens. In the present study, this coefficient is 0.99, which shows that the actual difference is negligible. This can be justified by the presence of long (60 mm) fibres that reduce the level of compaction in smaller specimens during the casting process.

The coefficient that converts the compressive strength from 150 mm cubes into standard cylinders (diameter of 150 mm) is 0.90, which is higher than ~0.8 used in the design standards EC2. In this case, the conversion factor accounts for different stress flow in the specimen. Shorter specimens, like cubes, are both compressed and confined at the loading surfaces, which increases the compressive strength. Due to the height (300 mm) being twice as the diameter, the confining effect at the middle of the specimen's height is not present. Therefore, the obtained strength is smaller and more realistic. Obtaining a coefficient of 0.9 instead of 0.8 shows that the coefficient suggested by the standards is on the safe side. To increase the value of the coefficient and eventually the efficiency of the use of concrete, more experimental investigations are needed to cover the main influencing aspects. The conversation factor from CO70 to CY150, which was 1.24, is opposite to 0.85 suggested by LVS 156-1. It should be noted that the cores extracted from the slab structure were subjected to lower air temperatures and fluctuating moisture content during the curing process. This must be taken into account when one is trying to predict the compressive strength of an outdoor structure using the laboratory test results of specimens cured in different conditions.

The effect of the values of the conversion coefficients can be evaluated by taking the current experimental test slab as an example. The mean value of the concrete strength used in the verification of the SFRC slab should be calculated as follows if 100 mm cubes were available:

$$f_{cm} = (0.95 \cdot 0.8) f_{cm,c100} \quad (7)$$

where 0.95 and 0.8 are the conversion factors suggested by standards resulting in 0.76, which is 83% of the one given in Table 3 (0.91).

Tensile strength

Load versus CMOD diagrams are plotted in Figure 4. The corresponding flexural tensile strength values are presented in Table 4. Three-point bending test results show a flexural strength of 4.93 MPa for SFRC-1 specimens and 6.65 MPa for SFSSC-1. Flexural strength for SFRC-2 is 5.46 MPa, and for SFRSSC-2 specimens is 6.06 MPa. For SFRC-1 specimens, the four-point bending test results show a flexural strength of 5.71 MPa, which is 13.7% higher than flexural strength from three-point bending test. The flexural strength of SFRSSC-1 in a four-point bending test is 6.19 MPa, which is 0.46 MPa lower than in a three-point bending test. While the results for SFRSSC-1 material support the assertion that three-point bending tests demonstrate greater flexural strength (Committee for Standardization, 2019b), albeit only for 7.4%, the results from SRFC-1 specimens display entirely opposite tendencies.

Figure 4
Load–CMOD diagrams

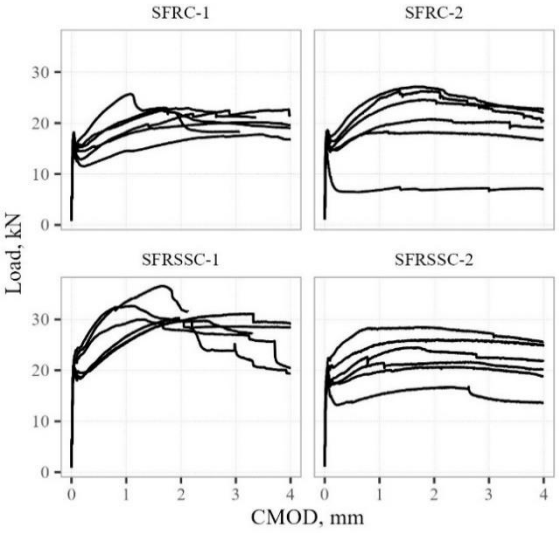


Table 4
Flexural strength f_{ctm}, MPa

Samples	***3-point bending***		***4-point bending***	
	$f_{ct,fl3}$	***CoV,%***	$f_{ct,fl4}$	***CoV,%***
SFRC-1	4.93	7.78	5.71	5.98
SFRSSC-1	6.65	4.36	6.19	5.49
SFRC-2	5.46	6.01		
SFRSSC-2	6.06	7.45		
PC-2			6.20	5.20

The uniaxial tensile strength f_{ctm} is calculated from the flexural strength $f_{ct,fl}$ using the Eurocode 2 (EC) method and the Model Code 2010 (MC) method, as presented in formulas (4) to (6) in this article. The results are compared with the uniaxial tensile strength

calculated from the compressive strength of concrete cylinders f_{cm} and are presented in Table 5.

Table 5
Uniaxial tensile strength f_{ctm}, MPa

Samples	*from $f_{ct,fl3}$*		*from $f_{ct,fl4}$*		*from f_{cm}*
	EC2	*MC*	*EC2*	*MC*	*EC2*
SFRC-1	3.35	3.16	3.94	3.49	3.09
SFRSSC-1	4.51	4.25	4.27	3.87	3.58
SFRC-2	3.70	3.49			3.65
SFRSSC-2	4.11	3.87			3.83
PC-2			4.28	4.14	

Uniaxial tensile strength for SFRC-1 specimens varies from 3.09 to 3.94 MPa, obtaining the highest values from four-point bending test results. For SFRSSC-1 specimen, tensile strength varies from 3.58 to 4.51 MPa. For these specimens, the three-point bending test provides the highest results. The tensile strength of SFFC-2 and SFRSSC-2 specimens are 3.70 MPa and 4.11 MPa, respectively. The tensile strength derived from the compressive strength of concrete cylinders exhibits the lowest values and, as such, can be regarded conservative.

Conclusions

1. The effect of the size and shape of the specimens on the compressive strength is significantly smaller than suggested by the conversion factors given in standards.
2. Strength ratio between cubes of 100 mm and 150 mm was 0.99 being higher than suggested coefficient 0.95 that can be justified by the presence of long steel fibres.
3. Concrete compressive strength in real structures can be underestimated if standard conversion coefficients are used (in the current study it is up to 83% of the measured cylindrical strength) and overestimated if curing conditions are ignored.
4. All the standard methods discussed in this paper used to obtain uniaxial tensile strength resulted in similar values if the specimens from test of the year 2024 are used (difference varies in a range of 0.28 MPa). The difference is in the range of 0.85 MPa for the specimens of the other test and the lowest values are obtained using the compressive strength.
5. The tensile strength of notched prism specimens derived from three-point bending tests shows results similar to those of four-point bending tests; therefore, it can be used to evaluate the uniaxial tensile strength of steel fibre reinforced concrete.

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DEVELOPMENT OF A CALIBRATION STAND FOR DEFORMATION SENSORS TESTING

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Abstract
In the 21st century, there is an increasing number of tasks that we allow electronics to perform autonomously. The monitoring of structural deformations is increasingly entrusted to automated systems based on high-precision sensors connected to monitoring systems. Engineers must be confident not only in the correct selection of the system and its components but also in the accuracy of the measuring sensors, which are at the forefront of deformation monitoring systems. This paper presents a comprehensive study on the calibration and accuracy verification of deformation measurement sensors used in structural health monitoring (SHM). Specifically, the focus is on accelerometers, inclinometers, and dynamic displacement sensor. The calibration process involves rigorous static and dynamic testing to ensure precise measurement capabilities. A test stand with the capability to control the deformation of the span was fabricated, enabling the comparison of real-life measurements with the data obtained from the sensors. The displacement sensor, accelerometer and inclinometer are subjected to controlled laboratory conditions to validate their performance under various deformation scenarios. The paper also discusses the integration of these sensors into a unified SHM system, emphasizing the importance of sensor calibration in maintaining the structural integrity and safety of engineering structures. Our findings indicate that with proper calibration, sensors can significantly enhance the accuracy and reliability of deformation measurements in SHM applications.
Keywords: deformation monitoring, accelerometers, inclinometers, dynamic displacement sensor, sensor calibration.

Introduction

Following the era of global industrialisation, society has not only experienced significant development but has also inherited a vast array of infrastructure that must be maintained in operational condition to ensure continued safe usage. Among these critical assets are various engineering structures, which require extensive time and resources for their structural health monitoring (Liu et al., 2023). Advances in electronics have introduced new possibilities for automated monitoring of engineering structures through the use of various types of sensors and computational capabilities, enabling real-time data processing (Hou et al., 2025).

However, sensors are not always calibrated and their accuracy is often uncertain (Zhu et al., 2020). In order to rely on automated monitoring systems equipped with deformation sensors, their precision must first be verified and, if necessary, calibrated. Only after this verification can the acquired data be used for accurate structural assessments, calculations, and long-term prognoses.

As part of the ongoing maintenance and repair programme of the Kalnciema overpass in Riga, Latvia, a project was commissioned to develop and install a deformation monitoring system for the central span, which is the highest section of the overpass. The monitoring of deformations in the Kalnciema overpass is crucial for estimating the remaining service life before major repairs are required and for assessing the current structural condition. After determining the optimal sensor installation points on the bridge span, three types of sensors were deployed: accelerometers, inclinometers and displacement sensors measuring vertical axis movement (Zhang et al., 2025).

Modern Dynamic Displacement Sensor (DDS) typically rely on acceleration-based measurements. These sensors determine displacement by integrating acceleration over time, using an internal algorithm rather than external computational resources. To assess the reliability of these sensors, two identical DDS sensors were installed at the same location to compare their readings.

During the analysis of data collected over a one-month observation period, discrepancies were observed between the two sensors, as illustrated in (Figure 1). This led to the conclusion that the sensors exhibit measurement errors, which may compromise the accuracy of long-term structural degradation assessments.

This study aimed to develop and implement a calibration stand to assess the accuracy of deformation sensors in structural health monitoring. Static and dynamic tests enabled error correction, improving data reliability for infrastructure assessment.

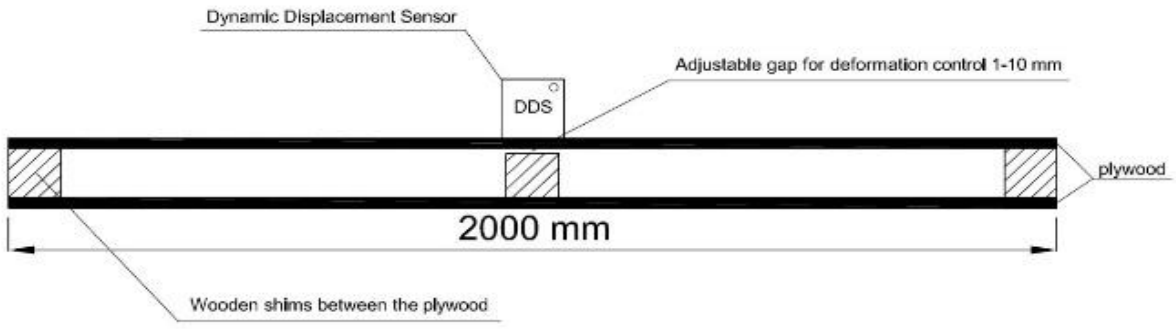
Figure 1
Deformation readings from two different DDS sensors installed in the same location

To improve measurement reliability, a decision was made to calibrate and evaluate the sensors under controlled laboratory conditions. This involved conducting tests on a calibration stand with adjustable, controlled and fixed deformation states to simulate bridge span behaviour. The experimental plan

included identifying the measurement error of each sensor under controlled conditions, applying necessary corrections to their readings and thereby increasing confidence in the data collected.
Following the completion of the calibration tests, the sensors were reinstalled on the overpass span, but their outputs were now adjusted in accordance with the derived correction factors. This adjustment ensures greater accuracy in deformation monitoring, improving the reliability of long-term structural assessments (Crognale et al., 2024).

Materials and Methods
A specialised calibration stand was designed and constructed to verify the accuracy of deformation sensors. The stand consisted of two plywood sheets with rigidly fixed corners and a central gap of 10 mm, allowing for controlled vertical displacement. The schematic diagram (Figure 2) presents the key parameters and external appearance of the stand, simulating the behaviour of a bridge span structure.
The stand was mounted on a welding table with a thick iron plate surface to ensure rigid fixation and stability against vibrations. One end of the stand was securely fixed, while the opposite end was designed to allow movement along the stand's axis. To achieve precise deformation measurements, the stand's surface was adjusted using 1 mm thick iron plates (Figure 3), which were inserted into the central gap. The gap width was measured using a vernier caliper before each test condition was modified structure. When the surface was abruptly released after being pressed down, damped real-world operational conditions of a bridge span oscillations occurred as the plywood span returned to its original position. Separate tests were conducted where the surface was smoothly returned to its initial state to eliminate damping oscillations and evaluate the effect of a steady deformation response.

Figure 2
Calibration stand



A total of ten primary tests were conducted, during which the readings from different types of deformation sensors were recorded and compared with the measurements obtained using the vernier caliper.

Figure 3
Adjustment of deflection using iron plates and a vernier caliper

In some test scenarios, additional vibration was introduced using two types of vibrators (20 mm and 35 mm in diameter) commonly used for concrete compaction. These vibrators generated different frequencies and amplitudes of oscillations, allowing an assessment of their influence on deformation sensor performance and potential measurement interference.
Additionally, different external forces were applied to the surface of the stand's movable section to simulate real-world various loads.
Beyond the primary tests, additional measurements were performed using a cylindrical iron mass, simulating a heavy vehicle travelling across a bridge. In these experiments, deformations gradually increased as the cylinder moved towards the centre of the stand. To introduce further oscillatory disturbances, a metal plate was placed at the beginning of the beam, simulating a heavy vehicle crossing an expansion joint (Figure 4).
For inclinometer testing, a location with the greatest change in tilt angle was selected. The inclinometer was mounted at the edge of the model, and both the initial and altered angles were calculated using a CAD-generated model, based on the deflection of the stand's surface and the distance to the sensor.
The sensors were simultaneously positioned at the centre of the model, as this region exhibited the highest

deformation levels and was closely monitored using a vernier caliper. The accelerometer and vertical displacement sensor operate on the same principle, with the latter converting registered acceleration and impulse direction into displacement data. By comparing the readings of these sensors with those obtained from the vernier caliper, as well as with each other, it was possible to assess their accuracy and consistency.

Figure 4
Expansion joint simulating

Thus, the conducted tests enabled the evaluation of the accuracy of different types of deformation sensors under conditions closely resembling real-world operational environments.

Results and Discussion

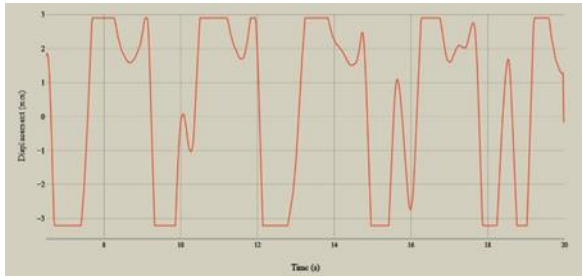
Table 1 present the key parameters of the ten tests conducted to evaluate the performance of the sensors in measuring the deformations of the span. The primary objective was to determine the discrepancies between the sensor readings, as well as to assess how these readings deviate from the physical measurements of the gap on the stand, obtained using a vernier caliper.

Table 1
Key parameters of the tests

Test	***Gap in mm***	***Vibrations***	***Damped oscillations***
1.	4.6	-	+
2.	1	-	+
3.	2	-	+
4.	1.5	-	-
5.	4	+	+
6.	1.8	+	+
7.	1	+	+
8.	9	-	+
9.	9	-	-
10.	9	+	+

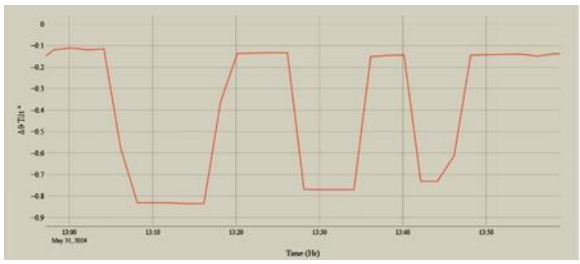
During the first test, the gap on the stand was set to 4.6 mm, with no vibrational noise applied, while damped oscillations were present. The graph in (Figure 5), derived from the data recorded by the DDS sensor, clearly illustrates the damped oscillatory behaviour following the release of the span, as well as the registered deformation value of 6 mm. This allows for a straightforward calculation of the discrepancy between the actual deformation and the sensor readings. Such a test enabled the determination of sensor measurement errors, which were subsequently used to correct the deformation data obtained from the real structure.

Figure 5
Readings of the DDS sensor



During the inclination angle test, the gap of the stand was set to 10 mm, resulting in an inclination angle of -0.57 degrees at a distance of 1 meter. The sensor readings at the upper position of the span indicated an angle of -0.1 degrees, suggesting that the table supporting the stand was not perfectly level. Consequently, the inclinometer readings should have displayed -0.67 degrees. The graph shown in (Figure 6) illustrates that, although minor variations are observed during identical oscillations, the average sensor readings correspond to the calculated inclination angle. Therefore, no correction to the inclinometer measurements is required when applied to the real structure and the sensor can be safely reinstalled on the Kalnciema Bridge.

Figure 6
Inclination test



Complex infrastructure assets, like other types of structures, are subject to dynamic loads, including wind. Such loads can induce vibrations that introduce undesirable noise into the recorded data. The objective of the test involving additional vibrations was to evaluate whether the sensor data would remain interpretable or if the readings would be obscured by

digital noise. (Figure 7) and (Figure 8) present the accelerometer readings under calm conditions and under conditions of additional vibration, respectively. It can be observed that while the vibration is reflected in the graph, the data regarding the span movement remains clear and readable. In the case of vibrations at the monitored structure, this will ensure uninterrupted acquisition of deformation data.

Figure 7
Accelerometer readings without additional vibration

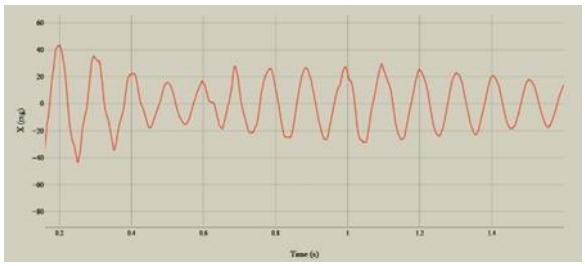
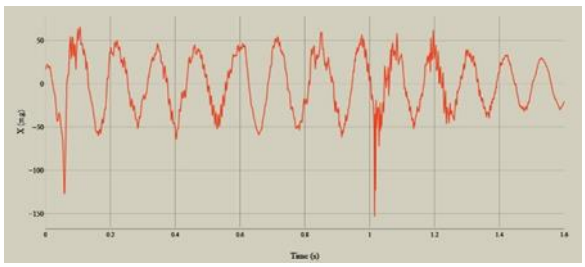


Figure 8
Accelerometer readings with additional vibration



The results of the conducted experiments revealed that the claimed accuracy of the sensors was not confirmed, and calibration is required. Additional tests were also performed to investigate the performance of sensors measuring vertical displacement. During these experiments, it was further identified that the limited data storage capacity of the sensor restricts the recording to a finite number of events. Consequently, if preliminary impulse deformations occur prior to a critical deformation event, there is a high probability that this significant event may not be recorded due to memory overflow. Moreover, the number of recorded events is dependent on the sampling frequency configured within the sensor's settings.

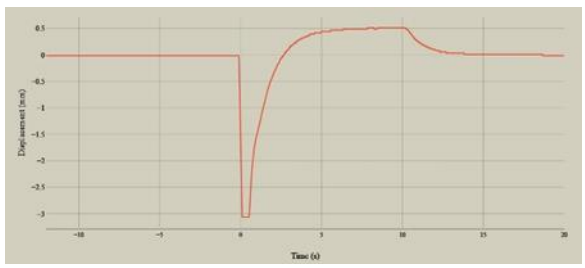
Under intensive traffic loads, the bridge span undergoes a continuous sequence of oscillatory vertical displacements, rendering this type of sensor unsuitable for deformation monitoring systems on bridges and overpasses, as the vast number of recorded events overwhelms the sensor's memory capacity.

Experiments involving vibrators connected to the calibration stand, which generated vibrational noise, demonstrated that such disturbances do not interfere with the sensors' ability to detect deformations. However, it was also found that the deviation sensor exhibited varying readings under identical deformation conditions although the average values remained within the specified accuracy range and corresponded to the actual deformations.

An interesting observation was made during the vertical displacement sensor test. When the span was deflected and subsequently fixed in its new position, the sensor returned the graph curve to the zero position by simply interpolating the data, rather than reflecting the actual sustained deformation. The span of the test stand was fixed in the lower position using a clamp to verify the readings of the DDS sensor (Figure 9). (Figure 10) illustrates how the displacement sensor recorded the deformation and then reverted to zero. Additionally, the experiment demonstrated that the recorded data showed significant discrepancies compared to the actual measured deformations. In real-life scenarios, where a bridge span or support gradually settles over time, the final sensor readings would consistently tend towards zero. In such cases, it is recommended that this type of sensor be replaced by levelling techniques, or laser-based tracking utilisation (LBTU) method, for long-term monitoring of structural settlement.

Figure 9
Span fixing in the lower position

Figure 10
Interpolated return of the graph to zero position, with the deformation fixed in the lower position



Conclusions

1. Displacement sensors do not retain data on their new position and instead interpolate measurements in a manner that returns them to the zero mark after an event. As a result, this type of sensor is unsuitable for monitoring structural settlement, where permanent

displacements need to be recorded. Such deformations should continue to be monitored using classical geodetic methods.

2. The experiment clearly demonstrates that by testing sensors on a calibration stand, it is possible to apply measurement corrections, thereby increasing the accuracy and reliability of the recorded data.

3. Traditional geodetic deformation monitoring systems, when integrated with high-precision sensors, facilitate structural condition assessment by generating continuous data trends and enabling predictive maintenance planning.

4. Sensor accuracy verification has shown that, to improve data reliability, calibration must be performed prior to sensor installation on the monitored structure.

5. The sensors exhibit resilience to vibrational noise, maintaining stable performance under dynamic loading conditions.

6. Long-term continuous monitoring enhances the operational safety of engineering structures and enables the efficient planning of maintenance and repair activities.

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VOLATILE AND CARBOHIDRATE PROFILE OF PERSIMMON EXTRACTS

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Abstract
Persimmon (*Diospyros kaki*) is an orange-coloured fruit renowned for its sweet, honey-like flavour when ripe. It is particularly valued for its versatility in culinary applications and as a rich source of essential nutrients, including vitamin C, pro-vitamin A, dietary fibre, and minerals. Despite these benefits, persimmon faces significant challenges due to its highly perishable nature, which limits its shelf life and utilization potential. One promising solution is the incorporation of persimmon derivatives into stable food products to reduce waste and enhance the value chain of this nutritious fruit. In this study, we aimed to examine the potential of persimmon for the development of confectionery food products by producing persimmon powder and syrup and analysing their chemical profiles. Volatile aroma profiles were evaluated using solid-phase microextraction (SPME) coupled with gas chromatography–mass spectrometry (GC–MS), while carbohydrate profiles were assessed using thin-layer chromatography (TLC) and ion chromatography (IC). Among the volatiles identified, furfural, a compound with a characteristic almond-like odour and significant application as a food additive, emerged as the most abundant volatile in both persimmon derivatives. Sugar profiles revealed that main sugars are sucrose, glucose, and fructose, with little to no fructooligosaccharides detected. These findings support the potential for persimmon derivatives to be used as ingredients in confectionery product formulations.
Keywords: food insecurity, carbohydrates, persimmon, food supply, volatiles.

Introduction

Persimmon (*Diospyros kaki*) is an orange-coloured fruit renowned for its sweet, honey-like flavour when ripe, which is highly valued for its versatility in culinary applications. Although it is originated in East Asia - particularly China, Japan, and Korea - its use has extended throughout the globe (Gea-Botella et al., 2021). It is rich in natural carbohydrates and is commonly processed into juice, jam, and other sweet products. Globally, persimmons are recognized for their dual role as a nutritional and medicinal resource. The fruit contains proteins, sugars, vitamins (A, B6, B12, C, D, E), carotenoids, polyphenols, flavonoids, and essential minerals such as potassium, calcium, and iron (Manach et al., 2004; Butt et al., 2015). Historically, persimmon leaves and fruits have been utilized in the treatment of various conditions such as stroke, apoplexy, angina, internal haemorrhage, paralysis, frostbite, and burns (Xie et al., 2015). More recent studies have highlighted the pulp, skin, and leaves of persimmons for their potential antioxidant, anti-edema, anti-hyperlipidaemic, and anti-diabetic effects (Xie et al., 2015; Kim et al., 2018). The high content of flavonoids and their antioxidant properties, which neutralize reactive oxygen species, play a significant role in persimmon's traditional use for conditions like hypertension, atherosclerosis, and metabolic disorders. These phytochemicals are also responsible for its documented anti-diabetic and anti-hyperlipidaemic effects (Manach et al., 2004; Xie et al., 2015).

Despite their promising culinary uses and health benefits, several tons of persimmons are discarded globally because of the rather low shelf life of persimmon fruits plus different factors including strict regulations by governments, high quality standards of supermarkets, and high expectations of consumers regarding fruit colour, size and shape (Porter et al., 2018; Gea-Botella et al., 2021). In Uzbekistan, thousands of tons of persimmons are wasted every year because of poor storage, late harvest, or inadequate market demand (Normakhmatov et al., 2024).

Even though persimmon is used in confectionary products and advances have been made in dried persimmon production, the fruit's processing remains relatively limited, and its large-scale industrial utilization has lagged behind that of other commercially significant fruits (Tsurunaga et al., 2021; Normakhmatov et al., 2024). Although some countries, including Uzbekistan, export dried raisins of the fruit, a more expansive range of products such as jams, vinegars, and ice creams, could potentially bolster the fruit's market. The incorporation of persimmon into those confectionary products could help to increase its shelf life and reduce fruit waste. A deeper investigation into both primary and by-product components of persimmon processing is therefore essential to help reduce these losses, extend shelf life, and explore new uses (Butt et al., 2015; Normakhmatov et al., 2024; H Al-Qaisi et al., 2025). Although persimmons have been grown in Uzbekistan since the last century, studies on local varieties of either fruits or derivatives are scarce.

This study aimed to develop and characterize a persimmon-based powder and syrup, obtained from a local variety of the fruit, for future confectionery applications, focusing on their volatile and sugar profiles to determine suitability for use in future confectionery formulations. To evaluate flavour and

aroma compounds in the persimmon extracts, volatile profiles were analysed using solid-phase microextraction (SPME) and gas chromatography–mass spectrometry (GC–MS). Besides, carbohydrate profiles were qualitatively investigated by thin layer chromatography (TLC) and ion chromatography (IC).

Materials and Methods

Raw Materials

For this study we used ripe Zenji-maru persimmon fruits grown in the Tashkent and Kashkadarya regions, sourced from local farmers. Colour of fruits ranged from flame to deep red. We based our variety selection on a previous study where persimmon varieties grown in Uzbekistan were evaluated for their suitability for drying (Normakhmatov et al., 2024).

Extraction of syrup and powder from persimmon fruits

Persimmon fruits were washed in cold water and dried. To obtain persimmon extracts, the fruits were cut into pieces, and the flesh and seeds were separated, thus obtaining the ʻpulp'. The pulp was placed in a blender with water added at a ratio of 3:1 and pureed. The puree was then transferred to a container, water was added at a ratio of 3:2, and the mixture was boiled at 80 °C for 30 minutes. The resulting product was separated into phases in a Hettich (Tuttlingen, Germany) centrifuge, model EBA 200, at 3000 rpm. The separated aqueous phase was transferred to a separate container, and the remaining solid material underwent re-extraction twice following the same procedure, thus obtaining the ʻfirst extract'. Syrup was obtained by concentrating the first extract in a rotary evaporator apparatus IKA RV8 with a heating device IKA HB digital (IKA, China) equipped with a recirculating water chiller YHLT-10/30 (Green Distill, China) and a diaphragm vacuum pump KNF N 035.3 AN.18 (KNF, Germany) (13 mbars abs. ultimate vacuum, according to specification sheet) until the extract volume decreased by 50%. Powder was obtained by drying the pulp in a Spray Dryer (Wenming, China), model WM-SP1500S, at a temperature of 85-100 °C until powder was achieved. Dried material was then ground into power using a mill. Weight was measured in a Kern (Balingen, Germany) analytical balance, model ABJ-4NM.

Volatile analyses

Analytical procedure was based on the method outlined by (Calvo-Gómez et al., 2004) with modifications. Samples were analysed by triplicate.

SPME Procedure

Divinylbenzene/ Carboxen/ Polydimethylsiloxane (DVB/CAR/PDMS) 50/30 μm SPME fibres and holders were sourced from Sigma-Aldrich (USA). Samples (1 g of persimmon powder -coded as P1- or persimmon syrup -coded as P3-) were loaded into 4 mL vials and hermetically sealed with septum-lined caps. Equilibration occurred at 30 °C for 1 h under static conditions. The SPME fibre assembly was introduced through the septum, secured in place, and exposed to the vial headspace for 30 min at 30 °C. Following adsorption, the fibre was retracted and promptly transferred to the GC injection port for thermal desorption.

GC-MS Analyses

Volatile compounds were analysed using an Agilent 7890/5977 GC-MS (Agilent, USA) system equipped with an HP-INNOwax capillary column (30 m × 0.25 mm ID, 0.15 μm film thickness; max temperature: 270 °C) (Agilent, USA). Operational parameters included: Injection: 1 minute desorption at 250 °C in splitless mode. Carrier Gas: Helium at 3 mL/min constant flow. Oven Program: Initial temperature 40 °C (5 min hold), ramped at 20 °C/min to 240 °C (5 min final hold). MS Settings: Electron ionization (70 eV), ion source (230 °C), quadrupole (150 °C), full-scan acquisition (m/z 50–550). Compound identification utilized spectral matching against the NIST/EPA/NIH mass spectral library.

Carbohydrate analyses

For retention time comparison, a standard was prepared: Glucose (G), fructose (F), and sucrose (S) were acquired from Sigma- Aldrich (Sigma-Aldrich, USA). And fructooligosaccharides (FOS): 1-kestose (1-kestotriose; 1K), 1-nystose (1, 1-kestotetraose; 1N), and DP5 (1-Fructofuranosyl-D-Nystose) were from Wako Pure Chemical Industries (Osaka, Japan). Compounds were diluted to a concentration of 0.5 mg mL^{-1} with deionized water (resistivity of 17 M Ω).

Thin Layer Chromatography

Analytical procedure was based on the method outlined in (Mellado-Mojica et al., 2022; Mellado-Mojica & López, 2015). The samples were diluted with deionized water (resistivity of 17 MΩ) to a concentration of 10 mg mL^{-1} and then filtered through 0.22 μm nylon membranes (Millipore, USA). One μL of solution was then applied on a silica gel 60 TLC plate (Merck Darmstadt, Germany), with aluminum support. TLC plates were developed in a butanol/ propanol/ water (3:12:4) solvent system, and carbohydrates were revealed using aniline/ diphenylamine/ phosphoric acid in acetone.

Ion Chromatography

Analytical procedure was based on the method outlined in (Mellado-Mojica et al., 2017, 2022). The carbohydrate profiles of all samples were examined using HPAEC-PAD on a Dionex DIONEX ICS-3000 ion chromatograph (Thermoscientific, USA). The system was fitted with a Carbopac PA-200 (40 × 250 mm) column and a precolumn (40 × 25 mm).

Before injection, the samples were diluted with deionized water (resistivity of 17 MΩ) to a concentration of 10 mg mL^{-1} and then filtered through 0.22 μm nylon membranes (Millipore, USA).

The separation gradient for the samples consisted of NaOH [0.23 M], CH_3COONa [0.5 M], and water, with a constant flow rate of 0.2 mL min^{-1}.

The sample separation gradient included NaOH [0.23 M], CH_3COONa [0.5 M], and water, with a constant flow rate of 0.2 mL min^{-1}. The separation began with a gradient of 70% water (A), 30% aqueous NaOH (B),

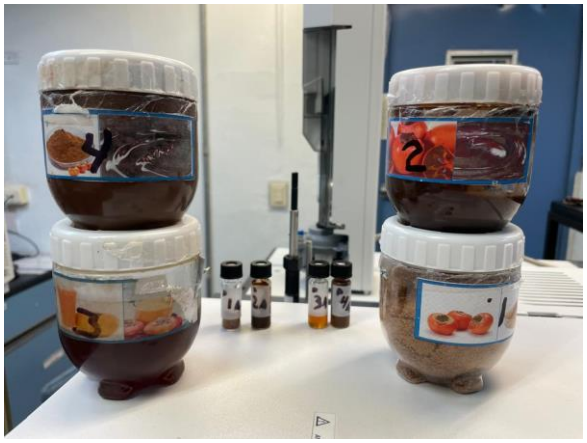
and 0% NaOH/CH_3COONa (C). The subsequent percentual ratios of A and B were as follows: 50:50 (5 min), 45:40 (8 min), 40:30 (27 min), 30:20 (15 min), 15:10 (10 min), and 50:50 (10 min). When the sum of A and B was less than 100%, the remainder of the mobile phase was composed of C. The compounds were detected using an amperometric detector, with the following potentials for amperometric detection: +0.1, −2.0, +0.6 y −0.1 V for E1 (400 ms), E2 (20 ms), E3 (20 ms), and E4 (60 ms), respectively.

Results and Discussion

Persimmon powder (labelled as 1) and syrup (labelled as 3) are depicted in Figure 1. It is worth mentioning that in the picture are also confectioneries (chocolate paste) prepared with both persimmon powder and persimmon syrup (2 and 4, respectively) but preparation of confectioneries from persimmon extracts is a work in progress, thus, it is beyond the scope of this work.

Figure 1

Persimmon extracts where 1: Persimmon powder. 2: Chocolate paste made from powder 3: Persimmon syrup. 4: Chocolate paste made from syrup

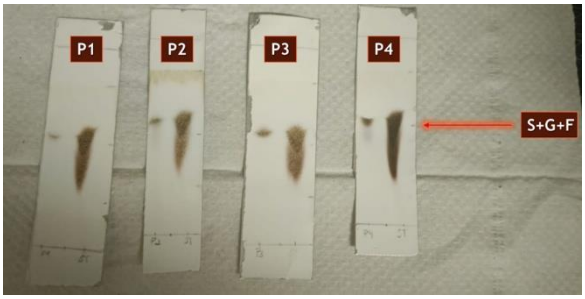


The results of SPME-GC-MS analyses are displayed in Table 1. We evaluated the volatile profile of persimmon extracts (both powder and syrup) to assess their potential as ingredients in confectionery products. Since the volatile profile is closely associated with aroma, we aimed to identify the aromatic compounds present. 19 compounds were identified in the powder whereas only 7 were identified in the syrup. This could be explained by the fact that in the syrup, part of the material (the bagasse) was discarded. Additionally, the powder was exposed to higher temperatures, which may have led to the formation of compounds resulting from thermal decomposition. The most abundant compound in both cases is furfural (32.12% in powder, and 67.56% in syrup). Furfural has been widely used as flavour enhancer for foods and drinks, since its smell is described as ʻAlmond, Caramel, Sweet, Woodyʼ with a ʻpleasant and aromatic odourʼ, albeit its threshold is relatively high thus it may not be recognized if used in a confectionery product (Eseyin & Steele, 2015; Rowe, 2004). Although it may be toxic for dogs, its toxicity for humans is low (Eseyin & Steele, 2015), since it is reported to have ʻnoneʼ in all of the following categories: genotoxicity, repeated dose toxicity, reproductive toxicity, skin sensitation, photoirritation/ photoallergenicity, environmental toxicity, and read-across justification (Api et al., 2024). Furfural has also been used as fungicide and nematicide (Eseyin & Steele, 2015). 3-phenylindole is the next abundant compound in both persimmon powder and persimmon syrup. It has been regarded as an antimicrobial compound (Sinha & Smejtek, 1983). The sum of furfural and 3-phenyl indole account for little over half of the relative abundance of volatile compounds in the case of persimmon powder (51.3%) whereas they account for the vast majority of the relative abundance of volatile compounds in persimmon syrup (89.38%).

In a study by Yang and colleagues in 2021, it was demonstrated that persimmon polysaccharide extracts had positive effects on the proliferation of lactobacilli (Yang et al., 2021). Although the authors did not report the presence of fructans, fructose polymers with well-documented prebiotic effects that favour lactobacilli growth (Mellado-Mojica et al., 2022; Mellado-Mojica & López, 2015), we aimed to measure the carbohydrate profile to evaluate the potential presence of fructans. For this purpose, we first employed TLC and then IC, using a standard composed of glucose, fructose, sucrose, and fructooligosaccharides (FOS). Results of TLC are displayed in Figure 2.

Figure 2

TLC plates of persimmon extracts where: P1: Persimmon powder, P2: Chocolate paste made from powder. P3: Persimmon syrup, P4: Chocolate paste made from syrup. S: Sucrose, G: Glucose, and F: Fructose



As mentioned in relation to Figure 1, there are also confectioneries (chocolate paste) prepared with both persimmon powder and persimmon syrup (P2 and P4, respectively) but preparation of confectioneries from persimmon extracts is a work in progress thus it is beyond the scope of this work. Although it can be seen in Figure 2 that no saccharide beyond S+G+F is present in either persimmon extract, we decided to use a more powerful technique to assess potential fructans.

Results of IC are displayed in Figure 3. Although IC analyses were not done quantitatively, it is still possible to confirm that carbohydrate profile of both persimmon powder and persimmon syrup is comprised of sucrose-fructose-glucose whereas little to no FOS are detected. Those results are in concordance with Yang et al. since they reported a carbohydrate composition of 98.2% glucose (Yang et al., 2021).

Figure 3

Ion chromatograms of persimmon extracts where: A: Standard, B: Powder, C: Syrup. Retention times for S+G+F and for FOS are indicated

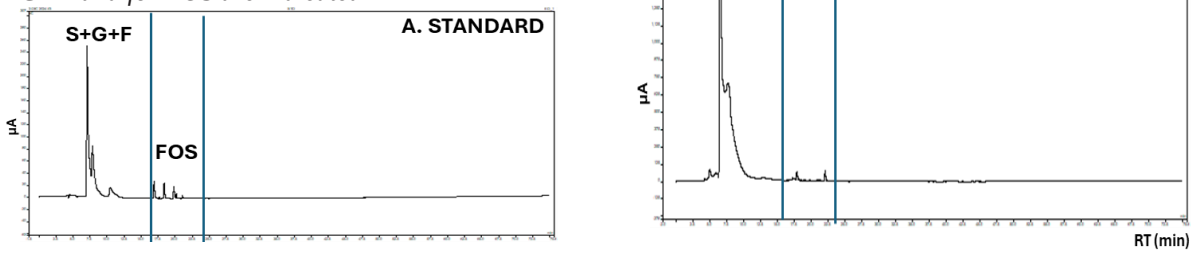


Table 1

Volatile compounds in persimmon extracts (powder and syrup) as analysed by SPME-GC-MS (values in % of total chromatogram area). C.V.: Coefficient of Variation (values in % of area percentage for each reported compound)

RT (min)	***Compound***	***Persimmon powder (%)***	***C.V. (%)***	***Persimmon syrup (%)***	***C.V. (%)***
17.192	Butanal	1.70	6.31		
17.489	Furfural	32.12	0.42	67.56	1.34
18.232	3-Phenylindole	19.19	0.90	21.82	1.65
18.576	N-(3-Methylphenyl)-4-(3-pyridinyl)-1,3-thiazol-2-amine	1.64	3.34		
18.745	1.5-Diphenyl-3-methylthio-1,2,4-triazole	5.73	0.82		
19.039	Benzaldehyde	0.15	6.17	0.92	5.71
20.124	2-Furancarboxaldehyde, 5-methyl-	0.27	4.89	1.84	2.21
20.728	Tetradecyl 2-methoxyacetate	1.95	0.42		
21.884	Benzeneacetaldehyde			0.22	4.21
22.231	1-Propanol, 3,3'-oxybis-	3.43	2.17		
22.243	Methane, diethoxy-	4.58	1.21		
22.28	2-Propanol, 1-[1-methyl-2-(2-propenyloxy)ethoxy]-	2.40	4.05		
22.387	3-Methyl-hexanoic acid			8.60	0.69
22.496	4,8,12,16-tetraoxaeicosan-1-ol	9.44	0.75		
23.919	Benzaldehyde, 3,4-dimethyl-	1.86	2.47		
23.928	Benzaldehyde, 4-ethyl-	1.62	3.31		
24.245	6-Tridecene, 7-methyl-	4.97	1.03		
26.224	Hexanoic acid	0.44	3.59		
26.243	Propyl octanoate	0.14	5.31		
28.319	3-Buten-2-one, 4-(2,6,6-trimethyl-1-cyclohexen-1-yl)-	6.25	1.18		

RT (min)	*Compound*	*Persimmon powder (%)*	*C.V. (%)*	*Persimmon syrup (%)*	*C.V. (%)*
30.364	2-Quinolinecarboxylic acid, methyl ester			0.61	4.12
31.254	Ethanol, 2-[2-(2-ethoxyethoxy)ethoxy]-	2.23	3.41		

Conclusions

1. The most abundant compound in the volatile profiles of both persimmon powder and persimmon syrup was furfural, a compound commonly used as a flavouring agent in the food industry. This highlights the potential of persimmon derivatives as natural sources of desirable flavour compounds.
2. The sugar profiles of persimmon powder and syrup revealed that most of their carbohydrates consist of simple sugars, including glucose, sucrose, and fructose, with little to no fructans detected.
3. The results demonstrate that persimmon powder and syrup could be used for the development of new, potentially more shelf-stable, confectionery products. Incorporating these derivatives can simultaneously reduce persimmon waste and enhance the utilization of this highly perishable fruit. However, it is important to mention that shelf-life studies should be performed in confectionery products made from both persimmon extracts.

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EFFECT OF ULTRASOUND AND PASTEURISATION ON BIOACTIVE COMPOUNDS IN SEA BUCKTHORN AND BLACK ELDERBERRY JUICES

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Abstract
Sea buckthorn and black elderberries are valuable ingredients in the food industry. They offer natural colourings, unique flavours, and potential health benefits due to their rich content of bioactive compounds. Pasteurisation (PA) is a widely used method in food processing that extends the shelf life of products and ensures consumer safety. Ultrasound treatment (UT) is a promising technique for enhancing product safety and preserving bioactive compounds in berry juices. This study aimed to investigate the impact of UT and PA on the bioactive compounds and physicochemical properties in black elderberry and sea buckthorn juice. It specifically analyses how PA and UT influence the total polyphenolic compound content (TPC), free radical scavenging activity (DPPH•), and carotenoid content (CC) in sea buckthorn juice, and TPC, DPPH•, and monomeric anthocyanin content (MAC) in black elderberry juice. Additionally, the effects of processing on juice pH and total soluble solids content were examined. The results indicated that UT did not affect the TPC of sea buckthorn juice. In contrast, the TPC of black elderberry juice decreased by 8.3% due to UT, and PA led to an even more significant reduction of 43.8%. Pasteurised sea buckthorn juice had the highest CC. However, the highest levels of MAC were found in untreated and ultrasound-treated black elderberry juice. Furthermore, the DPPH• results of pasteurised black elderberry juice were lower than those of untreated juice and juice treated with ultrasound. This study highlights UT's potential as an alternative or complementary method to traditional PA for preserving health-promoting compounds in berry juices.
Keywords: *Sambucus nigra*, *Hippophae rhamnoides*, anthocyanin content, carotenoid content, sonication.

Introduction

Fruit juices are popular beverages that provide essential nutrients and bioactive compounds with potential health benefits. Sea buckthorn (*Hippophae rhamnoides* L.) and black elderberry (*Sambucus nigra* L.) juices are particularly rich in bioactive compounds, including phenolics, flavonoids, and vitamin C, which contribute to their high free radical scavenging activity (Vujanoví et al., 2020; Chen et al., 2023). However, the traditional thermal processing method – pasteurisation – used to ensure microbiological safety can negatively impact the bioactive compounds of natural juices (Zhang et al., 2024). Specifically, pasteurisation may reduce the levels of flavonoids and anthocyanins (Vieira et al., 2018). Additionally, it can diminish the content of various volatile compounds in fruit juices, including terpene alcohols, esters, aldehydes, ketones, and sesquiterpenes, which may impact the sensory profile of the juice (Giavoni et al., 2022).

Ultrasound treatment is a promising non-thermal alternative to traditional pasteurisation for fruit juice processing (Margean et al., 2020; Türkol et al., 2024). This technology has shown the potential to enhance the extraction of bioactive compounds, improve juice quality, and maintain nutritional value while ensuring microbiological safety (Kidoń & Narasimhan, 2022; Kobus et al., 2023). Ultrasound treatment offers a significant advantage in enhancing the bioavailability of bioactive compounds. By disrupting cellular structures and minimising particle size, this technique increases the solubility and digestibility of active molecules, leading to more efficient absorption by the human body. Ultrasound treatment can also reduce the molecular weight of polyphenols and polysaccharides, facilitating their uptake and utilisation (Demesa et al., 2024).

This study aimed to investigate the effects of ultrasound treatment and pasteurisation on the bioactive compounds and physicochemical properties of sea buckthorn and black elderberry juices. By comparing these two processing methods, we sought to determine whether ultrasound treatment differed in its impact on the bioactive compounds in the juices compared to traditional pasteurisation. Additionally, we examined whether these effects differed between the two types of juice.

Materials and Methods

LLC Aneva J supplied both fresh and pasteurised sea buckthorn and black elderberry juice. The raw material for both juices originated from Latvia. After extraction, the fresh juice was filled into 500 ml polyethylene terephthalate containers, sealed, frozen, and stored for one month for further analysis.

The pasteurised juice was produced immediately after extraction by heating it to 85 °C for 5 seconds, then filling it into 200 ml glass bottles. Until analysis, the pasteurised juice was stored in a dark, cool (6 ± 2 °C) place for one month.

Before ultrasound treatment and analysis, fresh juice samples were thawed to 18 ± 2 °C for five hours.

Ultrasound treatment

The samples were processed using an ultrasonic homogeniser, the Sonopuls HD4200 (Bandelin Electronics GmbH & Co., Germany), equipped with a TS 104 probe with a diameter of 4.5 mm. 100 mL of each juice sample was poured into a beaker and sonicated in a cold water bath. The temperature of the samples at the end of the processing did not exceed 23 ± 2 °C, and the sonication was performed at a 15% amplitude level (which corresponded to 36 μm amplitude) for 10 min.

Total soluble solids content (TSS)

TSS was analysed using a digital refractometer DR301-95 (A.KRÜSS Optronic GmbH, Germany). The

analyses were performed according to the ISO 2173:2003 standard. The results are expressed in degrees Brix (°Bx), a measure of soluble solids. Measurements were performed in triplicate for each sample.

pH

The pH of each sample was determined using a Milwaukee MW102-FOOD digital pH meter (Milwaukee Electronics Kft., Hungary). The analyses were performed according to the ISO 5542:2010 standard, and the measurements of each sample were performed in triplicate.

Extract preparation for analysing total phenolic compound content and free radical scavenging activity (DPPH·)

40 mL of 80% (v/v) ethanol-water solution is added to 1 g of sample, then filtered through filter paper into a 50 mL volumetric flask. After filtering, the flask is filled to the calibration mark with the same ethanol-water mixture (80:20) (Tomsone, 2015).

Total phenolic compound content (TPC)

The quantification of TPC utilised a modified version of the Folin-Ciocalteu method, adapting protocols from Singleton et al. (1999) and Ozola & Kampuse (2017). The procedure combined 0.5 mL of the prepared extract with 2.5 mL of ten-fold diluted Folin-Ciocalteu reagent. After a 5 minute interval, 2 mL of 7.5% sodium carbonate solution was introduced and mixed. The mixture was then allowed to react for 30 minutes. A Jenway 6300 spectrophotometer (Baroworld Scientific, Great Britain) was employed to measure absorbance at 765 nm (Singleton et al., 1999; Avena et al., 2024).

Results were expressed as grams of Gallic acid equivalent per 100 grams of fresh weight (g GAE 100 g^{-1}). The analysis was conducted in triplicate for each juice sample to ensure reliability.

Free radical scavenging activity (DPPH·)

The free radical scavenging activity was assessed using the DPPH· (2.2-diphenyl-1-picrylhydrazyl) assay, following a protocol of Yu et al. (2003) (Tomsone, 2015). The absorbance of the test solution was measured using a UV-1900i UV-VIS spectrophotometer (Shimadzu Corporation, Japan) at 517 nm.

The results of the radical scavenging activity were quantified in fresh weight and expressed as micromoles of Trolox equivalent per gram of sample (μmol TE g^{-1}). To ensure reliability, the analysis was performed in triplicate for each juice sample.

Carotenoid content (CC)

The quantification of CC was performed using spectrophotometry, utilising a UV-1900i UV-VIS spectrophotometer (Shimadzu Corporation, Japan). The absorbance was measured at 440 nm, adhering to the methodology described by Kampuse et al. (2012). The calculation of CC followed the procedure outlined by Kampuse et al. (2015). The results were expressed in milligrams per 100 grams of fresh weight (mg 100 g^{-1}).

Total monomeric anthocyanin content (MAC)

The MAC content was determined using spectrophotometry based on the pH differential method outlined by Lee et al. (2005). Absorbance readings were taken at 520 nm and 700 nm using a UV-1900i UV-VIS spectrophotometer (Shimadzu Corporation, Japan).

Sample preparation was performed using the methodology described by Krasnova et al. (2023) with slight modifications. 2 g of juice was diluted with 30 mL of a solvent mixture (85% EtOH and 15% 1.5 N HCl). The mixture was then vortexed and allowed to extract for 30 minutes. Afterwards, the mixture was centrifuged and filtered. The MAC content was expressed by cyanidin-3-o-glucoside equivalents (CGE) in mg per CGE 100 g (mg CGE 100 g^{-1}) of fresh weight. The analysis was conducted in triplicate.

Statistical analysis

The average value and standard deviation were calculated for all sample measurements collected. A one-way analysis of variance (ANOVA) was conducted to evaluate the data, with a significance level set at $p < 0.05$. Tukey's Honest Significant Difference (HSD) test was applied to analyse the results further. Data processing and analysis were performed using LibreOffice Calc version 7.1.6.2, a software package for Linux-based operating systems.

Results and Discussion

The primary flavour characteristics of berry juice are determined by pH and total soluble solids (TSS) content. pH indicates the juice's acidity, while TSS represents the sugar content and other dissolved solids. This study found no significant differences ($p > 0.05$) in TSS and pH values among the different treatments of sea buckthorn and black elderberry juice samples. Specifically, there were no significant differences ($p > 0.05$) in TSS and pH values between untreated, pasteurised, and those treated with ultrasound. The TSS for sea buckthorn juice samples ranged from 8.5 to 8.7 (°Bx), while the TSS for black elderberry juice samples ranged from 9.6 to 9.9 (°Bx). Additionally, all sea buckthorn juice samples had a pH of 2.6, whereas the pH of the black elderberry juice samples ranged from 3.7 to 3.8.

Other authors also report that the effect of ultrasonic treatment and pasteurisation on juice pH and TSS is minuscule or insignificant (Salem et al., 2002; Renard & Maingonnat, 2012; Shen et al., 2021; Zhang et al., 2024).

Total phenolic compound content (TPC)

Table 1 presents the TPC of sea buckthorn juice. No significant differences ($p>0.05$) in TPC were found between the fresh and ultrasound-treated juice. However, PA led to a 5% reduction in TPC from the sea buckthorn samples.

In contrast, the fresh sample of black elderberry juice exhibited the highest TPC (Table 2). The TPC of the ultrasonically treated juice decreased by 8%, whereas the pasteurised juice showed a reduction of 44%. There were significant differences ($p < 0.05$) in TPC among all elderberry juice samples.

Interestingly, while ultrasound treatment did not significantly ($p > 0.05$) alter the TPC of sea buckthorn juice, it did lead to a significant ($p < 0.05$) decrease in

the TPC of black elderberry juice. However, for both types of juice, TPC decreased after pasteurisation. Wu et al. (2021) reported that TPC increased in blueberry juice after both pasteurisation and ultrasound treatment. Meanwhile, Xu et al. (2023) found that TPC in strawberry juice decreased with both pasteurisation and ultrasound. Similarly, Bhutkar et al. (2023) noted that neither pasteurisation nor ultrasound treatment significantly changed the TPC of kiwi juice. This indicates that the stability of TPC after processing varies depending on the specific product being processed.

The large difference in the effect of PA between the two analysed juices could be because the TPC profile of black elderberries is mainly composed of cyanidin-3-glucoside and cyanidin-3-sambubioside, which are thermolabile (Jiménez et al., 2017). In contrast, many phenolic compounds in sea buckthorn exist as glycosides (for example, isorhamnetin-3-O-rutinoside, isorhamnetin-3-O-glucoside), which are more heat-stable than aglycones. These glycosides resist degradation better under heat treatment (Liu et al., 2022). The observed differences in the effect of PA and UT between the two juices studied could be due to the different phenolic profiles of the berries.

Table 1

Bioactive compounds in sea buckthorn juice depending on the processing method

Sample	***TPC, g GAE 100 g^{-1}***	***DPPH$^{\cdot}$, µmol TE g^{-1}***	***CC, mg 100 g^{-1}***
Sea buckthorn juice fresh	0.582 ± 0.017^{a}	7.99 ± 0.13^{a}	129.6 ± 5.6^{b}
Sea buckthorn juice ultrasonically treated	0.593 ± 0.016^{a}	8.05 ± 0.30^{a}	126.4 ± 3.3^{b}
Sea buckthorn juice pasteurised	0.550 ± 0.007^{b}	7.74 ± 0.34^{a}	139.8 ± 1.1^{a}

TPC - Total phenolic compound content; GAE - Gallic acid equivalent; TE - Trolox equivalent; CC - carotenoid content; Results are expressed as mean value ± standard deviation (n = 3); Significant differences in the column are marked with different letters ($p < 0.05$, Tukey HSD test).

Table 2

Bioactive compounds in black elderberry juice depending on the processing method

Sample	***TPC, g GAE 100 g^{-1}***	***DPPH$^{\cdot}$, µmol TE g^{-1}***	***MAC, mg CGE 100 g^{-1}***
Black elderberry juice fresh	1.467 ± 0.005^{a}	14.13 ± 0.16^{a}	95.12 ± 1.85^{a}
Black elderberry juice ultrasonically treated	1.345 ± 0.002^{b}	14.75 ± 0.56^{a}	100.45 ± 7.95^{a}
Black elderberry juice pasteurised	0.824 ± 0.01^{c}	13.89 ± 0.46^{b}	56.12 ± 1.02^{b}

TPC - Total phenolic compound content; GAE - Gallic acid equivalent; TE - Trolox equivalent; MAC - monomeric anthocyanin content; CGE - Cyanidin 3-glucoside equivalent; Results are expressed as mean value ± standard deviation (n = 3); Significant differences in the column are marked with different letters ($p < 0.05$, Tukey HSD test).

Carotenoid content (CC)

CC in the analysed sea buckthorn juice samples are presented in Table 1. Pasteurised sea buckthorn juice had a significantly ($p < 0.05$) higher CC than both fresh and ultrasonically treated juice. However, no significant ($p > 0.05$) difference in CC was observed between fresh juice and juice treated with ultrasound.

Staicu et al. (2024), in the research on β-carotene extraction from sea buckthorn berries, reported that the content of β-carotene increased significantly when the temperature was raised from 50 to 70 °C.

An increase in carotenoid levels is often observed during heat treatment, which is usually associated with an improved ability to obtain these compounds. Moderate heat exposure to plant tissues increases the release of carotenoids from their natural matrix. Consequently, these beneficial pigments become more accessible for quantification during analysis (Renard & Maingonnat, 2012).

Carotenoid compounds are typically associated with pulp content when producing fruit juices. Juices that retain a significant amount of pulp, such as sea buckthorn juice, can contain notably high levels of these beneficial pigments (Renard & Maingonnat, 2012).

Total monomeric anthocyanin content (MAC)

The highest MAC levels were observed in fresh and ultrasonically treated black elderberry juice samples, with no significant differences ($p > 0.05$) between the two samples. However, pasteurised black elderberry juice showed a 41% decrease in MAC, resulting in a value of 56.12 ± 1.02 mg CGE 100 g^{-1}.

The observed significant effect of pasteurisation could be due to the fact that anthocyanins are sensitive to high temperatures, which can lead to degradation during processes like pasteurisation. As the temperature increases, the speed at which anthocyanins break down also accelerates. This degradation follows first-order reaction kinetics. As described by other researchers in the case of black elderberry juice, both the temperature during pasteurisation and the processing time significantly influence the extent of anthocyanin degradation (Casati et al., 2015). The elevation in temperature

triggers a breakdown of the bonds between sugar molecules and anthocyanins, resulting in the degradation of vibrant anthocyanin pigments. As a result, the original colour degrades into brownish compounds known as chalcones. This transformation not only changes the visual appearance of the juice but also affects its overall quality (Teneva et al., 2022).

Free radical scavenging activity (DPPH•)

The results of this study indicate that the juice treatment did not affect the DPPH• levels in sea buckthorn juice, which ranged from 7.74 to 8.05 µmol TE g^{-1}. In contrast, significant differences were observed among some samples of black elderberry juice. Following pasteurisation, the DPPH• value decreased to 13.89 µmol TE g^{-1}, which is significantly lower ($p < 0.05$) than the values of untreated and ultrasonically treated black elderberry juice, which were 14.13 and 14.75 µmol TE g^{-1}, respectively.

However, Wu et al. (2021) reported in their study that DPPH• in blueberry juice increases in both pasteurised and ultrasonically treated juice. In addition, increasing the ultrasonic treatment intensity increases the juice's DPPH•. Meanwhile, Khalil et al. (2023) reported in a study on carrot-orange juice blend that increasing the pasteurisation time decreases the DPPH• in the juice, while increasing the ultrasonic treatment time increases the DPPH• in the juice. These findings suggest that pasteurisation parameters and ultrasound treatment influence the DPPH•.

Conclusions

1. Pasteurisation generally had the most detrimental effect on bioactive compounds in sea buckthorn and black elderberry juices.
2. Ultrasonic treatment showed potential as a gentler alternative to pasteurisation, particularly for preserving anthocyanins and phenolic compounds.
3. Sea buckthorn juice appeared more resistant to processing-induced changes in DPPH• levels.
4. Black elderberry juice showed more pronounced changes in bioactive compounds across different processing methods.
5. Further research may be needed to optimise ultrasonic treatment parameters for maximum retention of bioactive compounds.

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COMPARATIVE ANALYSIS OF DRYING METHODS ON *IN VITRO* PROTEIN DIGESTIBILITY OF HOUSE CRICKET (*ACHETA DOMESTICUS*)

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Abstract
Insects can be considered high-quality protein sources for human diet; however, processing methods can influence protein digestibility, which is a critical factor for their nutritional value. This study evaluates the effect of different blanching and drying techniques on the protein digestibility of house cricket (*Acheta domesticus*) *in vitro*. Samples were water blanched (60 °C for 90 s; 100 °C for 60 s) or steam blanched (60 s, 90 s) using a non-pressurized domestic steam cooker operating at approximately 100 °C, before drying in a conventional dryer (at 85 °C and 100 °C), freeze-dryer, or microwave-vacuum dryer. Protein content was determined using the Kjeldahl method (kp = 5.33), and digestibility was assessed through *in vitro* gastrointestinal simulation according to the INFOGEST protocol. A total of 21 samples were processed. Results indicated no statistically significant differences in protein digestibility across drying methods ($p > 0.05$), suggesting that drying technique selection can be based on industrial feasibility, energy efficiency, and cost, without compromising nutritional quality. Blanching method and duration also had no significant impact on protein digestibility, raising questions about the necessity of this pre-treatment step. This study further highlights the importance of using accurate nitrogen-to-protein conversion factors, as conventional calculations (kp = 6.25) may overestimate protein content in insects due to chitin interference. By applying a corrected factor (kp = 5.33), more precise protein values were obtained. These findings contribute to optimizing insect processing for food applications, supporting sustainability and efficiency in edible insect production. The research aligns with broader efforts to improve alternative protein quality and develop evidence-based food labelling standards.
Keywords: *Acheta domesticus*, insect protein, *in vitro* digestibility, drying, blanching.

Introduction

The global interest in edible insects as an alternative protein source is increasing due to insects' nutritional value, complete protein and sustainability of raw material production (Mohamad et al., 2025). Insects are consistently a rich source of proteins across their various life stages, making protein the predominant nutritional component. The content of raw protein often ranges from 40 to 75 g 100 g^{-1} in insect dry matter (Lampová et al., 2024).

The studies have reported protein digestibility values for various edible insect species, stages, and processing methods applied (Oonincx & Finke, 2021). Protein digestibility is a significant factor influencing the bioavailability of amino acids – the building blocks of proteins – within the human body. High digestibility ensures that proteins are effectively broken-down during digestion, realising amino acids to be readily absorbed and utilized for various physiological functions, including tissue repair, enzyme production, and immune responses (Ajomiwe et al., 2024).The bioavailability of amino acids from dietary proteins depends on the degree of protein hydrolysis during digestion and the intestines capacity to utilize amino acids. Therefore, assessing protein digestibility is crucial to determine the nutritional value of protein sources, including edible insects (Rodríguez-Rodríguez et al., 2022).

Processing methods applied in the food industry significantly influence the protein digestibility of edible insects. For instance, blanching – brief exposure to boiling water or steam – can inactivate enzymes raising spoilage and preserving the colour and flavour of the product, thereby enhancing protein digestibility (Rodríguez-Rodríguez et al., 2022). Several studies have demonstrated that certain cooking methods, such as boiling and roasting, can decrease protein digestibility in edible insects. For instance, Mohd Zaini et al. (2023) observed that boiling insects led to a loss of protein due to leaching into the boiling water, resulting in a decrease protein digestibility *in vitro* up to 25%. Similarly, Manditsera et al. (2019) found that boiling and roasting significantly influence protein digestibility in *Tenebrio molitor* and *Gryllus assimilis*, with drying emerging as the most effective method for enhancing digestibility. Therefore, a selection of appropriate processing techniques is crucial to optimize the nutritional benefits of insect-based foods. Analysing the protein content of insects like house cricket (*Acheta domesticus*), process involves measuring total nitrogen content and applying a nitrogen-to-protein conversion factor. The conventional factor of 6.25, based on the assumption that proteins contain 16% nitrogen, is widely used in protein calculation (Janssen et al., 2017).

Applying this calculation, chitin nitrogen is rated as protein nitrogen, too. Chitin consists of 6.89 g 100 g^{-1}. During Kjeldahl or Dumas nitrogen analysis, this nitrogen generally falsifies the protein content resulting in an overestimation of data (Sudwischer et al., 2025).

Recent studies have proposed more accurate, species-specific conversion factor for *Acheta domesticus* protein. Ritvanen et al. (2020) calculated a factor of 5.09 for house crickets. Similarly, Janssen et al. (2017) suggested a factor of 4.76 for the same species. Boulos et al. (2020) in the study of 'Nitrogen-to-Protein Conversion Factors' confirmed that insect protein content has been significantly overestimated. Conclusively, the conversion factor *kp* = 5.33, which was determined as an average from 7 different batches of 3 insect species, reflects a more accurate true protein content.

This study evaluates the effect of different blanching and drying techniques on the protein digestibility of house cricket (*Acheta domesticus*) *in vitro*.

Materials and Methods

The house crickets (*Acheta domesticus*) were obtained from the supplier 'Eurocrickets' UAB (Lithuania). Crickets are farmed for human consumption and fasted for 24 hours before being subjected to humane freeze treatment. Crickets were delivered frozen in dry ice packaging and stored in the freezer at -18 °C until further processing. Frozen insects were thawed at room temperature for 10 min, weighed for 10 g, and processed accordingly.

Blanching was performed using two methods:

- water blanching: 60 °C for 90 s and 100 °C for 60 s (according to Cacchiarelli et al., 2022);
- steam blanching: 60 s and 90 s (adapted from Bawa et al., 2020).

Water blanching was performed by first bringing water to a boil in a stainless-steel pot. Insect samples were placed in a metal sieve and fully submerged in the boiling water for the specified time.

Samples were blanched using a domestic electric steam cooker (Philips Daily Collection HD9126/90, 900 W, Philips, Netherlands) equipped with three baskets and a freestanding reservoir. Steam cooker was not sealed and pressure not measured, water maintained at boiling temperature (approximately 100 °C).

After blanching, insects were submerged in an ice bath for 60 seconds, placed on filter paper to remove excess moisture, and kept for 4 minutes.

Blanched crickets were dried using three drying methods:

- conventional drying in oven (Memmert, UF55, Germany) at 85 °C and 100 °C till constant weight achieved (adapted from Purschke, et al. (2018) and Liang et al., 2024);
- freeze-drying – in a vacuum chamber of a lyophilization device FT33 (Armfield Ltd, UK) at a pressure of 6.4 Pa for 24 h. The temperature in the condensation chamber was -45±3 °C;
- microwave-vacuum drying (Musson 1, Russia): number of magnetrons 13–7–10, pressure 7.47–10.67 kPa, drum rotation speed 6 rpm, drying time 35 min, sample total weight before drying 700 g.

Dried samples were milled using a blade grinder (Stollar SKD600), producing a particle size distribution ranging from 300 to 1,000 μm, depending on the milling duration and sample properties. Samples for further analysis were kept in a plastic 15 mL tube with a lid at room temperature (21±2 °C).

The chemicals used in the study were purchased from Sigma Aldrich (supplied by a local company) and were the analytical grade. Protein digestibility was assessed using *in vitro* digestion simulation following the standard gastrointestinal digestion protocol INFOGEST according to Minekus et al. (2014).

In vitro protein digestibility protocol steps:

1. Gastric phase: 3.8 mL deionized water to 0.5 g sample was added, added 0.08 g pepsin (P7000, ≥ 250 U mL^{-1}), 6.2 mL simulated gastric fluid (SGF, pH 3.0) reaching the total volume 10 mL. The samples were incubated on a Premium Hot Plate Stirrer SMHS-3 (Germany) at 37 °C and rotation speed 80 rpm for two hours. pH checked in one hour after incubation started. Two hours after the gastric phase, pH was raised to 7 with 0.5 M NaOH.

2. Intestinal phase: to 10 mL digested gastric sample added simulated intestinal fluid (SIF, pH 7.0), 0.01g pancreatin (P1750, Sigma-Aldrich, 4xUSP), 0.0125 g chymotrypsin (C3142, Sigma-Aldrich,≥40 U mL^{-1}) and 0.083 g bile salts (48305, Sigma-Aldrich, 10 mM). The samples were incubated on a Premium Hot Plate Stirrer SMHS-3 (Germany) at 37 °C and 80 rpm for two hours. pH checked in one hour after incubation started. After two hours of incubation, samples were transferred to an ice bath, left for 15 min, and centrifuged ELMI Centrifuge CM-6MT SkyLine (USA) for 15 min, 3500 rpm. The supernatant was carefully separated from sediments, kept in the refrigerator till placed for further processing of protein analysis on the digestor (FOSS Tecator™, Denmark).

The samples were processed on a FOSS Tecator™ (Denmark) and Kjeltec™ 2100 (Denmark). The protein content was determined using the Kjeldahl method (AOAC, 2019), and the digestibility was calculated by measuring the nitrogen released after enzymatic hydrolysis.

Nitrogen content (%) was calculated using the formula:

$$N = \frac{(a-b)*k*14.007*100}{c}, \quad (1)$$

where:

N – nitrogen, %;

a – 0.1 M HCl used for sample titrating, mL;

b – 0.1 M HCl used for control titrating, mL;

c –sample weight, mg;

k – HCl molarity, 0.1.

Protein digestibility (PD) was calculated using the formula (Almeida et al., 2015):

$$PD = \frac{Ns-Nb}{Ns} * 100, \quad (2)$$

where:

PD – protein digestibility, %;

Ns – nitrogen content in the sample before digestion, %;

Nb – nitrogen content in the sample after digestion, %.

In this study, the conversion factor k_p = 5.33 is used to determine the protein content.

Data were analysed using Microsoft Excel (version 16.78.3.) and ANOVA paired-sample t-test was used to compare the digestibility differences across drying methods. Significance was set at $p < 0.05$.

Results and Discussion

The choice of an appropriate nitrogen-to-protein conversion factor significantly affects the reported protein content in edible insects. In this study, a paired-sample t-test was performed to calculate protein content for comparison using two different conversion factors (see Table 1). The factor k_p=6.25 is commonly used by insect farmers to determine the protein content in insect samples, but k_p=5.33 is a corrected factor suggested by Boulos et al. (2020). The results of ANOVA, comparing the data using factor k_p=6.25 and k_p=5.33, showed a statistically significant difference ($p < 0.0001$), leading to the conclusion that insect protein content is overestimated using a regular conversion factor of 6.25 (Formula 1). The protein content is overestimated by approximately 15–16% when using the 6.25 nitrogen factor instead of 5.33.

This finding is consistent with previous studies suggesting that a nitrogen factor closer to 5.33 may be more accurate for insects due to the presence of chitin and a unique protein profile.

These results highlight the need to reconsider the choice of nitrogen factor when reporting protein content in edible insects, especially in nutrition labels. Future studies should explore species-specific nitrogen factors to improve the accuracy of protein quantification and ensure standardization in the edible insect production. The slight differences in protein content may stem from natural variability in the sampled crickets (sample size per drying method 10 g), such as the male-to-female ratio. Female *Acheta domesticus* tend to be larger, potentially influencing protein and chitin content (Kulma et al., 2019).

Oven drying at 85 °C and 100 °C generally produced consistent results (see Table 1), with protein SDs mostly below ±2.5%. One steam-blanched sample dried at 100 °C showed higher variability (SD ±4.8%). Freeze-dried steam-blanched samples displayed moderate variation, with SDs up to ±3.7%. During freeze-drying, a visible structural difference was observed, which may have influenced protein uniformity in the final powder. Microwave-vacuum drying exhibited the highest variability in protein content. The observed standard deviation may have resulted from uneven moisture reduction (Zhang et.al., 2006), as microwave-assisted drying can lead to localized differences in drying intensity, potentially affecting protein conformation and retention.

However, the minimal variations were observed in digestibility results, these differences are not statistically significant ($p > 0.05$) and are unlikely to affect overall conclusions.

Table 1

The protein content of samples, calculated using two conversion coefficients: kp6.25 and kp5.33

Drying method	Sample	Nitrogen, %	Protein, % (k_p=6.25)	Protein, % (kp=5.33)
Convential drying	60 °C water blanch for 90 s, dried at 85 °C	10.17 ± 0.28	63.54 ± 1.77	54.18 ± 1.51
	100 °C water blanch for 60 s, dried at 85 °C	10.39 ± 0.38	64.96 ± 2.38	55.40 ± 2.03
	Thawed (no processing), dried at 85 °C	10.03 ± 0.13	62.69 ± 0.84	53.47 ± 0.71
	60 °C water blanch for 90 s, dried at 100 °C	10.17 ± 0.38	63.59 ± 2.35	54.23 ± 2.00
	100 °C water blanch for 60 s, dried at 100 °C	10.10 ± 0.14	63.15 ± 0.85	53.85 ± 0.73
	Thawed (no processing), dried at 100 °C	10.13 ± 0.36	63.30 ± 2.27	53.98 ± 1.93
	60 s steam blanch, dried at 85 °C	10.30 ± 0.22	64.41 ± 1.36	54.93 ± 1.16
	90 s steam blanch, dried at 85 °C	10.49 ± 0.40	65.55 ± 2.50	55.90 ± 2.13
	60 s steam blanch, dried at 100 °C	10.21 ± 0.33	63.82 ± 2.05	54.42 ± 1.75
	90 s steam blanch, dried at 100 °C	10.99 ± 0.90	68.68 ± 5.65	58.57 ± 4.82
Freeze-drying	Frozen (no processing), freeze dried	10.37 ± 0.35	64.83 ± 2.20	55.28 ± 1.86
	60 °C water blanch for 90 s, freeze dried	10.40 ± 0.47	64.98 ± 2.96	55.41 ± 2.53
	100 °C water blanch for 60 s, freeze dried	10.46 ± 0.44	65.35 ± 2.76	55.73 ± 2.35
	60 s steam blanch, freeze dried	9.96 ± 0.70	62.26 ± 4.35	53.09 ± 3.70
	90 s steam blanch, freeze dried	10.47 ± 0.37	65.44 ± 2.32	55.80 ± 1.98
	Thawed (no processing), frozen, freeze dried	10.28 ± 0.25	64.25 ± 1.53	54.79 ± 1.31
Microwave-vacuum drying	60 s steam blanch, microwave-vacuum dried	10.66 ± 0.69	66.63 ± 4.32	56.83 ± 3.68
	90 s steam blanch, microwave-vacuum dried	10.76 ± 0.63	67.25 ± 3.92	57.35 ± 3.34
	60 °C water blanch for 90 s, microwave-vacuum dried	10.81 ± 1.12	67.54 ± 6.98	57.60 ± 5.96
	100 °C water blanch for 60 s, microwave-vacuum dried	9.99 ± 0.45	62.41 ± 2.81	53.22 ± 2.40
	Thawed (no processing), microwave-vacuum dried	10.18 ± 0.27	63.64 ± 1.72	54.27 ± 1.46

Protein digestibility is an important factor in determining its quality. All samples in this study showed high protein digestibility (see Table 2), calculated according to Formula 2. The data differed slightly, which could be due to a small sample size, uneven grinding, or weighing inaccuracies. Statistical data analysis (ANOVA, $p = 0.1505$) showed no statistical difference between all samples, in each

repetition, regardless of the blanching or drying method applied. Statistical data analysis was also performed between individual drying methods, yielding results (ANOVA p = 0.07 - 0.79), which confirmed that the data were not statistically significant among themselves.

Table 2
Protein digestibility across samples

Drying method	Sample	Digestibility, %
Conventional drying	60 °C water blanch for 90 s, dried at 85 °C	76.53 ± 2.62
	100 °C water blanch for 60 s, dried at 85 °C	77.35 ± 1.80
	60 s steam blanch, dried at 85 °C	77.20 ± 3.74
	90 s steam blanch, dried at 85 °C	79.25 ± 4.30
	Thawed (no processing), dried at 85 °C	77.86 ± 3.17
	60 °C water blanch for 90 s, dried at 100 °C	78.17 ± 5.25
	100 °C water blanch for 60 s, dried at 100 °C	76.97 ± 2.99
	60 s steam blanch, dried at 100 °C	77.70 ± 3.59
	90 s steam blanch, dried at 100 °C	79.20 ± 2.46
	Thawed (no processing), dried at 100 °C	76.98 ± 3.20
Freeze-drying	60 °C water blanch for 90 s, freeze dried	77.93 ± 5.81
	100 °C water blanch for 60 s, freeze dried	77.79 ± 3.85
	60 s steam blanch, freeze dried	78.00 ± 5.40
	90 s steam blanch, freeze dried	77.98 ± 2.05
	Thawed (no processing), frozen, freeze dried	78.17 ± 4.58
	Frozen (no processing), freeze dried	75.97 ± 3.87
Microwave-vacuum drying	60 °C water blanch for 90 s, microwave-vacuum dried	78.91 ± 4.40
	100 °C water blanch for 60 s, microwave-vacuum dried	79.44 ± 5.71
	60 s steam blanch, microwave-vacuum dried	78.07 ± 3.85
	90 s steam blanch, microwave-vacuum dried	79.19 ± 3.29
	Thawed (no processing), microwave-vacuum dried	78.84 ± 4.49

However, the standard deviation in digestibility values varies across samples, primarily due to inconsistencies in sample handling for Kjeldahl analysis. These variations were not caused by experimental errors but rather by unavoidable circumstances that prevented a uniform methodology for storing and processing the digested samples. Future studies should ensure consistent handling procedures, preferably performing Kjeldahl analysis immediately after *in vitro* digestion, to minimize variability while maintaining the high-quality data integrity demonstrated in this study.

The *in vitro* protein digestibility of *Acheta domesticus* observed in this study aligns with existing literature, which reports digestibility values ranging from 79 to 93% (Hammer et al., 2023). These results confirm that crickets are a highly digestible protein source suitable for human nutrition.

According to Sánchez-Velázquez et al. (2023) data, different drying methods (conventional, freeze-drying and microwave) do not affect the protein digestibility. Similarly, Kröncke et al. (2018) concluded that drying methods affect only insect protein solubility. However, other studies showed contradictory results. For instance, Purschke et al. (2018) concluded that drying temperature above 100 °C affects protein digestibility, as protein denaturation occurs. In turn, Lier et al. (2024) indicate that microwave drying negatively affects the protein quality of black soldier fly larvae.

The absence of significant differences in digestibility data between drying methods is of specific relevance. These findings suggest that insect farmers can select any drying method based on its industrial feasibility, costs and energy efficiency rather than protein digestibility. This research contributes to the development of improved processing methods, showing that insect protein digestibility remains consistent regardless of the drying method used, enabling manufacturers to choose their processing methods to be more resource and environmentally sustainable, as well as revenue generating, without the fear of protein loss.

Conclusions

1. The study results reveal the need to reconsider the choice of conversation factor when reporting protein content in edible insects, especially in nutrition labels.
2. The results of *in vitro* protein digestibility across different drying methods – oven drying at 85 °C and at 100 °C, freeze drying, and microwave-vacuum drying revealed no statistically significant differences in house cricket (*Acheta domesticus)* protein digestibility values ($p > 0.05$)
3. Additionally, blanching or steam blanching did not significantly impact digestibility outcomes when followed by drying.
4. Based on these findings, it is recommended to assess the necessity and time for blanching, to minimize processing steps for improved sustainability.

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EXPLORING THE HEALTH BENEFITS OF MUESLI AND SELENIUM: A REVIEW

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Abstract
Regular breakfast consumption is associated with lower risks of cardiovascular disease, especially for those who consume more than 25 grams of dietary fiber daily. Systematic reviews show that breakfast cereals enriched with oats, barley, and fruits can effectively reduce cholesterol levels and lower the risk of diabetes and heart disease due to their fiber and bioactive compounds. Additionally, selenium plays a crucial role in the diet by supporting immune function, reproductive health, and reducing the risk of chronic diseases. Notably, selenium was chosen for this study because no muesli products currently exist that are specifically fortified with selenium. This study explores the health benefits of muesli and selenium through a review of literature from 2020 to 2025 using databases like Google Scholar, ScienceDirect, and EBSCOhost. The research highlights potential benefits of selenium-rich muesli, such as lower obesity rates, improved metabolism, and better thyroid health. A total of 63 articles were reviewed, reinforcing the significance of a nutritious diet in preventing cardiovascular diseases (CVD) and coronary artery disease (CAD). The paper encourages awareness and consumption of selenium-rich muesli to enhance overall health and well-being. The study highlights the significance of dietary choices in promoting better public health outcomes and the role of nutrition education in promoting healthier eating habits. Additionally, the results indicate that incorporating such nutrient-dense foods into daily diets could result in long-term health improvements and lower healthcare costs associated with managing chronic diseases.
Keywords: muesli health benefits, muesli nutrition, selenium and thyroid function, selenium and autoimmunity, selenium deficiency.

Introduction

Muesli is composed of a mix of cereals, nuts, and dried fruits, and has gained popularity as a nutritious breakfast option due to its potential health benefits. Research indicates that the soluble fibers found in muesli, particularly beta-glucan from oats and barley, may enhance satiety and contribute to heart health by lowering cholesterol levels (Hughes & Grafenauer, 2021; Santos et al., 2022). As dietary patterns evolve, muesli is emerging as a favored choice among health-conscious consumers, often promoted for its rich nutrient profile and versatility in meal preparation (Gréa et al., 2025).

In addition to the benefits associated with whole grains and dietary fibers, selenium - a vital micronutrient - plays a significant role in human health. Selenium contributes to various biological processes, including immune function and thyroid hormone metabolism (Hong & Diamond, 2020; Minich, 2022). However, selenium deficiency is a widespread issue, affecting populations in both developing and developed countries (Zhang et al., 2023; Azevedo et al., 2023). Understanding the interrelationship between muesli consumption and selenium bioavailability is critical for maximizing dietary health benefits.

This review specifically chose to compare selenium due to the absence of commercially available muesli products that are high in this essential micronutrient. Despite selenium's known benefits in supporting thyroid function and reducing thyroid autoimmunity, there is currently a gap in the market for muesli formulations enriched with selenium. By focusing on this nutrient, the review aims to explore the potential health benefits that a newly developed selenium-rich muesli could provide.

Materials and Methods

Monographic method was used for this study. Relevant scientific literature was gathered to investigate the health benefits of muesli and selenium consumption. Comprehensive searches were conducted using databases such as Google Scholar, ScienceDirect, and EBSCOhost. The literature review is based on published studies from the last 5 years, emphasizing the most recent studies. The selection of publications was based on the following criteria:

Language: Only articles published in English were considered.

Focus: Studies needed to address the health effects of muesli and selenium specifically, with a particular emphasis on articles that discussed the fortification of muesli with selenium.

Availability: Only publications for which the full text was accessible were included.

Despite targeted queries for articles focusing on the fortification of muesli with selenium, no studies were found that specifically addressed this topic. Most existing literature concentrated on the nutritional benefits of individual grains or general dietary sources of selenium, rather than muesli as a fortified product.

Initially, a total of 121 publications were identified through the search. After applying the inclusion criteria, 63 articles met the necessary requirements for detailed analysis in this literature review.

The search terms utilized and corresponding results are documented in Table 1, providing clarity on the keywords that guided the literature selection process.

This structured approach enables the review to thoroughly gather and present the latest research on the nutritional advantages of muesli and selenium. By doing so, it deepens our understanding of their health implications, especially given the identified gap in the

literature concerning muesli fortification. This detailed examination not only highlights the potential benefits but also underscores the need for further exploration in this area, paving the way for informed discussions and future research.

Table 1
Search terms used and number of papers identified

Search terms and number of papers identified	***Number of papers identified***
'Muesli health benefits'	6
'Muesli and cardiovascular disease risk'	5
'Muesli consumption and BMI'	4
'Muesli nutrition'	10
'Selenium and thyroid function'	6
'Selenium and autoimmunity'	7
'Selenium deficiency'	10
'Selenium deficiency in Latvia'	3
'Selenium bioavailability'	6
'Selenium supplementation'	6

Results and Discussion

Muesli nutrition

Many people around the world base their daily diets on grains. Grains are plant seeds that mostly fall under the legume, cereal, and pseudocereal botanical categories. In the human diet, they provide micronutrients like vitamins and minerals as well as macronutrients like proteins, fats, and carbohydrates (Carcea, 2020).

Muesli, a Swiss dish made from different cereals, nuts, and dried fruits, is added to dairy products and is being researched for its potential to increase satiety. Muesli prepared from rye or oats may be regarded as a source of soluble fibers like beta-glucan (Santos et al., 2023).

Oat groats have a protein level of 13–20%. About 30% of the oat embryo is made up of proteins. Antioxidant substances such tocols, phenolic compounds, and sterols are other trace amounts of oats that are linked to positive health effects. Tocopherols and tocotrienols, which together form tocols, are the primary contributors to vitamin E activity (Paudel et al., 2021). Oats have been shown to contain several phenolic compounds, including avenanthramides (AVAs), p-hydroxybenoic acid, vanillic acid, tricin, apigenin, luteolin, kaempferol, quercetin, ferulic acid, caffeic acid, protocatechuic acid, syringic acid, p-coumaric acid, sinapic acid, tricin, apigenin, luteolin, and caffeic acid (Paudel et al., 2021).

Beta glucan, a beneficial and chemically comparable polysaccharide, is present in both barley and oats. Depending on the type, barley has 4–10% w/w β-glucan and oats 6–8% (Hughes & Grafenauer, 2021). It is composed of a linear branched chain of D-glucose monosaccharides joined by a combination of β (1 → 3) and β (1 → 4) links and is one of the main constituents of soluble fiber. Known for several nutritional and functional qualities, including its ability to decrease cholesterol and prevent diabetes, it is thought to be the main active ingredient in oats (Paudel et al., 2021).

The research by Gréa et al. (2025) highlights significant trends in the Nutri-Score classification of breakfast cereals in Germany. It reveals an increase in fat content, particularly in children's muesli (39.0%), compared to other breakfast cereal categories, while non-children's muesli demonstrated a reduction in sugar content (9.2%). The study suggests that reducing saturated fat can notably decrease negative points in Nutri-Score ratings. Furthermore, substituting palm oil with healthier alternatives, such as sunflower oil, could effectively enhance the nutritional profile of mueslis. This emphasizes the importance of mindful ingredient choices in improving the healthfulness of breakfast cereals (Gréa et al., 2025).

When creating new muesli, a variety of nutrient-rich ingredients can be included to enhance both flavor and health benefits, e.g., nuts and seeds.

Hazelnuts: A great source of healthy fats, especially monounsaturated and polyunsaturated fatty acids, hazelnuts contain important lipids like palmitic, stearic, linoleic, and α-linolenic acids, the latter being a precursor for omega-3 fatty acids (Poșta et al., 2022).

Walnuts: Renowned for their high monounsaturated fatty acid content, walnuts are an excellent source of omega-3 fatty acids and antioxidants. They help in reducing cholesterol and oxidative stress (Bell et al., 2025).

Sesame Seeds: High in oil content (57–63%), sesame seeds are rich in protein and minerals such as iron and calcium. Their lignans, sesamin and sesamolin, contribute to antioxidant stability (Orngu & Mbaeyi-Nwaoha, 2022).

Flaxseeds: With around 41% fat and a high content of α-linolenic acid, flaxseeds are a valuable source of dietary fiber and phenolic compounds (Abbasi et al., 2022).

Chia Seeds: These seeds are rich in dietary fiber (30–34 g per 100 g), providing both soluble and insoluble fibers, as well as important minerals like calcium and phosphorus (Agarwal et al., 2023).

Sunflower Seeds: Containing about 51.46 g of total lipid per 100 g, along with protein, carbohydrates, and fiber, sunflower seeds are an excellent source of choline and betaine (Petraru et al., 2021).

Pumpkin Seeds: A great source of minerals like phosphorus and magnesium, pumpkin seeds are rich in trace minerals, making them a valuable addition to muesli (Marcel et al., 2021).

Matcha: Exceptionally rich in antioxidants, particularly catechins, with epigallocatechin gallate (EGCG) being the most significant one. These antioxidants are essential for combating oxidative stress and reducing inflammation within the body (Monfared et al., 2022).

Cacao: Integrating cacao into muesli not only enhances flavor but significantly boosts its nutritional profile, making it an even healthier breakfast option (Carmona-Rojas et al., 2022). Integrating these ingredients into muesli not only enhances its nutritional value but also offers a wider range of flavors and textures, creating a nutritious and satisfying breakfast option (Andrejaš et al., 2020).

Muesli and weight management

Regular consumption of muesli is associated with lower body mass index and a lower risk of obesity, especially for products rich in fiber (Santos et al., 2022). The effect of fiber and grain constituents can be explained by controlling the intestinal microbiota and preventing the growth of pathogenic bacteria for instance, avenanthramides from whole oats can be efficiently used by the gut microbiota, generating bioactive metabolites and preventing obesity (Zhang et al., 2020).

The findings from Liu & Cai (2023) study showed association between muesli consumption and improved health outcomes, particularly in the context of weight management. The genetically predicted intake of muesli was significantly linked to the reduction in body mass index, indicating its potential role in maintaining a healthy weight. Additionally, the suggestive associations with lower levels of LDL cholesterol and hemoglobin A1c further reinforce the idea that muesli may be beneficial not only for weight management but also for overall metabolic health (Liu & Cai, 2023).

The consumption of muesli and cereals is associated with several beneficial effects, including reductions in body weight and improvements in adiposity markers. Additionally, these foods may influence glyco-metabolic gastrointestinal hormones, mitigate oxidative stress, and promote genomic adaptations (Tang et al., 2024).

Health effects of muesli

Whole grains offer a substantial chance to prevent and treat increased cholesterol and reduce the risk of CVD (Hughes & Grafenauer, 2021). Muesli is one of the current trends in cereal foods, as people's lifestyles are changing due to the fast pace of life, but it is important to get all the nutrients (Chow et al., 2024). Recent studies have shown that eating breakfast is associated with a reduced incidence of cardiovascular disease. Regular daily breakfast intake is associated with lower total and cardiovascular mortality, especially when consuming fiber >25 g per day (King & Xiang, 2021). Some foods, such as oatmeal, barley, rye, psyllium, chia seeds, goji berries, apples, oranges and various berries, are effective in reducing low-density lipoprotein (LDL) levels (Kenneth & Feingold, 2024). Oats have been shown to improve gut flora and promote immunomodulation, which are both good for human health. Consumption of oats also helps prevent conditions including dermatitis, atherosclerosis, and some types of cancer (Paudel et al., 2021).

Two systematic reviews of studies that included nutritional analyses of breakfast cereals concluded that they help lower cholesterol levels, improve bowel function, and reduce the risk of diabetes and cardiovascular disease (Santos et al., 2022). Diets that include plant-based foods rich in fruits, whole grains, and limiting red meat, especially processed foods, reduce the risk of coronary artery and cardiovascular disease (WHO, 2021). It is still unclear whether specific foods have a direct effect on the risk of cardiovascular disease (Yang et al., 2023). Can we eat one food every day, such as muesli, and reduce the risk of coronary artery disease? A study conducted in Europe showed that regular muesli consumption was statistically negatively associated with the risk of coronary artery disease. The association between muesli and reduced risk of CVD was observed in population cohort studies (Park et al., 2024).

A large-scale longitudinal study found that consumption of breakfast cereals, bran cereals, and oat cereals did not demonstrate a significant association with a reduced risk of diabetes. However, muesli emerged as a potential protective factor against both diabetes and cardiovascular diseases. This suggests that muesli may offer unique health benefits that warrant further exploration (Tang et al., 2024).

It has been demonstrated that consuming 3 g of beta glucan daily significantly reduces blood cholesterol levels and circulating LDL cholesterol, two important risk factors for cardiovascular disease (Hughes & Grafenauer, 2021). The advantages of eating more whole grain meals on a regular basis are well established; Marshall et al. (2020) state that for every 16 g increase (one serving), the risk of cardiovascular disease is reduced by 9% (Marshall et al., 2020).

Health benefits of a muesli that is high in selenium

A muesli high in selenium offers numerous health benefits, particularly in promoting cardiovascular health and enhancing immune function. Selenium is a vital trace mineral that plays a crucial role in antioxidant activity, helping to neutralize free radicals and reduce oxidative stress, which is linked to various chronic conditions, including heart disease (Méplan & Hughes, 2020). Studies suggest that adequate selenium intake may significantly lower the risk of coronary artery disease (Sun et al., 2021), while enhancing thyroid function (Gärtner & Köhrle, 2022). Additionally, selenium's role in immune response has been well-documented, with research indicating that it may improve the body's ability against infections (Bell et al., 2024). While there has not yet been a muesli specifically focused on adding selenium, it is planned to fortify wheat grains by soaking them in selenium-containing solutions. Dūma & Kārkliņa demonstrated that wheat grains can be effectively fortified with the microelement selenium by soaking them in sodium selenate solutions (Dūma & Kārkliņa, 2006). Their findings revealed a remarkable increase in total selenium content, showing

an 81.5x increase when grains were soaked in the highest concentration of 200 mg L^{-1} sodium selenate solution. This method presents a viable approach for enhancing the selenium content in wheat grains.

By incorporating ingredients high in selenium such as Brazil nuts, sunflower seeds, and whole grains, consumers can benefit from the essential properties of selenium while enjoying a delicious and nutritious breakfast option (Jones & Poutanen, 2020).

Selenium requirements and sources

The World Health Organization (WHO) recommends an intake of 55 μg day^{-1} of selenium for adults, with an upper limit of 400 μg day^{-1} (Zhang et al., 2023). Meanwhile, selenium mostly generates the immune-boosting and antioxidant benefits, along with some anticarcinogenic effects, at a dosage of 150–200 μg day^{-1}. The tolerable upper intake level (UL) is set at 400 micrograms per day for adults. Consumption of selenium above this level, especially over a long period, can lead to toxicity (Minich, 2022). Maternal selenium requirements also increase during pregnancy and lactation, reaching 70 μg day^{-1} in pregnant women. Studies have shown that this amount of selenium intake is sufficient for the effective functioning of selenoenzymes, but the levels necessary for the regulation of autoimmunity have not yet been determined. Blood selenium levels mainly depend on recent dietary intake and selenium form ingested (Veisa et al., 2021).

Cereals are the main source of selenium; however, their selenium content is relatively low, ranging from 0.01 to 0.55 μg g^{-1}. Selenium content ranges from 0.08 to 0.7 μg g^{-1} in animal foods and less than 0.1 μg g^{-1} in vegetables and fruits. Brazil nuts are the richest dietary source of selenium, with selenium levels of up to 1920 μg 100 g^{-1}. To achieve the daily value of 55 mcg: 1 Brazilian nut (providing about 68-91 mcg) is sufficient to meet or exceed the daily requirement. Other foods such as oysters (154 μg 100 g^{-1}), tuna (108 μg 100 g^{-1}), chia seeds (100 μg 100 g^{-1}), and sunflower seeds (100 μg 100 g^{-1}) are also rich sources of selenium (Godos et al., 2022).

Soil is the main source of selenium in plants. If the total selenium content of the soil is below 0.1 mg kg^{-1}, it is considered a significant selenium deficiency in the soil, from 0.2–0.3 mg kg^{-1} is a low selenium content, and soil with a content of more than 0.4 mg kg^{-1} is considered a good source of selenium (Zhang et al., 2023).

Selenium bioavailability

In soils, the bioavailability of selenium (Se) is influenced by its chemical forms as well as the soil conditions. The primary abiotic factors that affect this include soil pH, redox potential, clay content, and the presence of organic matter (Kushwaha et al., 2021).

Soil microbes are the key biotic factor influencing selenium (Se) bioavailability in soils. The microbes most commonly associated with enhancing plant Se uptake include various fungi, such as arbuscular mycorrhizal fungi and endophytic fungi, as well as a range of bacterial groups. The bacteria that contribute to Se accumulation in crop tissues are referred to as selenobacteria (Feng et al., 2023).

The bioavailability of different forms of selenium (Se) in soil varies by plant, and selenium uptake by plants is also affected by soil pH, microbial activity, and organic matter. As much as 90% of the selenium present in the human body is absorbed as selenomethionine, which comes from sources such as selenium-enriched yeast, selenite, and selenate (Winther et al., 2020). The total amount of selenium in the human body is approximately 3–20 mg (Zhang et al., 2023).

Selenium is ingested from food and is present in the human body in the natural organic forms of selenocysteine and selenoprotein. They are stored in various organs and tissues: 30% in the liver, 30% in the muscles, 15% in the kidneys, 10% in the plasma and 15% in other organs. The concentration of selenium in the liver reflects the level of absorption in the intestine. The liver synthesizes selenoprotein P (SELENOP), which enters the bloodstream and delivers selenium to other tissues and organs (Zhang et al., 2023).

The importance of selenium in the body

Selenoproteins are essential for the metabolism of thyroid hormones, DNA synthesis, reproduction, and defense against infection and oxidative damage (Hong & Diamond, 2020). Selenium is involved in immune-cell function, redox, anti-inflammatory, anti-carcinogenic, and antioxidant processes. It also regulates thyroid hormone metabolism (Kobayashi et al., 2021). Selenium plays a key role in eliminating free radicals and shielding tissues and cells from harm caused by peroxide. Therefore, low levels of selenium in the environment may have an impact on the body's selenium levels (Li et al., 2024).

Selenium has anti-inflammatory, immunostimulating, and antioxidant properties (Joshi et at., 2022). Numerous selenoproteins have a role in controlling antioxidant activity. Selenium has a major function in controlling many inflammatory processes inside the body as a cofactor of enzymes involved in antioxidant protection (Kieliszek, 2021). Inflammatory skin conditions including psoriasis and atopic dermatitis are linked to an inadequate selenium level in the body (Jun et al., 2020). This explains why it is so crucial to monitor your blood serum selenium levels and incorporate foods high in selenium in your diet.

In the anti-inflammatory response in periapical dental tissues, authors discovered that selenium utilized for intracanal medicine might enhance the healing benefits of calcium hydroxide (Espaladori et al., 2020). According to Ceyhan et al. (2021), selenium showed a protective effect against oxidative damage caused by dental amalgam (Ceyhan et al., 2021).

Selenium deficiency

Selenium deficiency has been linked to an increased risk of several chronic diseases with inflammatory pathogenesis, such as cardiovascular disorders (Gröber &

Holick, 2021). Smokers also have reduced selenium levels, potentially because of increased oxidative stress (Yan et al., 2020). One of the main causes of Keshan disease (endemic cardiomyopathy) is a selenium deficit (Li et al., 2024). Children and women of reproductive age are the primary populations affected by Keshan illness. The illness persists even if its incidence is low nowadays (Hou et al., 2021). Iodine deficiency may worsen due to selenium deficit, which might raise the risk of congenital hypothyroidism in newborns. In addition to having very low plasma levels of thyroxine (T4) and triiodothyronine (T3) and very high levels of thyroid stimulating hormone (TSH), people with this illness also manufacture inadequate amounts of thyroid hormone (Hong & Diamond, 2020).

Numerous studies have already found links between low selenium and higher rates of thyroid, and viral infections as well as breast, prostate, and gastrointestinal malignancies (Zhang et al., 2020). People in some nations that eat a lot of vegetables that are cultivated in low-selenium regions have the risk of becoming deficient. Some regions of China have the lowest selenium intakes in the world, with soil selenium levels extremely low and a big percentage of the population eating mostly vegetarian food (Yang et al., 2025).

Because hemodialysis eliminates some selenium from the blood, patients on long-term hemodialysis frequently have much lower selenium concentrations than healthy people. Individual selenium status, however, also affects whether selenium concentrations in hemodialysis patients are adequate (Azevedo et al., 2023).

Low selenium concentrations are common in HIV-positive patients, possibly because of malabsorption or insufficient selenium consumption (Martinez et al., 2021). According to observational research, people with HIV who have decreased selenium levels are more likely to develop cardiomyopathy (Golin et al., 2022).

Selenium deficiency in Latvia

The findings from the study conducted in Latvia suggest a significant connection between selenium (Se) levels and the severity of COVID-19, indicating that acute patients exhibit notably lower concentrations of Se and its transport protein, selenoprotein P, compared to those recovering from the virus. The decreased selenium levels in acute patients, alongside elevated markers of oxidative stress, such as 4-hydroxynonenal (4-HNE) adducts, imply a compromise in antioxidant defenses during the acute phase of the illness (Šķesters et al., 2023).

The analysis of dietary habits among phenylketonuria (PKU) patients in Latvia reveals critical insights into their nutritional status, specifically concerning selenium levels. Despite the adequate selenium intake reported via food diaries for the majority of PKU patients across various age groups, it is concerning that 11% of those in the 13–18 age group exhibited inadequate serum selenium levels. This indicates that, while intake may be sufficient on paper, actual absorption and status may still be compromised (Lubina et al., 2023).

For example, during the pregnancy, serum selenium levels in the first trimester in Latvia were lower (101.5 μg L^{-1}) compared to certain countries, including the United States (151 μg L^{-1}), Japan (140.2±12.4 μg L^{-1}), Nigeria (107.4±15.8 μg L^{-1}), and Finland (106±15 μg L^{-1}). However, results for pregnant women were higher than those reported in other countries like Germany (89±1 μg L^{-1}), Serbia (63 μg L^{-1}), Finland (59 μg L^{-1}), and Poland (53.4±8.0 μg L^{-1}). Notably, around one-third (30.1%) of pregnant women in Latvia had selenium levels below 80 μg L^{-1}, indicating selenium deficiency (Veisa et al., 2021).

Selenium status

Selenium supplementation has shown effectiveness in viral diseases. Furthermore, it has been demonstrated that a lack of selenium is linked to a greater incidence of viral genome mutation in a number of RNA virus-induced viral illnesses, including SARS-CoV, HIV, Ebola virus, and influenza virus (Hiffler & Rakotoambinina, 2020). Numerous studies have evaluated the connection between body selenium levels and COVID-19 incidence, severity, and death. People who live in regions with low levels of selenium appear to be more at risk of viral diseases. Additionally, some research has looked at the relationship between soil selenium levels and the severity and prevalence of COVID-19 (Liu et al., 2021).

Table 2 presents data on selenium consumption from various food sources and corresponding blood concentration levels in different countries.

Table 2

Blood levels and consumption of selenium foods in various parts of the world

Country	***Daily intake (μg)[1]***	***Blood/serum (μg/liter)[2]***	***Source***
China	2-6990	5-7800	(Minich, 2022)
USA	94-132	~127	(Klein et al., 2023)
Australia	52-90	82-180	(Tinggi & Perkins, 2022)
New Zealand	25-77	~111	(Tinggi & Perkins, 2022)
Germany	38-47	89-98	(Minich, 2022)
Finland until 1984	~40	~69	(Minich, 2022)
Finland after 1984	~80	~109	(Minich, 2022)

[1]Adults should consume 55 μg of selenium each day (Zhang et al., 2023).

[2]Normal selenium concentration in adult human blood serum is between 110 and 165 mcg/L (Blazewicz et al., 2024).

The amount of selenium in human serum and daily consumption varies significantly between nations. Long-term improvements in population health and disease prevention were achieved with the introduction of dietary supplements containing selenium in areas of Europe (Germany and Finland) and Central Asia (China) where selenium consumption was inadequate before 2020 (Minich, 2022). Selenium blood serum levels in China vary significantly, ranging from 5 to 7800 μg L^{-1}. This variation is largely due to differences in soil selenium content across different regions. Selenium deficiency is observed not only in third world countries, but modern and highly developed countries, and it is important to prevent the deficiency in a timely manner (Lei et al., 2023).

Although this review provides valuable insights into the health benefits of muesli and selenium, several limitations must be acknowledged. First, the study is based on secondary data from existing literature and does not include original empirical analysis. Second, due to the narrative nature of the review, no statistical or meta-analytical methods were applied to quantify the effects. Additionally, variations in selenium bioavailability depending on food source, soil composition, and individual absorption were not deeply explored. Therefore, while the findings suggest promising health benefits, further clinical and population-based research is necessary to validate and generalize these conclusions.

Conclusion

1. The formulation of a selenium-enriched muesli leverages the bioactive properties of selenium, an essential trace element known for its role in antioxidant defense and immune function modulation. Such a product would provide a significant contribution to daily selenium intake, aligning with recommendations from health authorities regarding micronutrient consumption.
2. Incorporating a variety of nutritionally dense ingredients, such as whole grains, nuts, and seeds, facilitates not only a balanced macronutrient profile but also enhances the availability of selenium and other synergistic micronutrients. Selenium is a key nutrient for immune function and thyroid health, yet many are deficient.
3. The review highlights a concerning prevalence of selenium deficiency globally, which is linked to numerous health issues, including cardiovascular disorders, autoimmune diseases, and increased susceptibility to viral infections.
4. Despite promising findings, inconsistencies in current literature regarding muesli's effects on body weight and composition warrant additional research.

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DIETARY HABITS OF LACTATING MOTHERS AND THEIR RELATIONSHIP TO THE OLIGOSACCHARIDE COMPOSITION OF HUMAN MILK: A PILOT STUDY

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Abstract
Human milk is considered the gold standard in infant nutrition, providing essential nutrients and bioactive compounds that are crucial for infant growth and immune system development. Human milk oligosaccharides (HMO) are complex carbohydrates that are synthesised in the mammary glands from glucose, galactose, N-acetylglucosamine, fucose, and sialic acid. Their composition is influenced by maternal diet, especially the intake of carbohydrates such as galactose, glucose and other oligosaccharide precursors. HMO synthesis depends on the availability of maternal monosaccharides, which are shaped by overall carbohydrate intake. According to the Recommendations of the Ministry of Health of the Republic of Latvia (2017) and Nordic Nutrition Recommendations 2023 (Nordic Nutrition Recommendations, 2023), lactating mothers should increase their daily energy intake by approximately 500 – 600 kcal, with the recommended dietary intake for a 2500 kcal diet being 45–50 E% carbohydrates, 10 – 20 E% protein, and 20–35 E% fat. This study analysed the dietary habits of 25 lactating mothers in Latvia and their impact on HMO composition. Participants' macronutrient intake varied: carbohydrates averaged 51 E% (292–335 g day^{-1}), fat 35 E% (89–220 g day^{-1}), and protein 14 E% (80–136 g day^{-1}). The findings revealed excessive sodium intake and insufficient iodine intake. Saturated fat intake exceeded recommendations, while MUFA and PUFA were within acceptable limits. The results suggest that limited intake of dietary fibre, lactose and galactose-rich products may reduce the availability of key elements required for HMO biosynthesis. Increased dietary diversity and better access to key HMO precursors could improve the oligosaccharide profile in human milk.
Keywords: maternal nutrition, HMO synthesis, 72-hour food diaries, breastfeeding.

Introduction

Human milk is ideal food for infants, providing the nutrients for growth and health benefits for the young one (Ackerman, 2018). According to the World Health Organization (WHO) guidelines, infants are recommended to be exclusively breastfed for the first six months of life (WHO, 2023). WHO reports that only 44% of infants worldwide aged 0–6 months were exclusively breastfed in 2022. According to statistical data in Latvia, in 2022, 16.1% of infants were breastfed, while in 2023, only 15.7% of infants aged 0 to 6 months were exclusively breastfed (SPKC, 2025). In this context, the term 'breastfeeding' refers to the provision of human milk, whether directly from the breast or via bottle-feeding of expressed milk, as defined in public health monitoring. This statistical usage centres on nutritional intake and does not distinguish the emotional or physiological aspects of breastfeeding. One of the most significant advantages of breastfeeding is its effectiveness in protecting against gastrointestinal infections, a benefit seen in both developing and industrialized nations. Additionally, starting breastfeeding within the first hour after birth helps protect the newborn from infections and reduces the risk of neonatal mortality (WHO, 2023). These protective effects are increasingly attributed not only to immunoglobulins and cells in human milk but also to complex bioactive compounds such as human milk oligosaccharides (HMO), which play a critical role in shaping the infant gut microbiota and supporting immune development (Bode, 2012; Donovan & Comstock, 2016). HMO are complex carbohydrates that are synthesised in the mammary glands from glucose, galactose, N-acetylglucosamine, fucose, and sialic acid. Their composition is influenced by maternal diet. The relationship between maternal diet and HMO composition suggests that maternal diet is associated with changes in HMO composition and diversity, and some effects are dependent on maternal secretory status (Selma - Royo et al., 2022). HMO are found in relatively high quantities in human milk. After lactose, they represent the highest concentration of carbohydrates (Sadovnikova et al., 2021). The HMO concentration is estimated to be between 5 and 15 g L^{-1} in human milk samples (Mainardi et al., 2023). HMO are produced in the mammary glands of lactating women through glycosyltransferases. These enzymes add monosaccharide units to a lactose core, creating complex oligosaccharides (Chen, 2015). HMO are elongation products which can combine five different monosaccharides into more than 150 different HMO structures (Urashima et al., 2018). Fructosyltransferase – 2 (FUT2) synthesis corresponding gene influences the production and secretion of fucosylated HMO, such as 2'-fucosyllactose and 3-fucosyllactose (Neu, 2024). Individuals with an active FUT2 gene, have a greater presence of fucosylated oligosaccharides in human milk. This enhances protection against pathogens and supports the growth of *Bifidobacterium spp*. in the intestines (Bondue, 2019).

To promote the secretion and production of oligosaccharides in human milk, lactating mothers are encouraged to include fibre-rich products and prebiotic foods in their diet (Selma - Royo et al., 2022). Consuming fruits, vegetables, whole grains, legumes, nuts, and seeds can support healthy maternal gut microbiota, which may influence the composition of human milk (Selma - Royo et al., 2022). A healthy gut microbiota is crucial for determining the overall makeup of human milk, including HMO (Mokhtari et

al., 2024). In addition, fermented foods such as yogurt, kefir, sauerkraut, and kimchi, can introduce beneficial bacteria into the maternal gut (Favara et al., 2024). It is also important to incorporate omega-3 and omega-6 fatty acids into the diet by consuming healthy fats from sources such as fatty fish (salmon and mackerel), flaxseed, chia seeds, and walnuts (Favara et al., 2024). However, more research is needed to fully understand the direct impact of diet on HMO composition; maintaining a balanced intake of these fats is essential for overall health (Conlon & Bird, 2014). To enhance the understanding of how maternal nutrition influences the composition of HMOs, this study will focus on how specific dietary components may affect the diversity and concentration of HMOs.

Materials and Methods

Study design

The study was conducted from October 2024 to January 2025, during which 72-hour food diaries were collected from 25 mothers who were exclusively breastfeeding one infant aged 1 to 6 months, from various municipalities in Latvia. Prior to participation, each mother signed an informed consent form. Personal background data were collected for each participant, including maternal age and weight, delivery method, smoking habits, duration of pregnancy, infant's birth weight, sex, and age. Participants were required to complete a food frequency questionnaire (FFQ) adapted from the World Health Organisation Coordinated Survey (WHO, 2023). The questionnaire shows the most common portion sizes in grams together with pictures of each product. These portion images were obtained from the online nutrition analysis programme NutriData (FCD, 2025) and their use was approved by the Department of Nutrition and Sports of the Estonian National Institute for Health Development (NIHD, 2025). The FFQ included food groups such as cereals (including bread, granola, pasta), vegetables, fruits, berries, legumes, mushrooms, nuts, seeds, vegetable oils, milk and dairy products (including lactose-free, plant-based dairy alternatives), meat (their products, offal), eggs. Fish, seafood, fish products, sweets and confectionery, salty snacks (including gluten-free products), as well as condiments (spices, sauces, jams, etc.). It also covered both alcoholic and non-alcoholic beverages along the section on the use of nutritional supplements, including vitamin D, selenium, iron, calcium, zinc, and iodine. The following seven-point scale was used:

- 0 = I never consumed this product in the last week;
- 1 = I consumed it once or twice in the last week;
- 2 = I have consumed it three or four times a week;
- 3 = I have consumed it five to six times a week;
- 4 = I have consumed it once or twice a day;
- 5 = I have consumed it three to four times a day;
- 6 = I have consumed it five to six times a day;
- 7 = I have consumed it more than five times a day.

To analyse eating habits and their possible impact on the composition of human milk, study participants were asked to complete a 72-hour food diary. Study participants recorded the exact amount of food and drink consumed, including the brand name of the consumer product and the portion size (in grams, millilitres or household units, such as tablespoons). The time and context of meals (breakfast, lunch, snacks, dinner), dietary supplements and possible dietary restrictions (e.g. allergies, vegan or vegetarian diet) were also recorded. Calculated energy and nutrient intakes were compared with the Nordic Nutrition Recommendations, European Food Safety Authority and Ministry of Health of the Republic of Latvia (EFSA, 2009; Ministry of Health of the Republic of Latvia, 2017; Nordic Nutrition Recommendations, 2023).

Data analyses

The 72-hour food diaries were analysed using an online dietary analysis programme Nutri Data, version 13 (FCD, 2025). Energy intake was calculated in kilocalories (kcal day^{-1}), and the distribution of macronutrients was analysed to determine the percentage of total energy intake (E%). The fatty acid composition was examined, and saturated fatty acids (SFA), monounsaturated fatty acids (MUFA), and polyunsaturated fatty acids (PUFA) were distinguished to assess compliance with dietary recommendations. Specific attention was paid to the intake of lactose, glucose, dietary fibre, and prebiotic-rich foods due to their relevance to HMO biosynthesis. The study assessed the intake levels of minerals (sodium, potassium, calcium, iron, zinc, iodine, selenium) and vitamins (vitamins A, D, C and E). The bioavailability and interactions of various nutrients (e.g. iodine levels) were examined based on literature sources. Statistical analysis was conducted using SPSS software (version 2013). Descriptive statistics were calculated, and the median was used as the central tendency measure, dividing the data into two equal halves. Results are presented as mean ±standard deviation.

Ethical considerations

The study protocol was approved by the Ethics Committee of Rīga Stradiņš University (2-PĒK-4/616/2024, 21.10.2024.).

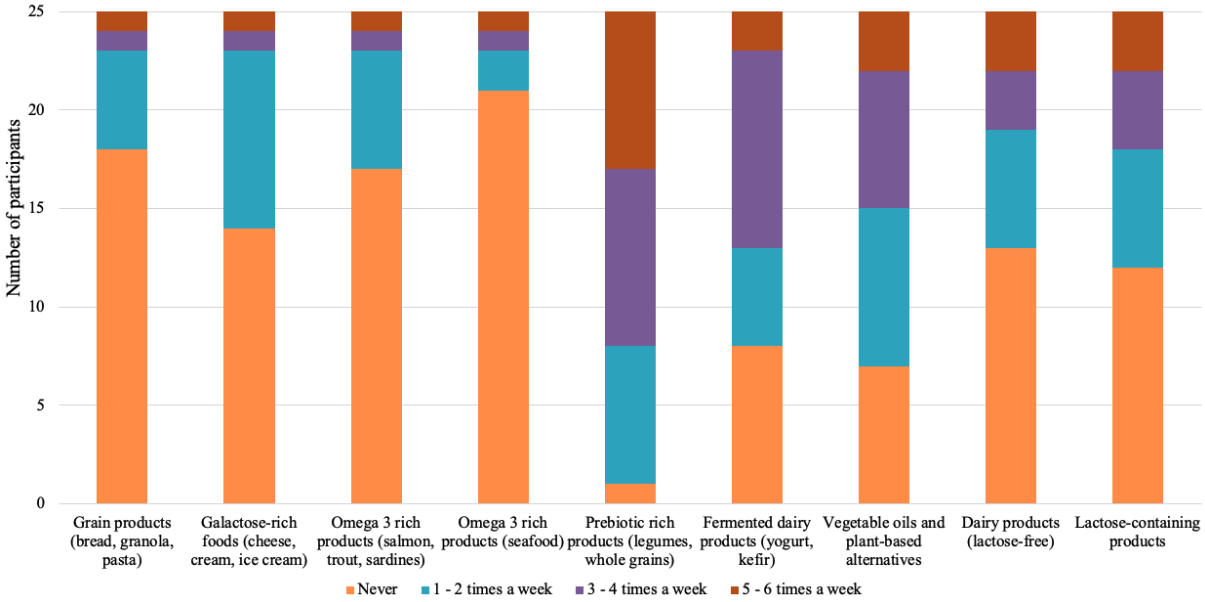
Results and Discussion

A total of 25 lactating mothers participated in the study. The mean maternal age was 31.26 ±4.44 years, ranging from 23 to 38 years. Regarding delivery method, the majority of participants (78.3%) delivered via cesarean section, while 21.7% had a vaginal delivery.

Among the infants, 60.9% were girls and 39.1% were boys. The average neonatal birth weight was 3499.52 ± 447.26 grams, with weights ranging from 3249.5 to 4500 g. Mothers reported an average weight gain during pregnancy of 14.44 ± 5.02 kg (range: 5–30 kg), and their current weight at the time of the study was 69.13 ± 7.45 kg (range: 58–90 kg).

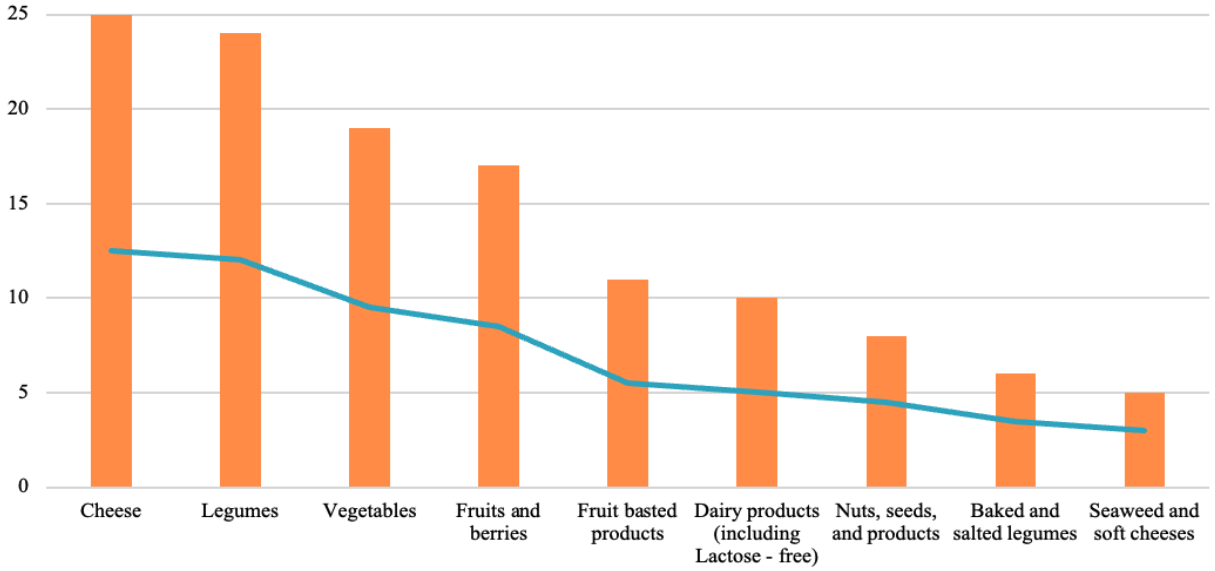
In terms of gestational age at delivery, 96.3% of mothers gave birth between 37 and 41 weeks, while 3.7% delivered at 42 weeks or later.
All twenty-five participants met the inclusion criteria, ensuring reliable and representative results for further analysis. Regarding dietary supplements, 26.1% of participants used multivitamins, 47.8% – omega-3, iodine, iron, and magnesium, while 26.1% did not use dietary supplements due to a lack of information. 21.7% of participants smoked heated tobacco before pregnancy.

Figure 1
Product consumption analysis of HMO-relevant food groups



To better understand the dietary patterns that may influence the biosynthesis of HMO, participants were asked to record the frequency of consumption of key product groups known to provide oligosaccharide precursors or modulate gut microbiota. The following summary, presented in Figure 1, shows the participants who consumed HMO-relevant food products at least once a week, as well as those who did not include these products in their diet. Beverage consumption patterns were analysed among participants, focusing on various beverages, including alcoholic and non-alcoholic beverages. Coffee and caffeinated beverages were consumed regularly by a small proportion of participants. Only 4 participants (16%) reported drinking coffee 1–2 times a week, and 2 participants (8%) drank coffee 3–4 times a week. Coffee or caffeinated beverages were not included in diet of 21 participants (84%). Juices and soft drinks were consumed rarely by participants, with only 4 participants (16%) consuming these beverages 1–2 times a week. Nectars, non-alcoholic cocktails, and flavoured water were consumed by 4 participants (16%) 1–2 times a week, while the majority, 21 participants (84%) did not consume these products at all. Alcoholic beverages were consumed by 1 participant 1–2 times per week, while 24 participants (86%) reported never consuming wine, champagne, or beer.
Figure 2 illustrates the frequency of various food consumption among the 25 participants. The blue line in the graph represents the median frequency of each product group, indicating the middle value at which half of the participants consumed the product more frequently and half less frequently. This visualisation helps to identify typical consumption patterns and outliers within the group, particularly for food categories relevant to HMO precursor intake such as fibre, lactose, galactose and probiotic products.
Fiber-rich foods, such as whole grains, legumes, fruits, vegetables, nuts, and seeds, were consumed by a limited number of participants; more than half of the participants (60%) reported never using the products as shown in Figure 2, while 12% (3 participants) consumed seaweed and soft cheese products (cottage cheese bars), 1–2 times a week.
In addition, 20% (5 participants) reported using fermented dairy products 3–4 times a week, while 8% (2 participants) indicated using it 5–6 times a week. Dietary restrictions among the participants varied: 13% avoided milk and lactose, 8% followed a vegan diet, 4% avoided legumes, 4% excluded honey, onions, and spicy foods, 4% abstained from sweets and flour, and 4% did not consume meat. Nuts, seeds, and their products were consumed by 8 participants (32%). In comparison, 4 participants (16%) consumed them 1–2 times a week, 2 participants (8%) consumed these products 3–4 times a week, and 2 participants (8%) indicated that they consumed nuts or seeds 5–6 times a week, while 4 (16%) participants did not include these products in their diet at all.

Figure 2
Daily nutrient intake among participants in comparison to dietary recommendations



Blue line represents the median frequency of each product group.

Compared to the Nordic Nutrition Recommendations (Nordic Nutrition Recommendations, 2023), the recommendations include at least 90 grams of whole grains, 20–30 grams of nuts per day^{-1}. Dairy products (yogurt, cheese, cottage cheese, sour cream) were consumed by 10 participants (40%), 7 participants (28%) consumed them 1–2 times a week, and 3 participants (12%) consumed them 3–4 times a week. The remaining 14 participants (56%) reported that they did not include these products in their diet. High lactose products, such as milk, cream, and ice cream, were also rarely consumed, 16 participants (64%) reported that they never consumed ice cream, while 6 participants (24%) consumed it 1–2 times a week, and 1 participant (4%) – 5–6 times a week. The Nordic Nutrition Recommendations (Nordic Nutrition Recommendations, 2023) recommend a daily intake of at least 350–500 milliliters of milk or dairy products.
Galactose sources, such as seaweed and soft cheeses (Brie, Camembert), were consumed 1–2 times a week by 20 participants (80%), while 5 participants (20%) included these cheeses in their diet 3–4 times a week. Legumes, such as beans, peas, and lentils, were consumed by 8 participants (32%), with 15 participants (60%) reporting consuming them 1–2 times per week, while only 1 participant (4%) reported consuming them 3–4 times per week. The remaining 8 participants (32%) reported never consuming legumes. Seaweed, which is also a source of galactose, was consumed by only 1 participant, while 24 participants (96%) reported never consuming them. Five participants (20%) consumed baked and salted legumes, and four (16%) reported using them occasionally. Although berries and vegetables are not direct precursors in the biosynthesis of HMO, their intake may indirectly influence HMO composition and concentration in human milk. HMO synthesis relies on monosaccharides derived from maternal carbohydrate metabolism, not directly from dietary sources. However, berries and vegetables provide fibre and bioactive compounds that can modulate the maternal gut microbiota and metabolic status, potentially affecting the secretion of HMO. Through their impact on the diet–microbiota–metabolic axis, these foods may help create favourable conditions for HMO production. Vegetables were one of the most consumed food groups, with 19 participants (76%) reporting their intake and an average daily intake of approximately 64.6 grams. Fruits and berries were consumed by 17 participants (68%), with an average intake of 55.9 grams per day. However, processed fruit processing products, such as juices, jams and dried fruits, were consumed by only 11 participants (44%), with an average intake of 11.5 grams per day. Compared to the Nordic Nutrition Recommendations (Nordic Nutrition Recommendations, 2023), which recommend a minimum daily intake of 500–800 grams of vegetables, fruits and berries combined, the intake reported in this study is significantly below the recommended range.

Analysis of 72-hour diary records

Although this study did not include a direct analysis of the HMO profile in the human milk, dietary data collected using 72-h food records provide a solid basis for assessing the potential for HMO biosynthesis. HMO are synthesised in the mammary gland using maternal monosaccharides such as glucose, galactose, fucose, and sialic acid. These precursors are derived from the maternal diet and metabolism, which means that specific dietary patterns, particularly the intake of lactose, galactose-containing foods, dietary fibre, and omega-3 fatty acids, may influence the diversity and abundance of HMO structures.

Table 1
Comparison of Macronutrient Distribution with Recommended Guidelines

Dietary Group	***Observed Intake (g day^{-1}), median range (g day^{-1}, E% range)***	***Ministry of Health of the Republic of Latvia, 2017, Ministry of Health of the Republic of Latvia, 2022 (g day^{-1}, E% range)***	***Nordic Nutrition Recommendations, 2023 (g day^{-1}, E% range)***	***EFSA, 2013, EFSA, 2010a, 2010b; EFSA, 2012 (g day^{-1}, E% range)***
Energy, kcal	2044 - 3642 2843	2460 – 3150	2500 – 2800	2650 – 2790
Carbohydrates	292 – 335 313.5 35-50	281 – 406 45 – 60	450 – 600 50 - 60	 45 - 60
Protein	80 – 136 108.0 12 – 22	 10 – 20	71.5 – 99 10 - 20	69
Dietary Fibre	17-45 31.0 3.33 – 4.9	25 – 35 1.6 – 2.9	≥25 1.7 – 2.8	25
Sugars, added	50 – 130 90.0 9.7 – 14.3	n.i ≤10	n.i ≤10	n.i
Glucose	15.2 15.2 1.7 – 2.5	n.i	n.i	n.i
Fructose	19.4 19.4 2.1 – 3.4	n.i	n.i	n.i
Lactose	11.6 11.6 1.1 – 1.9	n.i	n.i	n.i
Maltose	3.8 3.8 0.3 – 0.9	n.i	n.i	n.i
Sucrose	44.3 44.3 4.9 – 7.3	n.i	n.i	n.i
Galactose	0.22 0.22 0.0 – 19.8	n.i	n.i	n.i
Fat	89 – 220 154.5 35 - 56	56 - 97 25 – 30	56 - 97 20 – 35	 20 - 30
Saturated fatty acids (SFA)	7 – 24 15.5 3 – 6	 ≤10	 ≤ 10	n.i
Mono-unsaturated fatty acids (MUFA)	10 – 19 14.5 4 – 4.7	n.i.	 10 – 20	n.i.
Poly-unsaturated fatty acids (PUFA)	4 – 12 8.0 2 – 3	n.i.	 5 - 10	 6 - 10

[a] No information.

By examining the frequency and quality of maternal intake of these key components, this study provides valuable insight into how dietary habits may support or limit optimal HMO synthesis during lactation. The participants' daily energy intake was within the acceptable recommendations with an average of 2843 kcal, which is close to the recommended median of 2775 kcal (Ministry of Health of the Republic of Latvia,

2017) and 2650 kcal (Nordic Nutrition Recommendations, 2023; EFSA guidelines, 2022). Carbohydrate intake was generally adequate with a mean intake of 313.5 g day^{-1}, which is in line with the Ministry of Health of the Republic of Latvia recommendations of 343.5 g day^{-1}, adequate intake of total carbohydrates does not ensure sufficient availability of specific monosaccharides, for example, galactose and glucose, which are key precursors in HMO biosynthesis (Urashima et al., 2018). The intake of individual sugars varied substantially among participants. Median daily intakes were glucose 13.6 day^{-1} (range: 4.8–35.4 g), fructose 14.3 day^{-1} (0.0–44.2 g), lactose 11.6 day^{-1} (0.0–30.0 g), maltose 1.8 day^{-1} (0.2–17.6 g), and sucrose 40.9 day^{-1} (3.7–95.4 g). Sucrose contributed the largest share of total sugar intake. Galactose intake exhibited the highest degree of variability among all measured sugars, ranging from 0.0 to over 141 day^{-1}, highlighting the heterogeneous nature of participants' dietary patterns. While the median total sugar intake was approximately 90 day^{-1}, galactose — a key monosaccharide involved in HMO biosynthesis — contributed only minimally, with a median intake of 0.22 day^{-1}. Lactose, another major HMO precursor, averaged 11.6 day^{-1}, further illustrating the limited dietary supply of substrates required for endogenous HMO production. This imbalance suggests that high total sugar intake does not necessarily translate into greater availability of HMO-relevant monosaccharides. Notably, sugar intake in this cohort exceeded the recommended limit for added or free sugars (≤10% of total energy intake). However, the reported values reflect total sugar intake, including intrinsic sugars such as lactose and galactose, which are metabolically distinct from added sugars. The data reflect substantial variation in the consumption of dairy products, fermented foods, and specific fruits and vegetables. In several cases, the complete absence or minimal intake of galactose may constrain the endogenous supply of critical monosaccharides required for HMO synthesis in the mammary gland. Consequently, the relatively low and inconsistent consumption of lactose- and galactose-rich foods may not only limit overall HMO biosynthetic capacity but specifically impair the formation of core structures such as 2'-fucosyllactose and lacto-N-neotetraose. These findings underscore the potential dietary influence on interindividual variation in HMO profiles in human milk (Mokhatari et al., 2024). Protein intake among the participants was insufficient, with an average of 108 g day^{-1}, which is approximately 30 g day^{-1} less than the 141 g day^{-1} recommended in the Nordic Nutrition Recommendations. Dietary fibre intake reached an acceptable level, averaging 31 g day^{-1}, which is in line with the Ministry of Health of the Republic of Latvia of 30 g day^{-1} and slightly exceeding the EFSA recommendation of 25 g day^{-1}. Nevertheless, the overall intake of prebiotic rich products, for example legumes, whole grains and fermented products, was insufficient. Dietary fibre and prebiotic rich foods support maternal gut microbiota diversity (Favara et al., 2024). A healthy microbiota may influence the composition and complexity of HMO through immune system modulation and substrate availability (Selma - Royo et al., 2022). Fat intake was significantly above the recommended level, with the average intake being 154.5 g day^{-1}, which is almost twice the recommended 76.5 g day^{-1} set by the Nordic Nutrition Recommendations. Saturated fatty acid (SFA) intake was elevated, averaging 15.5 g day^{-1}, exceeding the recommended maximum of <10% of total energy intake (E%) per day. Excess saturated fat intake combined with insufficient omega – 3 may disrupt maternal lipid metabolism and immune responses, which are increasingly recognised as factors influencing sialylated HMO synthesis, particularly during early lactation (Favara et al., 2024). In addition, fermented dairy products like yogurt and kefir contribute to beneficial bacterial populations in the maternal gut microbiota. These bacteria may indirectly stimulate oligosaccharide production and influence the HMO profile in milk. Iodine deficiency among participants may also impair the enzymatic activity in the mammary gland, potentially limiting glycosylation processes critical for complex HMO production (Aumeistere et al., 2022). Polyunsaturated fatty acids (PUFA) and monounsaturated fatty acids (MUFA) were consumed within acceptable limits, median range 8 g and 14.5 g day^{-1}. Adequate intake of healthy fats may support overall immune regulation and could influence the profile of immunodulatory HMO as sialylated oligosaccharides (Favara et al., 2024). In addition to assessing dietary adequacy, this discussion focuses on how specific nutrient patterns may promote or limit the biosynthesis of HMO in human milk, based on current biochemical understanding and literature.

Analysis of 72-hour macroelement records

Potassium intake ranged from 2558 to 4824 mg day^{-1}, with only 3 participants reaching the optimal intake of 2800 mg day^{-1}. Iodine intake ranged from 0.062 to 0.401 mg day^{-1}, with 50% of participants below the recommended 0.29 mg day^{-1}, same situation was observed by Aumeistere et al. (2018) study. Calcium, which is essential for bone and tooth development (Vannuccit et al., 2018), ranged from 854 to 2089 mg day^{-1}, with 50% of participants partially meeting the recommended intake of 900 mg day^{-1} (Ministry of Health of the Republic of Latvia, 2017). Sodium intake among participants ranged from 1691 to 5443 mg day^{-1}, with 90% of participants exceeding the recommended limit of 2300 mg day^{-1}. Factors influencing sodium levels in human milk include lactose concentration and postpartum duration (Aumeistere et al., 2020).

Iron intake is critical for haemoglobin production (Friel et al., 2018) and ranged from 8 to 31 mg day^{-1}, with 30% of participants meeting the recommended 15 mg day^{-1} for lactating women (Ministry of Health of the Republic of Latvia, 2017).

Table 2
Comparison of macro and micronutrient distribution

Dietary Group	***Observed Intake (mg day^{-1}), median range (mg day^{-1})***	***LR Ministry of Health, 2017 (mg day^{-1})***	***Nordic Nutrition Recommendations, 2023 (mg day^{-1})***	***EFSA, 2015, EFSA 2016, EFSA 2017 (mg day^{-1})***
Potassium	2558 – 4824 3691	3100	2900	3500
Iodine	0.062 – 0.401 0.23	0.15 – 0.25	0.29	0.25
Calcium	854 – 2089 1471.5	900	1300	950
Sodium	1691 – 5443 3567	2300	1500	2000
Iron	8 – 31 19.5	15	13	15
Magnesium	170 – 450 310	280	400	310
Zinc	8.6 – 33 20.8	11	13	7.0 – 9.5
Selenium	0.048 – 0.127 0.087	0.06	0.07	0.07
Vitamin A	0.69 – 1.71 1.20	1.1	1.1	1.1
Vitamin D	0.0036 – 0.349 0.17	0.15	0.02	0.02
Vitamin C	95 – 110 102.5	100	120	115 – 120
Vitamin E	8.5 – 66 37.25	19.0	19	19

Magnesium intake among participants ranged from 170 to 450 mg day^{-1}, with the majority meeting or exceeding the recommended intake of 280 mg day^{-1}. Zinc intake ranged from 8.6 to 33 mg day^{-1}, with 80% of participants meeting the appropriate intake. Selenium intake was adequate in 95% of cases, ranging from 0.048 to 0.127 mg day^{-1}, reaching the recommended 0.06 mg day^{-1} (Ministry of Health of the Republic of Latvia, 2017). Vitamin A median intake was 1.20 mg day^{-1} which slightly exceeds the recommended daily allowance intake 1.1 mg day^{-1} for lactating women (Ministry of Health of the Republic of Latvia, 2017. Vitamin D intake ranged from 0.0036 to 0.349 mg day^{-1}, with 45% reporting inadequate intake and some exceeding the upper limit of 0.01 mg day^{-1} due to supplementation of diet with vitamin D dietary supplements. Vitamin C intake generally exceeded the recommended 100 mg day^{-1}, contributing to collagen synthesis and wound healing (Hollis et al., 2019; Bechara et al., 2022). Vitamin E intake was inadequate in 90% of participants, with the majority consuming less than 11 mg day^{-1} compared to the recommended 19 mg day^{-1}.

Conclusions

1. The limited intake of specific galactose rich and lactose containing foods indicates a potential restriction in the availability of key monosaccharides required for human milk oligosaccharide biosynthesis.
2. This dietary pattern indicates insufficient intake of both oligosaccharide precursors and prebiotic components that influence maternal gut microbiota, which may impact HMO diversity and functionality in human milk.
3. Enhanced dietary diversity including regular consumption of fibre, galactose and lactose rich products, and fermented products could improve the availability of substrates and microbial modulators necessary for the formation of immunologically active structurally diverse HMO.

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EFFECT OF SELECTED LACTIC ACID BACTERIA ON BUCKWHEAT BEVERAGE FERMENTATION

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Abstract
The buckwheat (*Fagopyrum esculentum*) has been an essential food ingredient for centuries. Fermentation of buckwheat using lactic acid bacteria (LAB) provides an opportunity to improve its nutritional value and bioavailability of nutrients and develop new functional beverages. This study investigated the effect of selected strains of LAB on the fermentation of buckwheat beverage base, analyzing pH changes, LAB growth patterns and sugar profile changes prior to and at the end of fermentation. Buckwheat samples were prepared at 8% and 10% (w v^{-1}) aqueous suspensions, with further sample inoculation with *Lactobacillus plantarum subsp. plantarum, Lactobacillus acidophilus, Lacticaseibacillus paracasei subsp. paracasei, Lacticaseibacillus rhamnosus* strains. The fermentation was carried out at 37 °C for a maximum of 8 hours, analyzing samples after 2, 3, 4 and 8 hours of fermentation. The initial pH of the buckwheat suspension was 7.57 (8% buckwheat base) and 7.44 (10% buckwheat base) depending on the concentration. During the first 4 hours of fermentation, the pH decreased rapidly in all samples. At the end of fermentation, the pH varied from 4.34 to 4.17 in all samples. The growth of LAB during fermentation was monitored using the plate count method. Faster growth of the studied LAB strains was observed in buckwheat (10%) substrate samples with added *L.plantarum* and *L.paracasei* from 8.59 to 8.75 $\log_{10}$CFU mL^{-1}. With the mentioned strains, the sucrose content in buckwheat samples decreased during fermentation, i.e. by 57%. The results show that lactic acid bacteria induced fermentation help to produce nutrient-rich buckwheat-based beverages.
Keywords: buckwheat, lactic acid bacteria, fermentation, sugars.

Introduction

Fermented foods and beverages are estimated to make up 1/3 of human diet (Mota de Carvalho et al., 2018). The consumption of fermented products in the daily diet can provide 1.0 % of the gut's commensal microbiota, with 10^{10} to 10^{11} bacteria being ingested (Tsafrakidou et al., 2020). Fermentation significantly increases the nutritional value of buckwheat (*Fragopyrum esculentum*), increasing the bioavailability of nutrients, reducing anti-nutritional factors, and adding beneficial compounds synthesized via fermentation.

The chemical composition of buckwheat consists of 63% carbohydrate, including 9.9% fiber, 11.7% protein, 2.4% fat, 11% water and 2% minerals, as well as balanced amino acid composition, abundant vitamin P and rutin, which reduce cholesterol content in the blood and makes buckwheat an almost perfect food (Mahata, 2018). The sucrose content in buckwheat grains is generally lower than in leaves and reaches of up to 48.13 g kg^{-1} total solids (Nešović et al., 2021). However, the amount of sucrose can vary between different buckwheat varieties under the same growing conditions, and the ripening time of the grains also depends on the genetic characteristics of the varieties (Nešović et al., 2021). The protein composition and technological properties of buckwheat grains indicate that buckwheat is an excellent raw material for gluten-free and vegan-friendly food product production. Buckwheat's energy value, protein and carbohydrate content are equivalent to wheat, while the fiber content is 40% higher and the fat content is 60% higher than wheat. 100 g of buckwheat contains 110 mg of calcium, 4 mg of iron, and magnesium, phosphorus and manganese are significantly higher than wheat (Pirzadah & Malik, 2020). Buckwheat is characterized with low glycemic index. The complex carbohydrates found in buckwheat are absorbed slowly into the bloodstream, providing longer satiety and supporting energy (Mahata, 2018).

New functional plant-based foods with probiotics are still being developed. Plant-based foods help probiotic bacteria reach the intestinal tract targeted due to the presence of indigestible fiber, such as cellulose (Küçükgöz & Trząskowska, 2022). Fermented plant-based products are becoming increasingly popular dairy analogous due to the absence of lactose or allergic proteins, lower saturated fats, also environmental and economic aspects should be taken into consideration (Hidalgo-Fuentes et al., 2024).

This study investigated the effect of *Lactobacillus plantarum subsp. plantarum, Lactobacillus acidophilus, Lacticaseibacillus paracasei subsp. paracasei, and Lacticaseibacillus rhamnosus* on the fermentation of buckwheat and fermentation outcomes.

Materials and Methods

The research was carried out at the Food Institute and Valmiera Technical School. The grain specimens under examination were harvested in 2024. The unprocessed green buckwheat variety 'AIVA' was purchased from the local producer (Kaņepītes, Latvia). Buckwheat beverage base was prepared with different grain concentrations - 8 % buckwheat (w v^{-1}) (coded as A), and 10% (w v^{-1}) (coded as B). The buckwheat was mixed with tap water, and boiled for 20 minutes. The insoluble buckwheat particles were separated through a sieve (size diameter 2 mm). The clarified beverage base was sterilized at 121 °C for 15 minutes in the sterilizer (Systec D-65, Systec GmbH, Germany), after sterilization the samples were cooled down to fermentation temperature 37 °C.

Single strain DVS starter cultures (Mediterrania Biotechnologie, Italy) - LBP 10 U *(Lactobacillus*

plantarum subsp. plantarum), LA 10 U *(Lactobacillus acidophilus)*, LCP 10 U *(Lacticaseibacillus paracasei subsp. paracasei)*, LCR 10 U *(Lacticaseibacillus rhamnosus)* were used for the study. 0.02 U of starter cultures were used for 1000 ml of the substrate inoculation. The fermentation process was provided up to reaching pH 4.3-4.5 at 37 ºC temperature using BD 23 serial incubator (Binder, Germany).

The pH of the substrate was analyzed initially and further every 2-3 hours during the fermentation, and the colony forming units of lactic acid bacteria were determined initially and after 4 and 8 hours of fermentation.

Microbiological analyses

Lactic acid bacteria were determined using MRS medium (Scharlau, Spain). Incubation of plates was provided in anaerobic conditions (37 °C, 72 hours) at an aerostat using anaerobic sacket BSM (Merck KGaA Darmstadt, Germany). MRS agar was prepared within LVS CEN ISO/TS 11133 – 1:2009. Pepton water was used for the preparation of corresponding dilutions. Microbiological analyses were performed in a laminar flow cabinet Biological Safety Cabinet SHANDONG 11237 BBC 86 (BIO BASE, China). The horizontal method of microorganism counting was used according to the LVS EN ISO 4833-1:2014 (ISO, 2014). After incubation, the colony forming units (CFU) of probiotic bacteria were determined using the automatic colony counter SCAN500 (INTERSCIENCE, France), and software version 8.6.12.0 v3.4 (INTERSCIENCE, France). The results were expressed in $\log_{10}$CFU mL^{-1}.

pH

The pH was measured using Milwaukee MW102-FOOD digital pH meter (Milwaukee Electronics Kft., Hungary). The electrode was calibrated with pH 4.00 and pH 7.00 buffer solutions. To ensure accuracy, each sample was tested in three replications.

Sugar analyses

Sugar analyses were conducted using high-performance liquid chromatography (HPLC). Buckwheat suspension samples were centrifuged for 10 min at 15000 rpm in Microtube PrO-Research Centrifuge (UK). 10 µL of the sample was injected into HPLC system Shimadzu. The equipment utilized included a Shimadzu LC-20 Prominence system chromatograph (Shimadzu Corporation, Japan) equipped with a photodiode M20A detector, LC-20A solvent delivery system, CBM-20A system controller, and LC solution data system software (Shimadzu Corporation, Japan). The chromatographic separation was carried out, using a deionised water as mobile phase at a flow-rate of 1.0 mL min^{-1} maintaining the column temperature at 40 °C. Peak areas were utilized for quantitative analysis. The calibration curves were prepared for raffinose or sucrose (Merck, USA) solution in water. Sugar (sucrose and raffinose) analyses were compared with the control sample - buckwheat substrate (B) without fermentation.

Statistical analysis

The Microsoft Excel 2013 software, designed for Windows 11, version 10.0.6.1000 operating systems, was employed for data processing. The pH, sugar, LAB CFU analyses were prepared in three replications, the mean value and standard deviation were calculated. A one-way analysis of variance (ANOVA) and Tukey's test were employed to assess the data. The resulting p-value indicated whether a statistically significant difference existed among the samples, with the significance level defined as $p < 0.05$.

Results and Discussion

The results of pH analyses are shown in Table 1. *L. acidophilus*, *L. paracasei* and *L. rhamnosus* metabolize carbohydrates, producing lactic acid and other metabolites, lowering the pH from 7.57 to 4.17 in the samples during 8 hours of fermentation. In samples with 8 and 10% of buckwheat grains, the pH decreases more rapidly within 4 or 8 hours. Zhou et al., 2022 indicated that a significant drop in pH was achieved during 8-12 hours of fermentation, while other researchers (Cardinali et al., 2021) found pH lower than 4.2 during 24 hours. It depends on the amount of dry matter in the buckwheat base, the fermentation temperature and the amount of starter added. For instance, Cardinali et al. (2021) reported initial pH values of 6.95 to 7.42 for different buckwheat bases. This difference could be due to variations in buckwheat species, solids and substrate preparation methods.

The pH values ranged from 4.20 to 4.60 (Cardinali et al., 2021; Kowalska & Ziarno, 2020) compared to our study where pH changed from 4.17 up to 4.88 at the end of fermentation. The study results on fermented oat and buckwheat beverages showed that pH of around 4.30 - 4.40 was well-accepted by consumers (Salman, 2024). Some studies have found that pH drops below 4.00 can negatively impact sensory properties and probiotic viability. After 4 hours of fermentation in 8% buckwheat substrate samples, the growth of probiotic bacteria ranged from 7.30 to 8.49 $\log_{10}$CFU mL^{-1} (see Table 2). In contrast, a higher LAB growth was found in 10% buckwheat substrate samples, where LAB ranged from 7.67 to 8.75 $\log_{10}$CFU mL^{-1}.

After eight hours of fermentation, the probiotic bacteria CFU in samples ranged from 8.54 to 8.97 $\log_{10}$CFU mL^{-1}, but the rapid growth of LAB was noticed in samples fermented with *L. plantarum* and *L. paracasei*.

Results are expressed as mean value ± standard deviation (n = 2). Significant differences between LAB CFU in fermented buckwheat after 4 and 8 h fermentation in columns are marked with different lower letters. Tukey HSD test $p \leq 0.05$.

L. plantarum and *L. paracasei* are widely used in sourdough bread production due to their ability to adapt different environmental conditions (di Renzo et al., 2018). *L. plantarum* is efficient in utilizing various sugars (Figure 1), contributing to rapid fermentation (Wang & Ma, 2024).

Table 1
The changes of pH during fermentation

Single strain culture	***Buckwheat sample***	***Fermentation time, h***				
		0	***2***	***3***	***4***	***8***
L. plantarum	A	7.57±0.01	6.26±0.01	5.27±0.02	4.90±0.00	4.31±0.01
L. acidophilus			6.35±0.02	5.23±0.01	4.96±0.00	4.26±0.01
L. paracasei			6.00±0.02	5.08±0.01	4.86±0.01	4.17±0.01
L. rhamnosus			7.08±0.01	6.85±0.00	6.34±0.01	4.98±0.01
L. plantarum	B	7.44±0.01	5.48±0.01	4.85±0.01	4.34±0.01*	-
L. acidophilus			5.51±0.00	4.95±0.00	4.55±0.01*	-
L. paracasei			5.46±0.01	4.82±0.01	4.55±0.01*	-
L. rhamnosus			6.66±0.02	5.54±0.01	5.00±0.01	4.72±0.01

*Fermentation process was finished reaching pH 4.30-4.50.

Table 2
Effect of single strain cultures on fermentation patterns

Single strain culture	***Buck-wheat sample***	***log₁₀ CFU mL⁻¹***	***log ₁₀ CFU mL⁻¹***
		4 h	***8 h***
L. plantarum	A	8.32±0.42^{c}	8.97±0.45^{a}
L. acidophilus		7.76±0.39^{b}	8.54±0.43^{a}
L. paracasei		8.49±0.42^{c}	8.95±0.45^{a}
L. rhamnosus		7.30±0.37^{b}	8.56±0.43^{a}
L. plantarum	B	8.75±0.44^{b}	8.97±0.45^{a}
L. acidophilus		7.83±0.39^{ab}	8.54±0.43^{a}
L. paracasei		8.59±0.43^{b}	8.95±0.45^{a}
L. rhamnosus		7.67±0.38^{a}	8.56±0.43^{a}

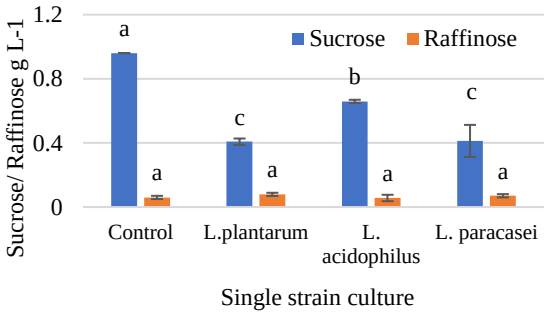
In fermented buckwheat beverage production, *L. plantarum* reached up to 8-9 $\log_{10}$CFU mL^{-1} after 6 hours of fermentation (Matejčeková et al., 2017), but in oat drinks fermented with *L. plantarum*, 8 $\log_{10}$CFU ml^{-1} were reached after 24 hours of fermentation (Gokavi et al., 2005). Likewise, *L. acidophilus* LACA 4 in the peanut-soy milk beverage production reached above 8 $\log_{10}$CFU mL^{-1} after 24 hours of fermentation (Valero-Cases et al., 2020). The lactic acid bacteria growth during fermentation influences the composition of the substrate, selected fermentation patterns.

In general, LAB strains typically reach populations of 7-10 $\log_{10}$CFU mL^{-1} in plant-based beverages during fermentation, with slight variations depending on the specific substrate and fermentation conditions (Salman, 2024). The growth patterns are similar across different plant-based media, including buckwheat, oats, and various fruits and vegetables.

After four hours of fermentation, the sucrose content in the samples decreased rapidly by 31–57%, but after eight hours the reduction was only 27%. Sucrose presents in significant amounts in buckwheat, particularly in the leaves, but it is also found in the grains. The sucrose and raffinose content in buckwheat substrate samples were analysed before and after fermentation. In the control sample the sucrose content was 0.958 g L^{-1} and the raffinose content - 0.056 g L^{-1}. During the first four hours, the sucrose content in buckwheat samples significantly decreased (Figure 1).

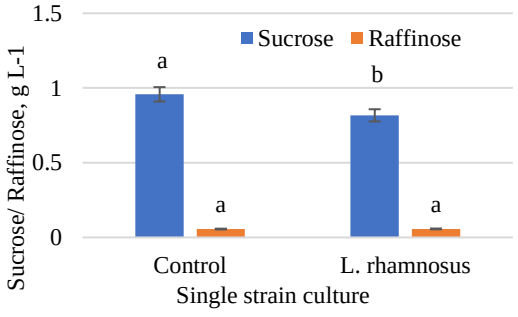
Also, changes were observed in the raffinose concentration due to pH and the LAB strain chosen. Some LAB strains can metabolize raffinose, others may not be efficient, such as *L.plantarum* and *L.paracasei* (Sanyal et al., 2023).

Figure 1
The changes of sucrose and raffinose content in buckwheat substrate samples (B) after 4 hours of fermentation



Results are expressed as mean value ± standard deviation (n = 4). Significant differences between sucrose and raffinose in fermented buckwheat substrate samples after 4 hours are marked with different lower letters (Tukey HSD test p≤0.05).

Figure 2
The changes of sucrose and raffinose content in buckwheat substrate samples (B) after 8 hours of fermentation



Results are expressed as mean value ± standard deviation (n = 4). Significant differences between sucrose and raffinose in fermented buckwheat substrate samples after 8 hours are marked with different lower letters (Tukey HSD test $p \leq 0.05$).

The acidity level after 4 hours of fermentation was pH=4.35-4.55, and after 8 hours of fermentation pH=4.72-4.75. The difference between both groups is not statistically significant $p \leq 0.05$. A greater reduction of sucrose was observed in samples with *L. plantarum* and *L. paracasei*. In contrast, after 8 hours of fermentation in samples with *L. rhamnosus* sucrose concentration was decreased only 27% (Figure 2). The ability of *L. rhamnosus* to metabolize sucrose might be limited compared to other sugars (Bertsch et al., 2020). *L. rhamnosus* GG efficiently metabolize glucose and fructose but has limited ability to metabolize lactose and sucrose (Corcoran et al., 2005; Bertsch et al., 2020), which could be an explanation of our results, as well as longer fermentation process due to availability of sugars for energy balance and multiplication.

Conclusions

In this study, single strain cultures were used to evaluate the buckwheat base fermentation ability with *L. plantarum*, *L. paracasei*, *L. acidophilus* and *L. rhamnosus* strains.

1. The study found that fermentation causes significant changes in pH and LAB growth during fermentation. *L. plantarum* and *L. paracasei* showed the highest potential, indicating their potential for the development of buckwheat beverages.
2. The rapid decrease in pH indicates a fastened fermentation, which influenced also the dose of added starter.
3. The changes of sucrose and raffinose were analyzed during buckwheat substrate fermentation. A reduction of sucrose from 27 to 57% was established by *L. plantarum, L. acidophilus, L. paracasei and L. rhamnosus.*

Acknowledgements

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ANALYSIS OF THE LANDSCAPE STRUCTURE AND OPTIMALITY OF THE CAPITAL REGION OF LITHUANIA

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Abstract
Problems related to landscape structure optimality typically involve challenges in balancing ecological, social, and economic needs while ensuring sustainability. The study utilized diverse scientific methodologies, including comparative analysis, grouping techniques, analytical approaches, statistical data analysis, and graphical representation. Formula calculations assessed natural and cultivated land proportions in Lithuania's Capital Region, evaluating deviation from the optimal ratio and determining optimality class. The study also examined landscape changes from 2004 to 2024. The analysis revealed that during this timeframe, the natural landscape expanded by 3.66 percent, the anthropogenic landscape increased by 12.55 percent, but the anthropogenized landscape decreased by 5.36 percent. When evaluating the composition of the Capital Region landscape, it becomes apparent that in 2024, the predominant portion of the country's terrain was characterized by natural landscape (47.89 percent), while the smallest proportion was attributed to anthropogenic landscape (7.43 percent), with anthropogenized landscape encompassing 44.68 percent of the Capital Region of Lithuania. Additionally, calculations were conducted, determining that the ratio of relatively natural land to cultivated land in the Capital Region, denoted as Rns, equaled 1.99. Upon assessing the relative deviation of the Capital Region of Lithuania from the optimal ratio value (Dr), it was determined to be Dr = 1.22, indicating that the region falls within optimality class A2.
Keywords: natural landscape, anthropogenized landscape, anthropogenic landscape, landscape optimality.

Introduction

Nature has created remarkably consistent geomorphic patterns on Earth's surface, which are often attributed to the optimal functioning of natural processes (Paik & Kumar, 2010).

Landscape perception plays a crucial role in the field of landscape studies. Within this, landscape preference represents an integral aspect, reflecting the combined outcomes of various perceptual processes (Cai et al., 2022).

The importance of landscape structure in regulating biodiversity and ecosystem services in agricultural landscapes is increasingly recognized. It comprises two primary components: landscape composition, which pertains to the variety and quantity of habitats, and landscape configuration, which relates to the shapes and spatial arrangement of these elements. Together, these components interact to influence ecological outcomes (Ali et al., 2023).

The concepts of 'ecosystems' and 'landscapes' focus on the horizontal dimension of the Earth's surface and highlight the integration of structures, processes, and functions (Luo et al., 2019).

The landscape offers essential resources such as food, water, and materials to support societal development. It also plays a vital role in regulating various phenomena and processes within a region, while providing numerous cultural and recreational opportunities (Bechera et al., 2023).

When discussing the functions performed by the landscape, its multifunctionality should be mentioned. Multifunctionality refers to the diverse beneficial functions that a landscape provides, spanning from a particular site or neighboring areas (local scale) to an entire region (regional scale). It encompasses various sets of landscape functions related to production, cultural, or ecological aspects. These functions represent a landscape's potential and capacity to sustainably meet fundamental, enduring, and socially validated material or non-material human needs (Galler et al., 2015).

The essential contribution of ecosystems to human well-being is broadly recognized, underscoring the importance of prioritizing the long-term conservation of multifunctional landscapes (Rodriguez-Loinaz et al., 2015).

The growing demand for land resources to deliver multiple benefits requires landscape strategies that optimize the provision of various ecosystem services. While previous research has primarily focused on changes in land use composition, the spatial configuration of different land use types also plays a key role in driving the supply of ecosystem services (Boesing et al., 2024).

Ecosystem service provision at any specific location within a landscape can be heavily influenced by its surrounding environment. Therefore, both landscape composition and configuration (the way various land use types are arranged) are essential in shaping multifunctionality (Duarte et al., 2018).

Environmental degradation has emerged as a major obstacle to sustainable development and global human well-being. Consequently, scientific efforts are directed at understanding the mechanisms behind environmental degradation and advancing sustainability. Critical Zone science and research on multifunctional landscapes are developing fields within Earth science that have the potential to support these efforts (Luo et al., 2019).

Research on landscape structure and its optimality is becoming increasingly relevant.

Landscape optimality is typically interpreted through a system of core anthropo-ecological criteria based on

land management methodologies. Landscape management is built on the creation of planning zones that apply different land use, protection, and management measures to achieve an optimal spatial structure. At the national level, the optimality of landscape structure should be assessed according to the alignment with strategic macro-zones, which are designed to balance ecological compensation and economic activity in accordance with the universal ʻgolden ratioʼ (~60:40) (Veteikis et al., 2016).

With the sustainable development of the modern world, the process of urbanization is accelerating. This urbanization has greatly altered the types and spatial structure of landscapes, leading to corresponding ecological impacts. During the development process, various challenges are often encountered, with ecological issues being among the most significant. These ecological problems are frequently caused by changes in the spatial structure of ecological landscapes. As contemporary urbanization continues to accelerate and deepen, the types and structures of ecological landscapes have undergone substantial transformations. However, these changes in the spatial structure of ecological landscapes inevitably impact the ecological environment (An, 2022).

To strike a balance between landscape conservation and the changing demands for land use and natural resources, it is essential to incorporate the ecological, socio-cultural, and economic values of the landscape into planning and decision-making. Landscape planning requires assessing various competing demands for often limited space. In this process, economic factors, especially financial considerations, tend to play a dominant role, often overshadowing ecological and socio-cultural values (De Groot, 2006).

The object of article is landscape structure of the Capital Region of the Republic of Lithuania.

The goal is to evaluate the optimality of the landscape structure in the Capital Region of the Republic of Lithuania.

Tasks to be carried out:

1. to examine the transformations in the natural, anthropogenized, and anthropogenic landscapes of the Capital Region between 2004 and 2024;
2. to determine the ratio of relatively natural and cultivated land in the Capital Region (Rns);
3. to evaluate the landscapeʼs optimality in the Capital Region of the Republic of Lithuania and its classifications.

Materials and Methods

To determine the optimality of the Capital Region landscape structure, an analysis of scientific articles related to the topic was conducted. The study provides a comparative analysis of changes in the areas of natural, anthropogenized, and anthropogenic landscapes between 2004 and 2024.

Using the grouping method, the components of these three landscape types were categorized, and changes in their areas were examined. The natural landscape components include forests, water bodies, and wetlands, while the anthropogenized landscape encompasses areas altered by human activities but still retaining some natural features. The anthropogenic landscape refers to fully human-modified land uses.

The analysis focuses on evaluating the area changes for each landscape category, utilizing data from relevant land fund statistics. The analysis was based on data from the Land Fund of the Republic of Lithuania for the period 2004–2024. Additionally, the percentage and hectare distribution of the Capital Region landscape types in 2024 were assessed.

The study also analyzed the ratio of relatively natural to cultivated land in the Capital Region.

Furthermore, the relative deviation (Dr) of the landscape structure in the Capital Region from the optimal ratio was calculated, and the optimality class was determined based on a reference table outlining the classification criteria for natural and artificial land use.

In addition to these methods, the study employed analytical and logical analysis approaches. Graphical representation techniques were used, with seven figures and one table included in the article.

Results and Discussion

The transformation of landscape areas in the Capital Region

This work analyzes the change in the areas of three types of landscapes in the Capital Region and the optimality of their structure.

The Capital Region of the Republic of Lithuania covers the entire territory of the Vilnius County, which spans an area of 972,981.51 hectares. This region consists of eight municipalities, six of which are district municipalities.

The transformation of the natural landscape

Changes in the natural landscape involve key elements such as forests, water bodies, and wetlands. Trends in forest cover provide a useful indicator of shifts in landscape naturalness. In the Capital Region, forests span 413,843.23 hectares, representing 42.53% of the total area. Between 2004 and 2024, forest cover increased by 22,096.80 hectares, reflecting a growth of 5.64%.

In 2024, water bodies accounted for 31,453.58 hectares or 3.23% of the region. From 2004 to 2024, their area grew by 841.57 hectares, an increase of 2.75%.

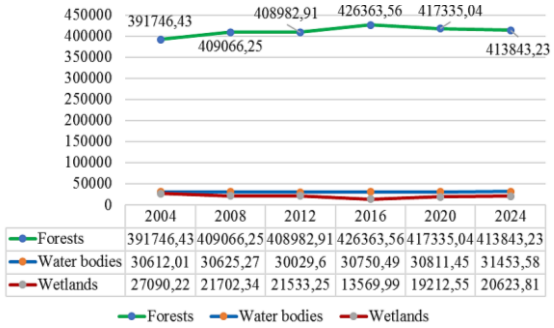
Conversely, wetlands, which are among the most vital and natural components of the landscape, experienced a significant decline over the same period. In 2004, wetlands covered an area of 27,090.22 hectares, providing critical habitats for diverse species, regulating water flow, and serving as natural buffers against floods. However, by 2024, this area had shrunk to 20,623.81 hectares, representing a loss of 6,466.41 hectares, equivalent to a staggering 23.87% reduction. This sharp decline could be attributed to factors such as urbanization, agricultural expansion, drainage for

land development, and possibly the impacts of climate change. The loss of wetlands not only diminishes biodiversity but also undermines their essential ecological services, such as carbon sequestration, water purification, and flood mitigation, highlighting an urgent need for conservation and restoration initiatives to address this critical issue.

So this analysis highlights that while forests and water bodies expanded between 2004 and 2024, wetlands experienced a notable reduction ‘Figure 1’.

Figure 1

The change in the area of natural landscape components from 2004 to 2024



	2004	2008	2012	2016	2020	2024
Forests	391746,43	409066,25	408982,91	426363,56	417335,04	413843,23
Water bodies	30612,01	30625,27	30029,6	30750,49	30811,45	31453,58
Wetlands	27090,22	21702,34	21533,25	13569,99	19212,55	20623,81

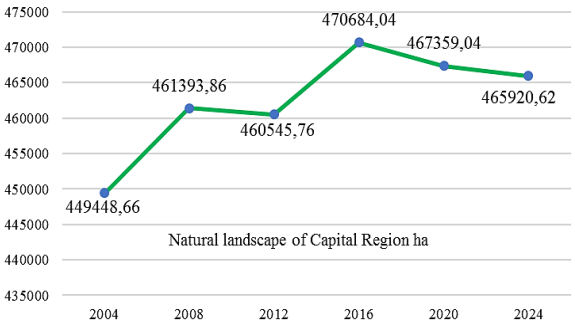
(Nacionaline…, 2004–2024).

Overall, the natural landscape in the Capital Region increased by 16,471.96 hectares, marking a 3.66% rise during this period ‘Figure 2’.

The natural landscape area has grown as a result of the expansion and development of forests and water bodies. This increase is driven by factors such as afforestation and reforestation projects, stricter conservation efforts, and natural processes. The water

Figure 2

Changes in the natural landscape area (in hectares) in the Capital Region from 2004 to 2024



(Nacionaline…, 2004–2024).

bodies area growth reflects the impact of natural processes, conservation efforts, and possibly human interventions aimed at restoring or creating aquatic ecosystems. Such an increase underscores the significance of water bodies in enhancing biodiversity, improving water resource availability, and supporting a balanced ecosystem in the region.

As forests regenerate and new water bodies form, the overall area of natural landscapes has expanded, contributing to improved biodiversity, climate regulation, and ecosystem stability.

Change in the area of anthropogenized landscape.

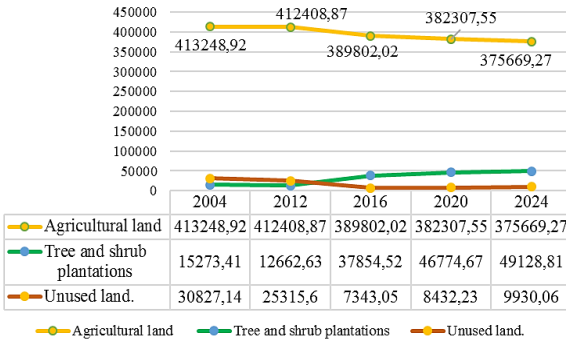
Changes in the area of anthropogenized landscape refer to the modifications in the environment brought about by human activities.

The anthropogenized landscape can include various components, such as agricultural land (arable land, orchards, meadows and natural pastures), tree and shrub plantations, and unused land.

Between 2004 and 2024, the area of agricultural land in the Capital Region decreased by 37,579.65 hectares, representing a 9.09% decline ‘Figure 3’. This significant reduction reflects broader trends in land-use changes, largely driven by human economic activities and shifting priorities in land management. As urbanization accelerates and the demand for residential, commercial, and industrial development grows, agricultural land is increasingly being repurposed for other uses, such as housing, infrastructure, and industrial zones.

Figure 3

The change in the area of anthropogenized landscape components from 2004 to 2024



	2004	2012	2016	2020	2024
Agricultural land	413248,92	412408,87	389802,02	382307,55	375669,27
Tree and shrub plantations	15273,41	12662,63	37854,52	46774,67	49128,81
Unused land.	30827,14	25315,6	7343,05	8432,23	9930,06

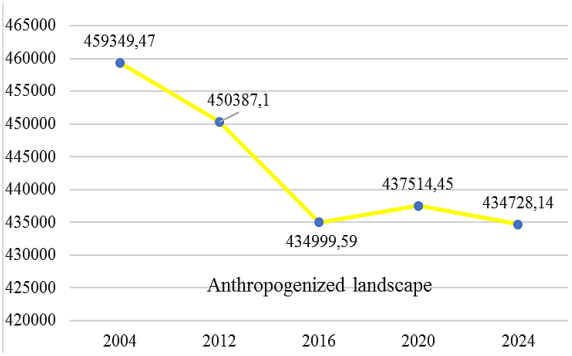
(Nacionaline…, 2004–2024).

The decline in agricultural land is a clear indication of the ongoing transformation of the region’s landscape, where natural and rural areas are gradually giving way to urban expansion and economic development. The conversion of farmland into built-up areas not only reduces the land available for food production but also affects local ecosystems, biodiversity, and the region’s capacity to provide ecosystem services such as carbon sequestration, water filtration, and soil fertility maintenance.

During the same period, the area covered by trees and shrubs increased significantly by 33,855.40 hectares, or 221.66%, primarily due to the expansion of green spaces and the implementation of afforestation programs.

Meanwhile, the area of unused land in the Capital Region shrank by 20,897.08 hectares, or 67.79%.
An analysis of these changes in the components of the anthropogenized landscape reveals that, between 2004 and 2024, agricultural land and unused land in the Capital Region declined, while areas covered by trees and shrubs grew substantially.
From 2004 to 2024, the anthropogenized landscape experienced a total area reduction of 24,621.33 hectares, equating to a 5.36% decrease ‘Figure 4’.
The decrease in the area of anthropogenic landscape was caused by the reduction of agricultural land abandonment and unused land areas.

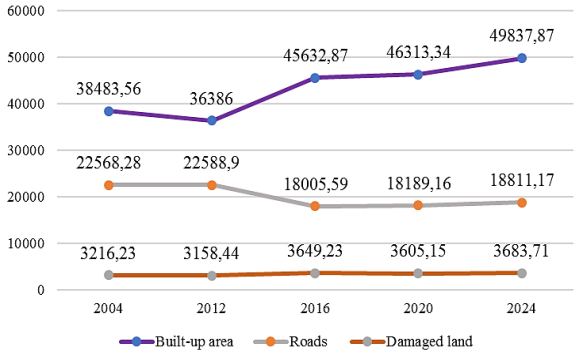
Figure 4
Changes in the anthropogenized landscape area (in hectares) in the Capital Region from 2004 to 2024



(Nacionaline…, 2004–2024).

Change in the area of anthropogenic landscape
The anthropogenic landscape comprises built-up areas, roads, and damaged land. Between 2004 and 2024, built-up areas in the Capital Region expanded by 11,354.31 hectares, a growth of 29.50%, reaching a total of 49,837.87 hectares in 2024.
Built-up areas are increasing due to urbanization, population growth, economic development, and rising demand for housing and infrastructure.
According to the Land Fund of the Republic of Lithuania (Nationaline…, 2004-2024), it was found that between 2004 and 2024, the road area in the Capital Region decreased by 3,757.11 hectares, or 16.65%. By 2024, the road area covered 18,811.17 hectares.
The observed decrease in road area can be attributed primarily to inaccuracies in the theoretical calculations conducted before 2015. These earlier estimates likely lacked precision and did not fully reflect the actual situation on the ground. However, a significant methodological improvement occurred in 2015 with the introduction of cadastral measurements, which provided a more accurate and detailed assessment of land use.
Since the adoption of cadastral measurements, the data on areas occupied by roads have been updated annually, ensuring a more reliable and up-to-date representation of road infrastructure. As a result, the apparent reduction in road area should not be interpreted as a physical decline in road infrastructure but rather as a correction stemming from improved measurement techniques. Therefore, the decrease in road area is considered conditional and reflects adjustments in data accuracy rather than actual changes in land use.
Between 2004 and 2024, the area of damaged land in the analyzed region increased by 467.48 hectares, or 14.54% ‘Figure 5’.

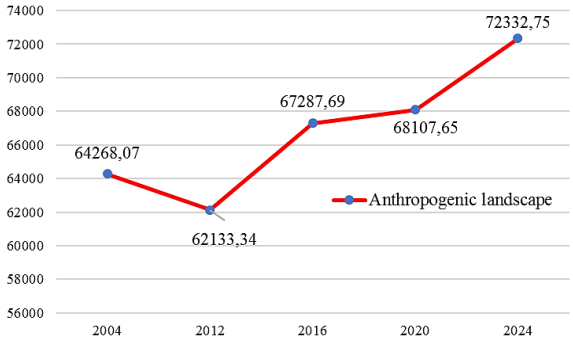
Figure 5
The change in the area of anthropogenic landscape components from 2004 to 2024



(Nacionaline…, 2004–2024).

Before Lithuania joined the European Union, numerous legal and illegal landfills operated across the country, including the Capital Region. With the introduction of a waste collection and disposal system, the Kazokiškės landfill in the Capital Region was opened in 2007. In 2013, the second section of the Kazokiškės landfill was launched.
The increase in damaged land areas was also influenced by the establishment of mineral extraction quarries. During the analyzed period in the Capital Region, mineral extraction began in the following quarries: Miškiniai gravel and sand, Papiškiai, Daniliškiai sand and gravel, Margis gravel, Bijūnai gravel, Gudakiemis gravel and sand, Šventininkai gravel and sand, Pagiriai-Kaišialakiai gravel and sand, Zujūnai gravel, Serapiniškės sand and gravel, Račkūnai deposit sand and gravel, Gojaus sand resources, Pašiliai sand and gravel deposit, Būda II sand and gravel, Vaidegiai sand and gravel, Dobrovolė II sand and gravel, Mačiuliškiai sand and gravel, Merešlėnai deposit sand and gravel, and other quarries.
After analyzing the changes in the Capital Region’s anthropogenic landscape between 2004 and 2024, it was found that the area increased by 8,064.68 hectares, or 12.55% ‘Figure 6’.
The increase in the anthropogenic landscape area is primarily due to the development of built-up areas (29.50%) and damaged land (14.54%). Together, these two factors have driven the overall increase in the anthropogenic landscape, highlighting the ongoing transformation of natural and rural areas into spaces dominated by human activity.

Figure 6
Changes in the anthropogenic landscape area (in hectares) in the Capital Region from 2004 to 2024

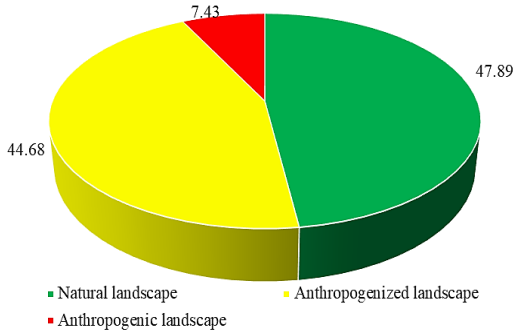


(Nacionaline…, 2004–2024).

This trend underscores the need for sustainable development strategies to balance human needs with environmental conservation.

After analyzing the landscape of the Capital Region, it was found that in 2024, the natural landscape covered the largest portion of the region (47.89% or 465,920.62 hectares), while the smallest portion was occupied by the anthropogenic landscape (7.43% or 72,332.75 hectares). The anthropogenic landscape in 2024 accounted for 44.68% of the region's total area ‘Figure 7’.

Figure 7
The distribution of landscape types in the Capital Region by percentage in 2024



While the dominance of natural landscapes is indicative of the area’s ecological richness, the presence of anthropogenic landscapes reflects the region’s economic and societal development. Striking a balance between these contrasting land uses remains crucial for ensuring sustainable development and environmental conservation in the region.

Examination of the proportion of relatively natural versus cultivated land in the Capital Region

The analysis of the ratio of relatively natural and cultivated land in Capital Region involves examining the proportion of land that remains in its natural state versus the land that has been modified for agricultural or human use. Relatively natural land refers to areas with minimal human intervention, such as forests, wetlands, and other natural ecosystems. Cultivated land includes agricultural areas like arable land, orchards, and pastures, as well as areas developed for infrastructure.

The methodology for landscape formation, as described by Kavaliauskas et al. (2013), defines the optimal landscape structure of a country based on the geoecological compensation index. According to this approach, 38% of the land should consist of active anthropogenic (human-modified) areas, while 62% should remain passive or relatively natural (Skorupskas & Kavaliauskas, 2007).

A landscape is not considered optimal if the minimum required percentage of natural areas necessary to balance anthropogenic impacts is not achieved.

From the analysis and ‘Figure 7’, it is evident that in 2024, natural areas in Capital Region constituted 47.89% of the landscape, while anthropogenic and anthropogenized areas together accounted for 52.11%.

Given the variety of land uses, the ratio of relatively natural to cultivated land (Rns) can be calculated for any sufficiently large region with defined boundaries using a specific formula:

$$R_{ns} = \frac{P+M+0.5\,A+0.8\,V}{U+T+0.5A+0.2\,V}, \quad (1)$$

where Rns represents the ratio of relatively natural land (numerator fraction) to relatively cultivated land (denominator fraction) within the territory: P denotes wetlands, M represents forests, A stands for agricultural land, U and T refer to urban and technological components, and V signifies water bodies.

After calculating using the given 1 formula, the ratio of relatively natural land to cultivated land (Rns) in Capital Region was determined to be 1.99.

A landscape is considered natural when Rns equals Ro, the optimal ratio value, which is 1.63.

The optimality of a territory’s landscape structure can be evaluated using these formulas:

$$Dr = \frac{Rns}{Ro}, \; when \; Rns > Ro \quad (2)$$

or

$$Dr = -\frac{Ro}{RoRns}, \; when \; Rns < Ro \quad (3)$$

where: Dr is the relative deviation from the optimal ratio value (Ro), Rns is the ratio of relatively natural land to relatively cultivated land within the territory, Ro is the optimal ratio value.

After calculating the Dr value, it was determined that the relative deviation from the optimal ratio value in the Capital Region is 1.22. Once Dr is calculated, the landscape structure’s optimality class can be identified using the criteria outlined in ‘Table 1’.

The Capital Region has been assigned the A2 landscape structure optimality class because, based on the calculations, the landscape structure of this region meets the optimality criteria, but with some deviation from the ideal ratio (A1).

The A2 class indicates that the region has a sufficient amount of natural areas (47.89%), but certain measures may be needed for the protection or further restoration of the natural environment.
The study shows that urbanization is occurring in the Capital Region – during the 2004-2024 period, the area of built-up land increased by 29.50%, and the total area of anthropogenic landscape increased by 12.55%. If urbanization in this region continues at such a rapid pace, it may pose a threat to the landscape structure.

Table 1
Determining the optimality class of a site based on the deviation of its natural and artificial land use ratio from the ideal value

Ratio of natural and cultivated land (R_{ns})	***R_{ns} deviation from optimal value (D_r)***	***Optimality classes***
>78.25	>48.00	A6
13.37...78.24	8.01...48.00	A5
3.27...13.36	2.01...8.00	A4
2.46...3.26	1.51...2.00	A3
1.97...2.45	**1.21...1.50**	**A2**
1.631...1.96	1.00...1.20	A1
1.629...1.36	-1.00...-1.20	B1
1.35...1.09	-1.21...-1.50	B2
1.08...0.82	-1.51...-2.00	B3
0.81...0.20	-2.01...-8.00	B4
0.19...0.03	-8.01...-48.00	B5
<0.03	<-48.00	B6

(Lietuvos Respublikos aplinkos..., 2015).

To maintain the landscape structure of Capital Region and ensure its optimality, the following measures should be taken:

- Protect natural areas: to maintain the portion of natural land, it is essential to ensure the protection of existing forests, wetlands, water bodies, and other natural ecosystems.
- Management of agricultural activities: sustainable agricultural practices need to be implemented to reduce the negative impact of agriculture on the landscape and nature. This includes promoting organic farming and managing the intensity of agricultural land use.
- Encourage a mosaic landscape by avoiding monocultural landscapes: the preservation of mixed lands (forests, meadows, agricultural areas) should be encouraged, as they can ensure biodiversity and ecosystem services.
- Control of urbanization: the development of intensive urbanization and infrastructure in natural areas should be limited to maintain landscape integrity and balance the ratio of natural and anthropogenic lands.
- Landscape planning and management: it is essential to consider the condition of the region's ecosystems, their conservation, and sustainable use.
- Education and public involvement: raising public awareness about the importance of landscapes and encouraging local residents and businesses to contribute to environmental conservation, particularly in environmental protection initiatives and sustainable land use.

Conclusions

1. Between 2004 and 2024, the natural landscape in the Capital Region grew by 16,471.96 hectares, reflecting a 3.66% increase. This expansion was primarily driven by the growth of forests (5.64%) and water bodies (2.75%). During the same period, the anthropogenized landscape decreased by 24,621.33 hectares, a 5.36% reduction. This decline was largely due to the decrease in abandoned agricultural land (9.09%) and unused land areas (67.79%). However, the analysis of changes in the anthropogenic landscape revealed an increase of 8,064.68 hectares, or 12.55%, largely attributed to the growth of built-up areas (29.50%) and damaged land (14.54%).
2. After analyzing the landscape of the Capital Region, it was determined that in 2024, the natural landscape comprised the largest portion of the region (47.89% or 465,920.62 hectares), while the smallest portion was taken up by the anthropogenic landscape (7.43% or 72,332.75 hectares).
3. After calculating the ratio of relatively natural land to cultivated land (Rns) in the Capital Region, it was determined that the Rns is 1.99. Upon calculating the Dr value, it was found that the relative deviation from the optimal ratio value in the Capital Region is 1.22.
4. The Capital Region has been classified under the A2 landscape structure optimality class because, according to the calculations, its landscape structure meets the optimality criteria, albeit with some deviation from the ideal ratio (A1). The A2 class signifies that the region possesses a sufficient proportion of natural areas (47.89%), but some actions may be necessary to safeguard or further restore the natural environment.

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AIR QUALITY IN JELGAVA: IMPACTS OF INDUSTRIAL OPERATIONS

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Abstract
Air pollution in urban areas remains a critical challenge, particularly in densely populated cities. Industrial activities contribute significantly to air quality deterioration through the emission of heavy metals and trace elements that pose risks to human health and the environment. This study investigates the spatial variability of air pollution in Jelgava, Latvia, with a focus on areas impacted by industrial emissions. Snow samples were collected across the city to monitor air pollution, with analyses targeting metals such as lead, arsenic, nickel, copper, zinc, and cadmium. Using cluster analysis, regions were categorized by pollution intensity, uncovering distinct spatial patterns. Results indicate that industrial zones and areas near major roadways exhibit significantly elevated concentrations of toxic metals, often exceeding regulatory thresholds. Seasonal variations, particularly increased emissions from winter heating, were found to exacerbate pollution levels. These findings underscore the importance of continuous monitoring, stricter regulations, and targeted pollution control measures to mitigate health risks and environmental impacts. The study emphasizes the need to integrate pollution management into urban planning and public health policies, providing a foundation for informed decision-making and sustainable urban development. By identifying pollution hotspots, this research provides a foundation for informed decision-making to minimize health risks and promote sustainable urban development in Jelgava. Additionally, the use of snow sampling as a cost-effective and practical method for monitoring airborne pollutants offers valuable insights for other cities facing similar challenges.
Keywords: air pollution, heavy metals, urban monitoring, emissions.

Introduction

Air pollution from industrial activities is a critical environmental and public health concern, particularly in urban areas where industrial facilities are located near residential populations (Zhang et al., 2022). The emission of trace metals, including lead (Pb), cadmium (Cd), nickel (Ni), zinc (Zn), arsenic (As) and copper (Cu), from industrial processes can have severe health implications, as these metals are known to be toxic even at low concentrations. Chronic exposure to airborne heavy metals has been linked to respiratory diseases, cardiovascular issues, neurological disorders, and developmental impairments, especially in vulnerable populations such as children and the elderly (Kampa & Castanas, 2008). According to recent studies, particulate matter (PM2.5) is often enriched with these trace metals, enhancing their ability to penetrate deep into the respiratory system and increasing associated health risks (Guo et al., 2022).

In urban centres worldwide, industrial sources such as metal smelting, waste incineration, and chemical manufacturing contribute significantly to the atmospheric load of heavy metals (Janta et al., 2020). A study conducted in China's zinc smelting districts, for example, demonstrated high concentrations of heavy metals in air and soil, emphasizing the health risks posed to nearby communities (Zheng et al., 2010). Similarly, urban centres in Europe have also reported elevated levels of heavy metals near industrial zones, highlighting the global nature of this environmental issue (Ahmed et al., 2021). In Latvia, as in other European Union member states, air quality is regulated by strict limits on pollutant concentrations to protect public health. However, data on trace metal concentrations in ambient air are limited, particularly in cities with significant industrial activity like Jelgava. Jelgava, an industrial hub in Latvia, hosts a variety of industrial operations that potentially contribute to heavy metal emissions, affecting air quality and posing health risks to its residents. Past research has highlighted the challenges in monitoring and managing trace metal emissions, given the complex interactions of industrial, transportation, and seasonal sources (Martiņsone, 2011).

The aim of this study is to analyse the spatial distribution of trace metal concentrations in Jelgava city using cluster analysis to identify zones with varying pollution levels. By employing snow sampling as a proxy for air pollution, the study will assess concentrations of heavy metals and examine the influence of proximity to industrial sources on these concentrations. This approach will provide a detailed understanding of pollution hotspots in the city, enabling the identification of areas at higher risk of exposure. The findings will contribute to the development of targeted pollution mitigation strategies and inform future monitoring and regulatory policies in Jelgava.

Materials and Methods

Jelgava is one of the largest cities in Latvia and serves as a significant centre of the Zemgale region. The city is located on the banks of the Lielupe River, approximately 40 kilometres from the capital, Riga. Jelgava hosts a range of industrial enterprises with key activities concentrated in metal processing, chemical production, and related sectors. Samples were collected in December 2020. A total of 59 monitoring points were selected within the city boundaries, along with one control point in a rural area southwest of Jelgava. Sample collection took place following the first snowfall. The snowfall period, which covered sample accumulation, lasted five

days. Samples were collected 5 meters from the road edge. Snow depths at the monitoring points ranged from 7 to 15 cm (SLLC 'Latvian Environment, Geology and Meteorology Centre', 2025).

A steel ring with an inner diameter of 25 cm was used to define the sampling area, ensuring standardized and replicable sampling. The ring was fixed vertically onto the undisturbed snow. Snow samples were collected from the ring into sterile plastic containers using disposable dust-free nitrile gloves and transported to the laboratory. In the laboratory, the collected snow samples were melted and acidified with nitric acid (HNO_3) to a 1% concentration (m/m). After 72 hours, the samples were filtered and analysed.

The samples were analysed by means of an inductively coupled plasma mass spectrometer (ICP-MS, 'Agilent 8900 ICP-QQQ'). The elements analysed included nickel (Ni), copper (Cu), zinc (Zn), arsenic (As), cadmium (Cd), and lead (Pb). For calibration, an ICP-MS standard solution (10 $mg \cdot L^{-1}$, High Purity Standards, ICP-MS-68 A, NIST SRM 3100) was used. The calibration curve was established for concentrations ranging from 0.1 $\mu g \cdot L^{-1}$ to 100 $\mu g \cdot L^{-1}$. A 10 $\mu g \cdot L^{-1}$ internal standard solution containing Bi, Ge, In, Sc, Tb, Y, and Li was used for internal system stability control. Measurements were performed in MS/MS configuration using helium as the collision gas (flow rate of 5 $mL \cdot min^{-1}$) (Grinfelde et al., 2021).

Results and Discussion

Metals – Ni, Cu, Zn, As, Cd, and Pb – are all common pollutants associated with industrial processes.

Figure 1
Sample locations based on clusters

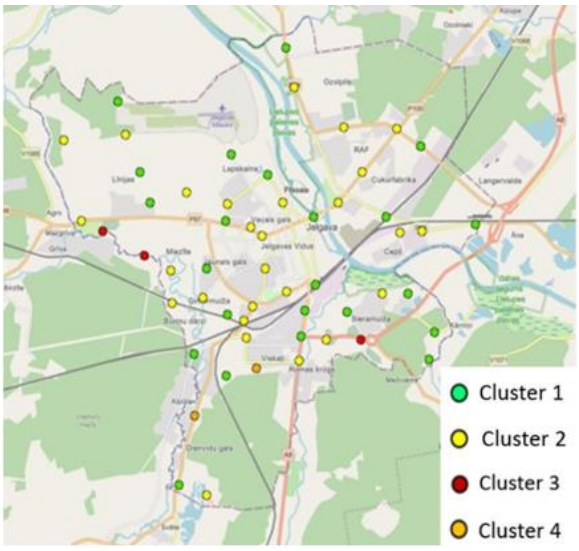


Figure 1 shows a map of Jelgava city with sampling locations categorized by cluster. The clusters are represented by differently coloured markers.

Cluster 1 (green): predominantly low contamination levels, spread across various parts of the city. Most of these points are located on the outskirts and suburban areas, suggesting lower pollution levels due to distance from industrial sources

Cluster 2 (yellow): represents moderate contamination. These points are spread across the city, with some concentration near central and moderately industrialized ar eas, indicating moderate exposure to pollution.

Cluster 3 (red): indicates the highest contamination levels. The red points are concentrated near industrial zones and major roadways, suggesting significant pollution due to proximity to emissions from industrial activities.

Cluster 4 (yellow–red): shows specific metals unique to certain industries, scattered but located near industrial sources. This cluster helps in identifying contamination that may be specific to certain industrial processes.

Figure 2
Ni concentration in each cluster

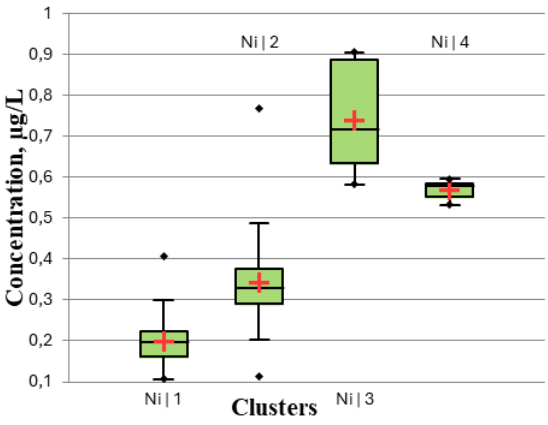


Figure 2 illustrates Ni concentrations in different clusters. It shows that Cluster 3 has the highest nickel concentrations and the greatest variation, with Cluster 2 exhibiting a significantly higher range compared to other clusters. Clusters 2 and 4 demonstrate notably lower Ni concentrations, while Cluster 1 shows the lowest concentrations but still contains some variations. The box plots indicate that Ni levels vary among these clusters, possibly due to industrial activities or proximity to specific pollution sources.

Figure 3 shows the concentration of Cu in each cluster. Cluster 3 has the highest concentration, with values reaching up to 14 $\mu g \cdot L^{-1}$, indicating a significant pollution source in that area. Clusters 2 and 4 show a moderate concentration, while Cluster 1 has lower values. These variations in Cu concentrations suggest different levels of industrial or environmental influence across the clusters, with Cluster 3 likely being the most impacted by Cu emissions.

Figure 4 shows the concentrations of Zn across the clusters. Cluster 3 has the highest concentration of Zn,

with a range extending up to approximately 30 $\mu g \cdot L^{-1}$, suggesting a significant pollution source in this area. Cluster 2 exhibits moderate Zn concentrations, with values ranging between approximately 5 and 20 $\mu g \cdot L^{-1}$. Cluster 1 has very low Zn concentrations compared to others, indicating minimal environmental or industrial impact. Cluster 4 also shows low Zn concentrations, with very narrow variability, likely reflecting a negligible source of Zn pollution. These patterns may correspond to varying levels of industrial activity, traffic density, or natural environmental factors influencing each cluster.

Figure 3
Cu concentration in each cluster

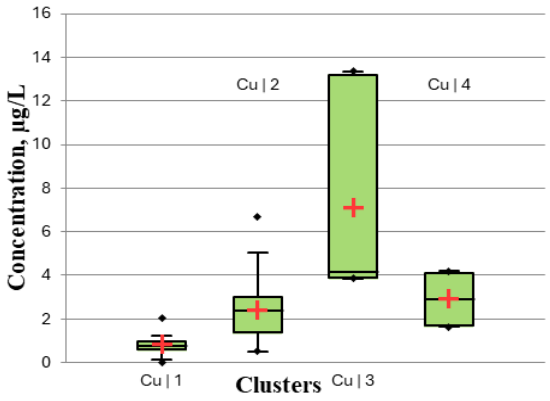
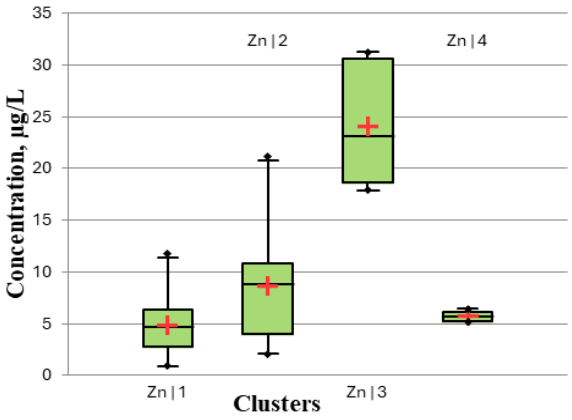
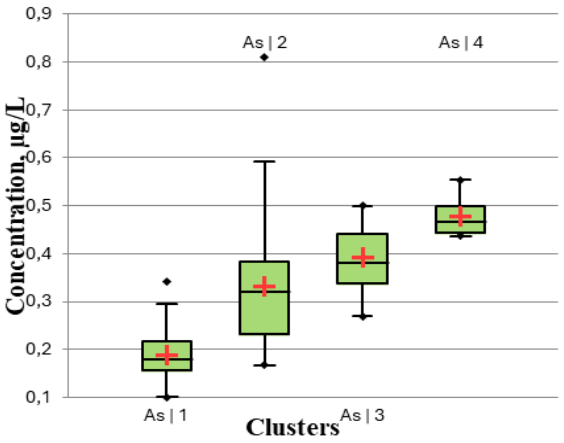


Figure 4
Zn concentration in each cluster



The results of As concentration analysis in clusters are represented in Figure 5. Cluster 1: As concentration is the lowest among all clusters, with values centred around 0.1 to 0.2 $\mu g \cdot L^{-1}$. The range is minimal, indicating low variability and consistent environmental conditions with limited As pollution sources. This cluster may represent less industrialized or rural areas. Cluster 2: the highest As concentration is observed in this cluster, with values reaching up to 0.8 $\mu g \cdot L^{-1}$. There is a wide range of As levels, with an outlier indicating potential localized pollution spikes. This cluster likely includes significant pollution sources, such as industrial activities or agricultural runoff, as several monitoring points in cluster 2 are located near agricultural areas (monitoring points located along Lithuanian highway). Cluster 3: moderate As concentrations are seen in this cluster, with values ranging between 0.2 and 0.6 $\mu g \cdot L^{-1}$.

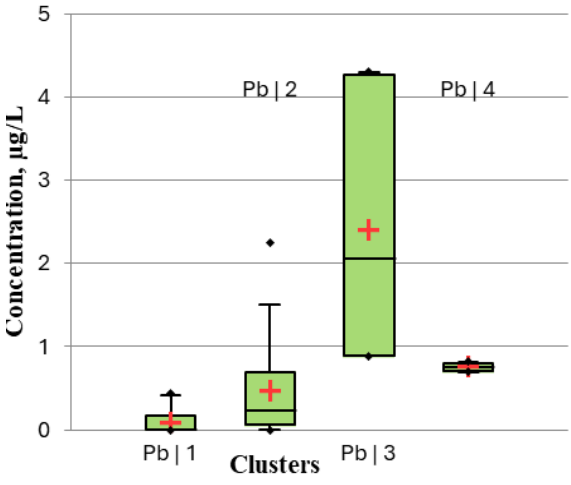
Figure 5
As concentration in each cluster



The wider interquartile range reflects variability in As levels, possibly due to mixed land-use or multiple pollution sources. The cluster indicates the presence of moderate human or industrial activity. Cluster 4: the As concentration in this cluster is the highest and relatively stable, ranging between 0.3 and 0.4 $\mu g \cdot L^{-1}$. The narrower range suggests consistent pollution levels, likely from specific localized sources. This cluster reflects moderate human or industrial influence, less variable than Cluster 3.

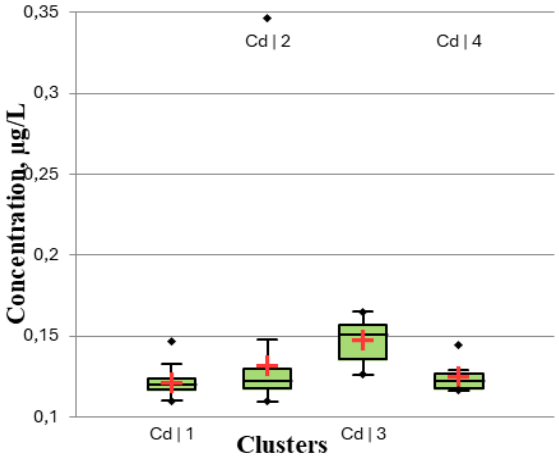
Pb concentration across clusters is illustrated in Figure 6. Cluster 1: minimal pollution. Pb levels are the lowest, around 0.5 $\mu g \cdot L^{-1}$, with minimal variability. Likely represents rural or suburban areas with limited pollution sources.

Figure 6
Pb concentration in each cluster



Cluster 2: moderate pollution. Concentrations reach up to 1 $\mu g \cdot L^{-1}$ with some variability, suggesting mixed pollution sources like vehicle emissions or small-scale industry.
Cluster 3: high pollution. This cluster shows the highest Pb levels, nearly 4 $\mu g \cdot L^{-1}$, with significant variability. Likely linked to heavy industry or traffic emissions, requiring focused mitigation. Cluster 4: low and stable levels. Concentrations are stable around 0.5 $\mu g \cdot L^{-1}$, reflecting limited and consistent pollution sources, possibly from controlled environments.
Cd concentration analysis across clusters is represented in Figure 7. Cluster 1: minimal Cd pollution. Cd levels are low, around 0.1–0.15 $\mu g \cdot L^{-1}$ with minimal variability.

Figure 7
Cd concentration in each cluster



This suggests limited pollution sources, likely representing less industrialized or rural areas. Cluster 2: moderate Cd pollution. This cluster shows slightly higher Cd levels, with occasional outliers reaching up to 0.35 $\mu g \cdot L^{-1}$. The variability indicates potential localized pollution sources, such as industrial runoff or emissions. Cluster 3: consistent but moderate levels. Cd levels are moderate, ranging from 0.1 to 0.2 $\mu g \cdot L^{-1}$, with a tighter range compared to Cluster 2. The relatively consistent levels suggest stable but moderate pollution sources, likely from small-scale industry or urban activities. Cluster 4: stable and low levels. Cd concentrations are similar to Cluster 1, around 0.1 $\mu g \cdot L^{-1}$ with a few outliers. This reflects limited pollution, likely from controlled or natural sources.
The study of heavy metal concentrations in urban environments, particularly in Jelgava, reveals significant spatial variations that are closely linked to industrial activities and road traffic. The findings indicate that areas near industrial zones and major transportation routes exhibit elevated levels of metals such as Pb, Ni, and Cd, often exceeding regulatory limits. This observation is consistent with previous research that has established a strong correlation between proximity to industrial and high- traffic areas and increased pollution levels.
For instance, studies have shown that urban areas with high traffic density and industrial activities tend to have higher concentrations of heavy metals due to emissions from vehicles and industrial processes (Li et al., 2010; Saulnier et al., 2020; Liu et al., 2023).
A noteworthy aspect of this study is the innovative use of snow sampling as a proxy for assessing airborne pollution. Snow acts as a natural accumulator of airborne pollutants, enabling researchers to detect trace metal concentrations effectively in urban environments. This method is particularly advantageous in colder climates where snow cover is prevalent, allowing for a spatially comprehensive assessment of air pollution without the need for continuous air sampling. Previous studies have highlighted the effectiveness of snow sampling in capturing recent emissions, particularly during winter when heating activities and industrial processes are intensified (Berisha et al., 2016; Pilecka et al., 2018; Zhang, 2023). However, it is important to note that the method is limited by seasonal variability, and the timing of sample collection can significantly influence the results (Li et al., 2010; Zhang et al., 2015).
The variations in pollution levels across different clusters suggest that industrial emissions are a primary source of certain metals, particularly Ni and Cu, which are found at elevated levels near industrial facilities. Additionally, the high concentrations of Pb near major roads indicate that vehicular emissions continue to be a significant contributor to urban pollution, despite existing regulations aimed at reducing Pb emissions from transportation sources (Saeedi et al., 2012; Dong et al., 2017). This finding emphasizes the urgent need for targeted pollution control measures in industrial and high-traffic areas to mitigate health risks associated with long-term exposure to these toxic elements (Zhao et al., 2012; Zhong et al., 2015).
While the study provides valuable insights into the spatial distribution of heavy metal pollution in Jelgava, it also acknowledges several limitations that warrant further investigation. Expanding sampling efforts to include other seasons could help determine whether the observed contamination patterns are consistent year-round or specific to winter conditions. Additionally, incorporating other bioindication methods, such as moss or lichen sampling, could complement snow sampling by offering year-round pollution data and enhancing the understanding of trace metal deposition rates over extended periods (Zhao et al., 2012; Berisha et al., 2016).
This research highlights the importance of continuously monitoring air quality in urban centres, particularly those with significant industrial activity. By identifying pollution hotspots, the study offers a basis for informing targeted policy interventions, including the implementation of stricter emission

regulations for industrial sources and the expansion of air quality monitoring efforts in residential zones.
These findings also highlight the importance of integrating environmental considerations into urban planning to reduce human exposure to airborne pollutants, ultimately improving public health outcomes in industrialized cities (Guo et al., 2012; Abah et al., 2014; Kang et al., 2017).

Conclusions

1. The study successfully identified sampling and industrial locations and created corresponding maps. Cluster analysis was conducted, and areas with relatively low, medium, and high concentrations were identified.
2. The study successfully identified specific areas within Jelgava with elevated concentrations of heavy metals, particularly near industrial zones and major roadways. This confirms that industrial activities and vehicular emissions are primary sources of urban air pollution in the city, contributing significantly to Pb, Ni, and Cd levels above regulatory thresholds. Although the Latvian regulatory thresholds apply to annual average concentrations in ambient air and surface waters, these values provide a useful benchmark for evaluating the potential sources and risks of the heavy metals detected in snow samples.
3. Snow sampling proved to be an effective method for assessing airborne pollution, serving as a reliable proxy for detecting trace metals in urban environments. This approach provided comprehensive spatial data on pollution distribution and highlighted the potential of snow sampling as a cost-effective and practical method for air quality monitoring in colder climates.
4. The timing of sample collection, following the first snowfall, indicated that seasonal factors, especially heating during the winter, exacerbated air pollution. This finding underscores the importance of seasonal air quality management, particularly in winter, to address increased emissions from heating and industrial activities.
5. The elevated levels of heavy metals in urban areas near industrial facilities and high-traffic roads present potential health risks for residents, especially vulnerable populations such as children and the elderly. Long-term exposure to metals like Pb and Cd is associated with respiratory, neurological, and cardiovascular health issues, highlighting the need for targeted interventions to reduce human exposure in affected areas.
6. The study highlights the need for enhanced air quality monitoring and stricter regulatory measures to control industrial emissions in Jelgava. To build on these findings, future research should expand sampling efforts to include additional seasons and incorporate a variety of bioindication methods. In particular, collecting snow samples prior to firework events – such as during the second half of December before New Year's Eve – and at other key periods thorough the year would help assess whether elevated metal concentrations are confined to late winter or persistent year-round. Such comprehensive data collection would support a more detailed understanding of temporal pollution patterns and inform the development of more effective, targeted mitigation strategies.

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PHOSPHORUS RECOVERY AND REUSE AS SOIL AMENDMENT FROM DIVERS SORBENT MATERIALS

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Abstract
Phosphorus (P) is an essential macronutrient for plant growth, yet its inefficient use and finite supply present major challenges to agricultural sustainability and environmental protection. Excessive P losses from agricultural runoff contribute to eutrophication, while the depletion of phosphate rock raises concerns about long-term food security. Sustainable P management strategies, including recovery and reuse, have gained attention as viable solutions. Sorbent materials, including mineral-based, waste-derived, and modified materials, offer promising approaches for P capture, removal from wastewater, and potential reuse in agriculture. This review evaluates the efficiency of different sorbent materials in P recovery and their application as soil amendments to enhance P availability. Mineral-based sorbents, such as calcium silicates and iron oxides, provide cost-effective solutions but have limited regeneration potential. Waste-derived sorbents, including biochar and industrial by-products, contribute to a circular economy by repurposing waste materials but require further assessment due to potential heavy metal contamination. Modified sorbents, such as lanthanum- and magnesium-modified materials, exhibit superior P adsorption and slow-release properties but face challenges in scalability and cost. Additionally, microbial interactions play a crucial role in P bioavailability, with phosphate-solubilizing bacteria enhancing nutrient release. Despite advancements in P recovery technologies, challenges remain regarding economic feasibility, regulatory frameworks, and long-term field performance. Standardized testing protocols, risk assessments, and policy support are necessary to facilitate the adoption of sorbent-based P management strategies. The integration of these materials into agricultural systems offers a sustainable pathway to improving P efficiency, reducing environmental impact, and promoting circular nutrient use.
Keywords: phosphorus recovery, phosphorus capture, soil amendment, sorbent materials, circular economy.

Introduction

Phosphorus (P) is an essential macronutrient for plant growth, playing a crucial role in energy transfer, photosynthesis, and root development. It is indispensable for global agricultural productivity and food security, with phosphate fertilizers being a primary input for enhancing crop yields (Roberts & Johnston, 2015). However, P is a finite and non-renewable resource, predominantly sourced from phosphate rock, which is being depleted at an alarming rate. Estimates suggest that global phosphate rock production may peak by 2035, raising concerns about long-term agricultural sustainability (Cordell et al., 2011). Despite its critical role, P use in agriculture remains inefficient, with a significant proportion lost through soil fixation, runoff, and erosion (Roberts & Johnston, 2015).

The loss of P from agricultural fields contributes to severe environmental issues, particularly eutrophication. Excess P leaching into water bodies accelerates the growth of harmful algal bloom, leading to oxygen depletion, fish mortality, and disruption of aquatic ecosystems (Alewell et al., 2020; Yang et al., 2021).

Agricultural runoff, soil erosion, and the overuse of P-based fertilizers are primary contributors to this issue, making it a global concern (Zou et al., 2020). Studies indicate that over 50% of total P losses in some agricultural systems occur due to soil erosion, particularly in regions with intensive farming and inadequate nutrient management (Alewell et al., 2020).

Due to P scarcity and environmental degradation, sustainable P management strategies are urgently needed. Efficient P recovery and reuse from waste streams, including manure, wastewater, and crop residues, have been proposed as viable solutions (Sarvajayakesavalu et al., 2018). Innovations in P recycling technologies, including biochar-based amendments, targeted fertilization, and microbial-assisted P mobilization, can improve P use efficiency while reducing environmental risks (Yang et al., 2021). Integrated nutrient management practices, focusing on optimizing P application and minimizing losses, are crucial for achieving a more circular P economy (Schneider et al., 2019).

To mitigate P loss and its associated environmental impacts, various technologies have been developed for P removal from wastewater and agricultural runoff. Among these, sorbent materials have emerged as an effective and sustainable solution for P sequestration (Altamira-Algarra et al., 2022). Sorbent materials are substances capable of adsorbing or precipitating P, thereby preventing its release into water bodies. These materials can be classified into natural sorbents (e.g., biochar, clay minerals), industrial by-products (e.g., red mud, steel slag), and modified materials (e.g., metal oxides, modified biochar) (Gubernat et al., 2020; Nobaharan et al., 2021).

One of the applications of sorbent materials is in wastewater treatment systems, where they enhance P removal mainly through adsorption, ion exchange and chemical precipitation mechanisms (Zhou et al., 2021). Phosphorus-binding materials, such as calcium- and iron-rich sorbents, bind P ions, forming insoluble compounds that can be easily separated from wastewater (Stávková & Maroušek, 2021). Constructed wetlands and modified P filter systems often integrate these sorbents to improve P capture efficiency (Kasprzyk et al., 2021). Additionally, waste-based adsorbents, such as modified biochar and industrial residues, are gaining attraction as cost-effective alternatives for P removal (Pap et al., 2020).

Additionally, these sorbent materials hold potential for reuse in agriculture as soil amendments. When

saturated with P, sorbent materials can serve, for example, as slow-release fertilizers, replenishing soil P reserves while minimizing environmental losses (Altamira-Algarra et al., 2022). Studies have demonstrated that biochar-based sorbents, lanthanum-modified clays, and calcium-rich industrial by-products enhance P availability in soils while improving soil structure and water retention (Gubernat et al., 2020; Nobaharan et al., 2021). The integration of P sorbents into agricultural systems aligns with the principles of a circular economy, promoting nutrient recovery and sustainable soil management (Zhou et al., 2021).

By bridging wastewater treatment and agricultural nutrient management, sorbent technologies offer a promising pathway to reduce P dependency while mitigating environmental impacts. Their integration into systems such as treatment plants, constructed wetlands, and filtration units can significantly enhance P recovery efficiency, supporting the transition toward a more circular and sustainable P economy (Stávková & Maroušek, 2021; Altamira-Algarra et al., 2022).

As P recovery technologies evolve, optimizing the application of sorbent materials will play a critical role in balancing economic feasibility, environmental impact, and long-term resource security. This methodological approach ensures a comprehensive evaluation of different sorbent materials, highlighting their effectiveness in P capture and reuse while assessing their potential impact on soil fertility, microbial activity, and overall environmental sustainability.

This review aims to evaluate various sorbent materials, including natural sorbents, industrial by-products, and modified materials, for their effectiveness in P recovery and their potential as soil amendments to enhance P availability and improve overall soil health.

Materials and Methods

This review follows a structured approach to systematically analyze and synthesize existing research on P recovery and reuse using various sorbent materials. The methodology includes defining selection criteria, identifying relevant literature, and categorizing sorbent materials based on their composition and potential for P recovery and reuse as soil amendments.

The literature search was conducted using academic databases such as Scopus, Web of Science and ScienceDirect. Studies were selected based in their relevance to P recovery, their evaluation of sorbent reuse in soil, and their contribution to sustainable nutrient management. The review focused on publications from the past decade to ensure coverage of recent advancements in P recovery technologies.

Results and Discussion

Traditional P recovery methods from wastewater and sludge, such as chemical precipitation, enhanced biological P removal (EBPR), adsorption, and thermal treatment, have been widely implemented, but each comes with significant limitations. Chemical precipitation using calcium, magnesium, iron, or aluminum salts is highly effective but requires substantial chemical input and can lead to unwanted co-precipitation, making it less cost-effective, particularly for low P concentrations. EBPR, which relies on phosphate-accumulating organisms (PAOs), offers a biological alternative but is sensitive to wastewater composition and produces excess sludge requiring further treatment (Di Capua et al., 2022). Adsorption and ion exchange technologies, employing materials like modified clays, biochar, or ion-exchange resins, provide selective P removal but are constrained by high operational costs and limited regeneration cycles (Zhang et al., 2022). Meanwhile, thermal treatment of sewage sludge, including incineration and acid leaching, demands significant energy inputs and poses challenges related to heavy metal contamination and complex post-treatment requirements (Vu et al., 2023).

P adsorption efficiency varies significantly depending on the type of sorbent material, its surface chemistry, and the environmental conditions in which it operates. The mechanisms of P adsorption primarily include ligand exchange, electrostatic attraction, surface precipitation, and ion exchange, which are influenced by the mineral composition and functional groups present in the sorbent material (Du et al., 2022).

To overcome the challenges associated with P loss and limitations in conventional recovery methods, it is essential to develop sustainable and cost-effective solutions with high selectivity, reusability, and reduced chemical dependency (Di Capua et al., 2022). In this review, the proposed categories - mineral-based, waste-derived, and modified sorbents - each demonstrates distinct strengths and limitations in P capture.

Mineral-based sorbents, including zeolite, bentonite, iron oxides, and calcium silicates, exhibit effective phosphate binding due to their high surface area and natural ion-exchange capabilities (Zhao et al., 2024). Iron and aluminum oxides demonstrate a strong affinity for phosphate through ligand exchange reactions, forming stable inner-sphere complexes that prevent leaching in soil applications (Dai et al., 2014). Similarly, iron oxides and hydroxides, commonly used in wastewater treatment, effectively bind phosphate due to their large surface area and high ligand exchange capacity (Jin et al., 2024). However, calcium-rich sorbents, such as wollastonite and calcium silicate, facilitate P precipitation, but often exhibit limited adsorption capacity in acidic conditions, which affects their overall efficiency in wastewater treatment (Gustafsson et al., 2008). While naturally abundant and effective in ion exchange, mineral-based sorbents generally have lower adsorption capacities compared to modified alternatives, which enhance phosphate retention and release properties (Vu et al., 2023).

Waste-derived sorbents, such as biochar, sludge char, and industrial by-products like steel slag and fly ash,

offer sustainable alternatives for P capture while simultaneously reducing waste accumulation (Altamira-Algarra et al., 2022; Di Capua et al., 2022). Biochar and activated carbon, produced from pyrolyzed biomass, offer high adsorption efficiency due to their porous structure and surface functionalization (Kaljunen et al., 2022). Additionally, treated biosolids and pyrolyzed sludge char have shown high P recovery potential, particularly when modified with metal ions to enhance adsorption capacity (Maroušek & Gavurová, 2022).

Modified sorbents demonstrate superior P adsorption due to their tailored surface functionalities and high selectivity (Du et al., 2022; Zhang et al., 2022). Functionalized biochar, modified with Mg, Ca, or La, has been developed to enhance P adsorption efficiency and controlled nutrient release (Zhao et al., 2024). Additionally, composite materials such as nanomaterials and polymer-coated sorbents have been studied for their enhanced selectivity and efficiency in P binding (Ding et al., 2023). Lanthanum-doped hydrocar shows P adsorption capacity >50 mg/ g across a wide pH range (2.5-10.5), making it a promising material for large-scale wastewater treatment (Dai et al., 2014). Nevertheless, the complexity and cost of producing modified sorbents remain key barriers to their widespread adoption (Zhao et al., 2024).

The ability to regenerate sorbents and reuse them in subsequent cycles is a critical factor in determining their feasibility for long-term P recovery. Mineral-based sorbents, particularly calcium silicates and iron oxides, show moderate regeneration potential but often experience decreased adsorption efficiency over multiple cycles due to structural degradation (Zhao et al., 2024). While some natural minerals, such as zeolites, can be regenerated via ion exchange, others, such as bentonite, require chemical washing or thermal treatment to restore their P adsorption capacity (Altamira-Algarra et al., 2022).

Modified sorbents offer the highest potential for reuse, with modifications designed to enhance their stability and longevity (Biswas et al., 2023). Layered double hydroxides (LDHs), for instance, have demonstrated strong regeneration potential through chemical treatments, allowing for multiple cycles of P capture and release without significant loss in efficiency (Zhao et al., 2024). Additionally, metal–organic frameworks and functionalized nanomaterials have been designed to facilitate controlled P desorption, ensuring that recovered P remains bioavailable for agricultural use (Gao et al., 2023). However, cost and environmental concerns related to the synthesis and disposal of modified sorbents continue to limit their large-scale implementation (Biswas et al., 2023).

Table 1 presents a comparative analysis of various sorbent materials based on their P adsorption capacity, removal efficiency and reuse potential.

The use of P-enriched sorbents as soil amendments is a promising strategy for improving P availability in agricultural soils while enhancing soil health. The efficiency of these sorbents in releasing P depends on various factors, including soil pH, microbial activity, and mineral interactions. Different sorbent materials release P at varying rates, influencing its bioavailability to crops and its long-term effectiveness as a fertilizer substitute.

Table 1

Efficiency of various sorbents in phosphorus removal and recover

Sorbent type	***Sorbent***	***Reuse Application***	***Adsorption capacity (mg·g^{-1}) / Removal efficiency (%)***	***Phosphorus source***	***Reference***
Mineral-based sorbents	Filtra P	Soil amendment, Fertilizer (slow-release)	98.20%	Synthetic P solution	Gustafsson et al., 2008
	Polonite	Soil amendment, Fertilizer	96.70%		Gustafsson et al., 2008
	Wollastonite	Limited soil use	51.10%		Gustafsson et al., 2008
	Zeolite	Soil amendment in high ion-exchange areas	73.62%	P rich wastewater from WWTP	Jiang et al., 2013
	Hydroxyapatite /calcium silicate hydrate	Remediation, Soil amendment for acidic soils	138.00 mg·g^{-1}	P rich wastewater from farmland	Liu et al., 2021
Waste-derived sorbents	Biochar	Soil amendment, Fertilizer (slow-release), Carbon enrichment	40.00 mg·g^{-1}	P leachate from wastewater sludge	Kaljunen et al., 2022
	Sludge Char	Soil conditioning, Fertilizer (slow-release)	50.00 mg·g^{-1}		
	Commercial Lignin	Organic amendment, Fertilizer (slow-release)	40.00 mg·g^{-1}		
	Humus Extract	Fertilizer (slow-release)	40.00 mg·g^{-1}		

Sorbent type	***Sorbent***	***Reuse Application***	***Adsorption capacity (mg·g^{-1}) / Removal efficiency (%)***	***Phosphorus source***	***Reference***
Modified sorbents	Lanthanum-doped Hydrochar	Soil amendment, Fertilizer (slow-release)	61.57 mg·g^{-1}	Synthetic P solution	Dai et al., 2014
	CaP enriched biochar	Fertilizer (80% plant-available P), Economic use	31.80 mg·g^{-1}	P from sludge water	Stávková & Maroušek, 2021
	Magnetic Biochar	Potential fertilizer	48.83 mg·g^{-1}	Synthetic P solution	Manoko et al., 2022
	MgO-biochar modified by hydroxyl and amino groups	Fertilizer, Biochar regeneration	43.27 mg·g^{-1}		Zhang et al., 2024
	Zirconium-modified red mud	Long-term P stabilization	33.14 mg·g^{-1}		Li et al., 2021
	MgO-impregnated magnetic biochar	Fertilizer	121.25 mg·g^{-1}		Li et al., 2016

Biochar-based sorbents, derived from agricultural residues, sludge char, or industrial by-products, exhibit slow-release P properties, making them particularly valuable in high P-fixing soils (Carneiro et al., 2021). Biochar enriched with P through pre- or post-pyrolysis treatments has been shown to increase soil P reserves, enhance plant uptake and sustain P availability over multiple growing seasons (Carneiro et al., 2021). Studies indicate that P-enriched biochar fertilizers can replace conventional P fertilizers without compromising crop yield, demonstrating both short-term efficiency and long-term sustainability (Carneiro et al., 2021).

Mineral-based sorbents, such as calcium silicates, iron oxides, and zeolites, exhibit varying P desorption capacities depending on soil conditions (Hemati Matin et al., 2020). Calcium silicate materials, for example, are highly effective in alkaline soils where they slowly release P in bioavailable forms. However, in acidic soils, P may become less available due to interactions with aluminium and iron oxides, requiring additional modifications or amendments (Hemati Matin et al., 2020). Studies suggest that modified sorbents can enhance P efficiency by over 90%, ensuring sustained crop nutrition (Chen et al., 2022).

P availability in soil is influenced by several factors, including soil pH, microbial activity, nutrient interactions, and long-term residual effects. Soil pH plays a critical role in P solubility and plant uptake. In acidic soils, P tends to bind with aluminium and iron oxides, forming insoluble complexes that reduce its accessibility to crops (Chen et al., 2022). Conversely, in alkaline soils, calcium-bound P dominates, which can be effectively released from calcium silicate-based sorbents, ensuring a more sustained P supply to plants (Chen et al., 2022). The interaction between soil amendments and pH highlights the importance of choosing the appropriate sorbent materials based on specific conditions to optimize P availability.

Microbial activity is another crucial factor that determines how efficiently P is released from sorbent materials and made available for plant uptake (Cho et al., 2020). Phosphate-solubilizing bacteria (PSB), such as *Pseudomonas* and *Bacillus sp*., enhance P solubilization by producing organic acids and enzymes that break down P complexes (Kalayu, 2019). This microbial action is particularly beneficial when using biochar-based and waste-derived sorbents, as these materials provide a habitat for microbial colonization, thereby facilitating P release into the soil (Leader et al., 2008). In biologically active soils, the combined use of P-enriched sorbents and microbial inoculants can significantly improve P bioavailability for crops (Cho et al., 2020).

Nutrient interactions also play an important role in P uptake efficiency. The availability and uptake of P are closely linked to the presence of other soil nutrients, particularly nitrogen, calcium and iron. Studies indicate that nitrogen-phosphorus interactions influence root structure and P absorption, with evidence showing that combined applications of biochar-based sorbents and nitrogen fertilizers can enhance P efficiency (Leader et al., 2008). Additionally, iron and aluminium oxides present in some mineral sorbents may contribute to P retention, reducing leaching losses while ensuring slow and steady P release over time (Chen et al., 2022).

Long-term residual effects of P-enriched sorbents further influence soil P dynamics. Unlike synthetic fertilizers that release P immediately, sorbent-based P amendments contribute to the long-term P reserve in soil. Biochar-

based phosphate fertilizers, for instance, increase the non-labile P fraction, maintaining nutrient availability for multiple growing seasons (Carneiro et al., 2021).

The gradual P release from these sorbents reduces the risk of nutrient runoff and enhances the sustainability of soil P management (Chen et al., 2022). Overall, the integration of P-enriched sorbents into soil amendment practices provides a long-term strategy for improving P efficiency while promoting soil fertility and sustainability.

P-enriched sorbents pose several challenges that must be addressed for widespread adoption in agricultural systems. One major concern is the potential accumulation of heavy metals or contaminants in soil. Waste-derived sorbents, such as biosolids, industrial by-products, and biochar from municipal sludge, may contain trace amounts of heavy metals like cadmium, lead and arsenic, which can accumulate in soil over time and pose risks to food safety (Chen et al., 2022). Regulatory measures must be implemented to ensure that these materials undergo rigorous testing and treatment before application to agricultural lands.

The economic feasibility of large-scale P recovery and reuse also presents a challenge. While P-enriched sorbents offer long-term benefits, the initial cost of processing, modification, and application can be significantly higher than that of conventional P fertilizer (Cho et al., 2020). The production of modified sorbents, such as lanthanum-modified biochar or nanocomposite sorbents, involves high material and synthesis costs, making them less accessible for widespread use (Chen et al., 2022). To improve economic feasibility, incentive programs, subsidies, and cost-sharing initiatives could encourage farmers to adopt these materials as part of sustainable soil management practices.

Lastly, regulatory considerations for applying recovered materials to farmland are crucial to ensure environmental safety and effectiveness. Many P sorbents, particularly waste-derived materials, must comply with agricultural and environmental regulations regarding heavy metal content, nutrient composition, and leaching potential (Nanda et al., 2020). However, existing fertilizer policies often lack clear guidelines for P-recovered materials creating regulatory uncertainty that hinders their adoption (Barquet et al., 2020). Recent updates to the EU Fertilizing Products Regulation aim to integrate waste-derived fertilizers, improving market access, yet many national policies remain fragmented, limiting large - scale implementation (Nanda et al., 2020).

Establishing standardized testing protocols, risk assessments, and certification programs for P-enriched sorbents will be essential to gaining farmer trust and ensuring safe, effective agricultural use (Nanda et al., 2020; Barquet et al., 2020).

Conclusions

1. P recovery and reuse through sorbent materials is a sustainable strategy to address global P scarcity and environmental challenges. The study highlights the potential of mineral-based, waste-derived and modified sorbents in improving P management efficiency.
2. Mineral-based sorbents, such as iron oxides, calcium silicates, and zeolites, offer cost-effective and naturally abundant solutions for P recovery. However, their limited regeneration potential and dependency on soil pH affect long-term performance.
3. Waste-derived sorbents, including biochar, treated biosolids, and industrial by-products, provide a sustainable approach to P recovery while reducing landfill waste. Their performance variability and potential heavy metal contamination require further treatment and regulatory oversight.
4. Modified sorbents, such as lanthanum- and magnesium- modified biochar, demonstrate high P adsorption efficiency and slow-release properties. However, their high production costs and scalability challenges hinder widespread agricultural application.
5. P-enriched sorbents improve soil fertility, crop productivity, and nutrient efficiency, offering a slow-release alternative to conventional fertilizers. Their ability to reduce P leaching mitigates the environmental risks of eutrophication.
6. Microbial interactions significantly influence P bioavailability from sorbents, with P-solubilizing bacteria playing a crucial role in nutrient release and uptake. Enhancing microbial compatibility in sorbent applications can improve long-term soil health.
7. Challenges in large-scale P recovery include economic feasibility, heavy metal accumulation, and regulatory compliance. Policy frameworks must support the safe and effective integration of recovered P materials into agricultural practices.
8. Future research should focus on optimizing sorbent modifications, improving P desorption mechanisms, and conducting field-scale evaluations to enhance the practical viability of these materials in sustainable farming.
9. The integration of P recovery into circular economy models is essential for long-term food security, environmental sustainability, and resource conservation, reducing dependence on finite phosphate reserves and promoting resilient agricultural systems.

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MUNICIPAL ENVIRONMENTAL GOVERNANCE MONITORING IN LATVIA: TOWARDS VERTICAL AND HORIZONTAL INDICATORS SYSTEM

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Abstract
Municipal Development Programs cover a wide scope of policies, but environmental governance monitoring has been weak. After the 2021 reform with aggregation of municipalities in the country, the situation started gradually improving. Considering the voluminosity of Environmental Governance sector and its tendency to grow, there is a need to review the set of monitoring indicators. The aim of study was to evaluate the monitoring practices in Environmental Governance sector for all 3 basic administrative levels in Latvia (municipal, regional, national), carrying out an analysis of both vertical and horizontal integration and aggregation, and finally, to develop recommendations for municipal monitoring programs and system. The document studies methods were applied. All statutory planning documents (three main documents of each municipality) were reviewed of 7 municipalities of Riga planning region. Besides document studies in Kekava municipality, detailed semi-structured interviews were conducted with municipal experienced specialists. There are accounted for around 80-100 comparatively unique indicators in total. The best monitored are Communal Infrastructure Sector and Climate Change Management Sector (also many various infrastructure indicators) with 54 and 50 indicators respectively, which have high continuity also with higher level documents and good linkages horizontally between municipalities. All planning documents mention reducing GHG emissions, air pollution, green infrastructure etc. During this project study the related recommendations for all sectors were prepared, both for particular case of Kekava municipality and in general for municipal monitoring systems.
Keywords: development program, indicators in the planning process and documents, public monitoring.

Introduction

The value of environmental indicators was emphasized already in the 1970s, highlighting their role in neighbourhood decision-making and guidance to municipalities (Berenyi, 1972). Early recognition of indicators as a bridge between technical data and policy action laid the groundwork for modern municipal sustainability metrics. More recently, there is available already wide literature on various case studies and best practice examples in different countries across a globe, e.g. like the one case study conducted in Palmela, Portugal, (Moreno-Pires & Fidelus, 2012) showing how well-designed local indicator systems can also foster collaborative governance, strengthen institutional capacity, and not only to track well the long-term environmental performance at the municipal level.

Various studies provide insight into sustainability indicators in municipalities, especially urban and smart cities. The bibliometric and taxonomic analyses reveal a growing emphasis on circular economy, climate resilience, and digital infrastructure within urban indicator frameworks (Tomadon et al., 2024). These sources also demonstrate how emerging technologies and data-driven instruments are shaping next-generation sustainability assessments, particularly in fast-growing urban areas. For example, producing the Assessment of Sustainability of Cities in South Korea (Hong et al., 2019), based on a national framework, combining mandatory and voluntary indicators to monitor municipal performance, acquired findings highlighted the importance of adapting indicator systems to specific governance contexts while maintaining consistency across regions. The study underscores how such systems, when institutionalized, can help municipalities balance environmental, economic, and social goals effectively.

Nowadays municipal environmental indicators have become an essential instrument for assessing sustainability and guiding urban policy, but just the matter still is how those indicators and/or their systems gave been developed, implemented and monitored. Unfortunately, by pragmatic approaches-based and in limited capacities functioning, local municipal practice situation still could be improved also in high-developed countries. For such a conditions, exactly the bottom-up approach for developing and monitoring of indicators - where local communities and stakeholders actively participate - can significantly enhance the relevance and acceptance of environmental management strategies (Criollo et al., 2019) For example, the case study in Colombia produced 40 practical indicators that reflect local socio-environmental priorities, providing a replicable model for participatory governance in other municipalities (Criollo et al., 2019). In other regions and particularly in Europe there are to be found rich diversity of various best practice examples.

While international research demonstrates a wide range of approaches to developing and applying municipal environmental indicators, it is crucial to examine how these insights align with the context of Latvia. Given Latvia's administrative structure, environmental challenges, and growing emphasis on sustainable development, assessing the current use of indicators at the municipal level can reveal both strengths and gaps.

In Latvia, 7-year municipal Development Programs (DP) are the key documents for **socio-ecological system (SES) development**, integrating sectoral policies. It possesses also related monitoring of the program implementation. However, this monitoring planning and practice, particularly, **environmental governance sector monitoring,** has been **still in**

necessary further development stage, including type, number and especially adherence not only to main actionable dimensions, but main work directions etc. even after the administrative-territorial reform 2021 reducing number of municipalities from 119 to 42, seen gradually however unevenly improving.

All statutory planning documents (three main documents of each municipality) were reviewed for 7 municipalities of Riga planning region (RPR) as one of five planning regions in Latvia, - Adazi, Ropazi, Salaspils, Kekava, Olaine, Marupe municipalities and Jurmala city municipality.

Monitoring and evaluation of development planning documents at all administrative-management levels is essential for their effective implementation as required by the Law on Development Planning system (2009). Statutory required monitoring reports reflect the actions taken, the indicators of results achieved, and the progress made toward the set objectives during the reporting period. The evaluation process for the implementation of the municipal development programme requires the preparation of an annual monitoring report on the programme's implementation, as well as a three-year review report.

In the course of the work, monitoring practices and their continuity at 3 administrative/management levels were studied - national (Latvian Sustainable Development Strategy until 2030 - LSDS, the National Development Plan of Latvia for 2021-2027 - NDP, Environmental Policy Guidelines for 2021-2027 - EPG), regional (Riga Planning Region Development Programme – RPR DP) and local (municipal Development Programmes - DP). The aim of the study was to collect, assess and evaluate the monitoring practices in the Environmental Governance sector for all 3 basic management levels in Latvia (municipal, planning regions, national), carrying out qualitative analysis of both vertical and horizontal integration and aggregation, and finally, to develop a set of system recommendations for the municipal monitoring programs and system. The problem is that municipal development programs have a wide scope of actions, but monitoring has been comparatively weak until the administrative-territorial reform even in 2021. Considering the size of the environmental management sector and the tendency to grow, it is necessary to evaluate the monitoring procedures and content, towards the increase of its effectiveness.

Local municipalities play a key role in environmental governance, as they are responsible for implementing national and regional policies at the local level, while also addressing local sustainability challenges. As sustainability challenges become more complex, municipalities must strengthen their governance frameworks, improve strategic planning, and enhance monitoring mechanisms to ensure that environmental policies are both effective and adaptable to evolving climate and societal needs (Guyadeen et al., 2023).

Public engagement in environmental governance enhances transparency, accountability, and decision-making (VARAM, 2015, 2022; Azevedo et al., 2025). However, for public participation to be meaningful, it must be supported by well-structured environmental governance frameworks that ensure the efficient coordination of policies across different levels of government. Effectiveness of multi-level environmental governance depends on strong collaboration among local, regional, and national institutions, enabling development of robust sustainability frameworks that guide municipalities in implementing climate and environmental policies (Guyadeen et al., 2023).

To effectively integrate sustainability into governance, municipalities increasingly adopt strategic planning as a proactive approach to anticipate and address complex environmental and climate challenges. This involves defining long-term objectives, identifying priorities, and allocating human and financial resources accordingly. While discussion has taken place regarding the scope, content, and methodology of strategic planning, less attention has been given to the quality of municipal strategic plans (Azevedo et al., 2025). Many local strategies lack crucial components, such as a comprehensive evidence base to justify goals and clear mechanisms for implementation, monitoring, and evaluation. Without these elements, even the best-intentioned policies may fail to achieve their desired impact. Therefore, significant improvements are needed to ensure that municipal planning is cohesive, actionable, and aligned with broader sustainability goals (Lemos & Agrawal, 2006).

Both researchers and policymakers increasingly recognize that local-level actions play a pivotal role in achieving climate change mitigation targets. Municipalities exercise direct control over critical environmental policies, such as land-use regulations, urban development, resource management, and transportation planning, all of which significantly impact sustainability. Additionally, they oversee licensing for buildings, public transport operations, and municipal energy consumption, allowing them to set an example through sustainable practices. Given their proximity to communities, municipalities are also better equipped to understand local behaviours, cultural contexts, and energy consumption patterns, ensuring that environmental policies are not only effective but also socially acceptable and practically implementable (Azevedo et al., 2025).

Recognizing their influence and responsibility, many municipalities have proactively adopted climate action strategies. Over the past decade, more than 6,000 European municipalities have voluntarily joined the Covenant of Mayors, a significant initiative aimed at enhancing climate resilience and promoting local sustainability actions. As climate initiatives continue to expand, it is essential to assess their overall impact.

Evaluating the effectiveness, relevance, and efficiency of municipal climate and environmental policies provides valuable insights for policymakers, facilitates the development of improved governance strategies, and promotes best practices in sustainability. However, accurately assessing these policies remains challenging, as their outcomes depend on multiple external factors, including economic conditions, technological advancements, and national regulatory frameworks (Meadowcroft, 2007).

Local municipalities shall act within a framework of normative documents, but they also can issue their own local regulations and implement voluntary activities, including sectoral development planning as management of waterbodies etc. Functions of local governments in Latvia are described in law, laying down the legal basis, structure, competences and duties of a local government. These functions are directly related with environment governance at local level and form a framework of binding obligations important for local citizens, entrepreneurs and society in general (VARAM, 2022).

There in the new Local Government Law since 2023 and there is included new function of local governments – **to contribute to climate change mitigation and adaptation**. The inclusion of the new function is a response to current global and national challenges related to climate change. It highlights the important role of municipalities in mitigating climate change and adapting to its effects. It helps ensure sustainable development, improve the quality of life for local communities, and fulfil international and national commitments in the field of climate action. Municipalities become key partners in this global challenge, and implementing this function represents a significant investment in the future (Lemos & Agrawal, 2006).

The statutory national environmental laws play role of a second source of legal responsibilities in the environmental sector for municipalities, in addition to the basic law on municipalities and its autonomous functions described below. Various other national regulatory acts impose obligations on local municipalities in different environmental sectors, such as the Waste Management Law, Water Management Law, Spatial Development Planning Law, Air Protection Law, Biodiversity Protection Law, and Climate Change Adaptation Law.

While **municipalities in Latvia are not directly responsible for environmental monitoring**, they play a key role in implementing and supporting national policies (Local Government Law, 2025). Their responsibilities include organizing and overseeing waste management systems, ensuring sustainable land use planning, promoting biodiversity protection measures, and facilitating local initiatives for climate adaptation and environmental awareness. Environmental monitoring, such as air and water quality assessments, biodiversity evaluations, and pollution control, is carried out by national institutions and agencies, with municipalities often cooperating by providing relevant data, local expertise, facilitating community engagement in environmental protection efforts (Local Government Law, 2025).

The participatory municipal budgeting. There in the new Local Government Law is provided potential financing source for improvement of socio-economical activities in the local communities, but potentially also for nature resources management, water quality, air quality etc. Participatory budgeting is one of the ways to promote public participation in local government, including by fostering cooperation between the two sides, given that it is the citizen who will propose a solution to a problem that is important to him, his community or his territory (Local Government Law, 2025; Azevedo et al., 2025). The objective of participatory budgeting in promoting the development of the territory is not only to implement infrastructure projects, but also to plan the development of the territory in such as to improve the quality of the living environment, make sustainable, efficient and rational use of the territory and other resources, develop targeted and balanced economy.

Starting from 2023, the municipality shall provide in the annual budget of the municipality funding for the participation budget of at least 0.1 per cent of the average annual personal income tax and real estate tax revenues of the municipality, calculated for the last three years. Thematic scope of the participatory budget and expected results of projects proposed by the public are defined by municipality in the development programme, including considering the needs of the population (Local Government Law, 2025).

Materials and Methods

During the development of this study, the environmental governance monitoring practice and its continuity were studied at all the **3 administration/planning levels in Latvia.** The Research-and-Development framework was employed to dome to actionable policies and indicators development recommendations. **Case Study Research** methodology was used, including, the core study of all related documents, particularly, statutory planning documents at all three administration levels and, complementary, express interviews with 5 experts and municipal specialists from chosen piloting municipality of Kekava (Riga planning region) in relation to the design, approval and implementation of the development planning documents.

The national level was covered by the following development planning documents: LSDS; NDP; EPG. Next level is called planning regions level (governed by the council of chairpersons of all local municipalities of particular region) - Development Program of Riga Planning Region (RPR DP). Further on the Development Programs of local municipalities/governments (DP) were studied.

Latvia 2030 or LSDS is the national long-term development strategy aimed at creating a sustainable, competitive, and balanced society. The strategy focuses on economic growth, social well-being, and environmental protection, aligning with European and global sustainability goals. NDP2027 is Latvia's only overall medium-term development program, guiding policies and investments to ensure economic growth, social well-being, and sustainability. It aligns with EU priorities and focuses on building a smart, green, and inclusive society. The EPG as overall medium-term environmental sector planning document is outlining Latvia's strategic approach to sustainability, climate resilience, and environmental protection. The policy aligns with EU Green Deal objectives and aims to balance economic growth with ecological responsibility. For this investigation was chosen one, the RPR, case, which contains 7 municipalities and Riga capital city, however the statutory development planning documents were examined initially for all local municipalities in Latvia (43 municipalities altogether after administrative-territorial reform of 2021) covering altogether existing 5 planning regions as regional level authorities.

There are in total almost 800 local environmental governance indicators described/found for monitoring of municipal Development Programs to measure the planning implementation progress in all 43 municipalities in Latvia, even main part of those thematic indicators overlaps or are similar. Narrowing the scope of municipalities for detailed studies, the document studies within RPR case was applied and, in total, all the statutory planning documents (three main development planning documents for each municipality – Sustainable Development Strategy, Development Program (incl. also Action Plan and Investment Plan as short-term planning documents) were reviewed of all the 7 municipalities of RPR (except Riga capital city) as one of five planning regions in Latvia, actually most developed one since in direct proximity to the Riga capital city, being by far largest city (above 0.5 milj. inhabitants) in Latvia. The local municipalities studied namely are Adazi, Ropazi, Salaspils, Kekava, Olaine, Marupe municipalities and Jurmala township municipality.

Total area of the examined 7 municipalities is 2 100 km², total number of inhabitants – 223.3 thousand (total number of inhabitants in Latvia – 1.87 million, but in Riga City – 605 thousand, total area of Latvia is 64 594 km²). The RPR is the heart of Latvia's economy and culture, offering a dynamic and diverse environment for business, tourism, and innovation. With a strong infrastructure, skilled workforce, and a strategic location, it plays a crucial role in Latvia's development and integration into the European and global economy.

Special attention was paid to the Action Plans and Surveillance Plans for the Development Programs, which contain the main lines of action, priorities for different time periods, tasks, expected results as well as monitoring indicators. For the necessary overall framing and content wise structuring of the municipal Environmental Governance branch itself and its monitoring indicators analysis, three main environmental governance sectorial dimensions were used (actually, already four dimensions now, but newly approaching climate change management issues are to be more sectorized and prescribed now) as the basic set of sectorial dimensions grouping model:

1. **Environmental Infrastructure** sectorial dimension as all the mandatory communal services/u sectors as prescribed by the Local Government Law (municipal autonomous responsibility functions) and very well-known in practice and quite well implemented in the municipalities.
2. **Environmental Protection** sectorial dimension as voluntary and ever-growing number of new environmental sectors (actually, also instruments) besides those statutory municipal infrastructure autonomous responsibility functions.
3. **Environmental Governance and Environmental Communication** sectorial dimension as known from models and our previous research papers, finally nowadays are increasingly taking place in the municipal overall/sectorial development planning documents and procedures, however still not fully prescribed by regional and particularly national authorities and/or voluntarily developing.

However, in pragmatic sectorial understanding of municipal practice is step-wise developing and the model of **8 thematical sectors of environment governance content spectrum** was chosen (Natural Environment, Urban Environment, Communal Environment, Environmental Protection, Health Environment, Climate Change Management, Communication Environment, Governance Environment) as it mainly coincides with municipal law and Environmental Policy Guidelines, as well as DP Planning Recommendations from the Ministry of Smart Administration and Regional Development.

Environment governance monitoring practice audit in Latvia has been realized at all three levels of government and both Action Plans (short 1-3 years planning) and Supervision/Monitoring Planning, as the statutory part of the municipal Development Programs are discussed in particular, as includes the main courses of action, priorities of different deadlines, tasks, expected results, as well as monitoring indicators are found.

Initially national and regional level indicators studies are to be explored, continued by municipal level study of all 7 municipalities of RPR, and finalizing our studies with Kekava local municipality as one of those 7 mentioned, to go into detail of local municipal monitoring, applying research-and-development frame, including recommendations for system and list of municipal indicators, e.g. public monitoring.

Environmental management monitoring practices at the state, regional, and local government levels follow a vertical integration (top-down) approach. This involves reviewing their statutory framework, key policy documents, and specific monitoring reports.

Results and Discussion

1. Environment governance monitoring audit: national and regional level

There are several key environmental management indicators across different levels of governance in Latvia, including LSDS, NDP2027, RPR DP2027, and EPG2027. While national policies set the overall framework, regional and municipal plans tailor environmental strategies to local needs, ensuring a comprehensive and integrated approach to environmental governance.

Key environmental management indicators used at different governance levels in Latvia—national, regional, and municipal, cover a wide range of environmental sectors, including nature conservation, urban environment, communal services, environmental protection, public health, climate change management, communication, governance, and other environment-related sectors. These metrics provide insight into the priorities and strategic directions of institutions regarding sustainability, resource efficiency, and climate action goals.

Closer look reveals that nature conservation indicators primarily focus on protected areas, biodiversity, and the efficient use of natural resources. They reflect progress in areas such as forest coverage, organic farming expansion, and the conservation status of protected species and habitats. In contrast, urban and communal environment indicators emphasize waste management, water supply quality, and access to essential resources such as clean drinking water. National-level documents tend to outline broader strategic goals, while regional and municipal plans set more specific targets and implementation measures.

Particularly significant section is climate change management, which includes greenhouse gas (GHG) emission reduction, renewable energy usage, energy efficiency improvements, and public transport development. These indicators are crucial in context of the European Union's climate policy, as they determine Latvia's ability to meet the Green Deal objectives and reduce dependence on fossil fuels. Additionally, governance and communication aspects highlight importance of digitalization, public access to environmental information, and private sector involvement in environmental management.

In the natural environment sector, in all the documents considered (LSDS, NDP, EPG, RPR DP), the share of specially protected nature territories is mentioned as an indicator, which is important for following the European Union's Green Deal and increasing the area of specially protected nature areas to 30%.

In the communal environment sector, all documents except the NDP pay special attention to the share of recycled, sorted waste, with the desire to increase the amount of sorted waste.

In the environmental protection sector, the EPG mentions soil radioactivity monitoring and seismic process monitoring, and LSDS mentions the need to monitor the inflow of nitrogen/phosphorus compounds into surface freshwater bodies, whereas nothing was found in the NDP and RPR DP.

In the health environment sector, monitoring indicators were found only in the EPG, which includes premature deaths due to air pollution and the number of residents receiving drinking water of adequate quality. The climate change management sector is the widest, it has the most monitoring indicators, all documents talk about reducing GHG emissions, air pollution, green infrastructure are also mentioned, the RPR DP has several indicators related to shared cars, public transport, regional cycling infrastructure, etc. Both LSDS and RPR DP, the share of energy from renewable sources is mentioned but no such indicators were found in the other documents.

In the communication environment sector, the monitoring indicator was found only in the EPG, which is related to environmental noise, so that citizens have access to high-quality information about noise sources and their impact on objects related to industrial activity. In the management environment sector, the LSDS mentioned a monitoring indicator related to the use of e-government, while the RPR DP mentions an indicator on the basic budget expenditure of the region's municipalities for the management of territories and housing, as well as on sustainable energy development strategies in households.

In general, it can be concluded that environment indicators in national level are set in accordance with basic EU requirements, they are monitored mostly by state company Latvian Environment, Geology and Meteorology Centre (LEGMC). Results of monitoring are available publicly on the LEGMC website but information about such availability is not channeled to local level municipalities and general public.

Regional level planning documents are less populated with environmental indicators somehow leaving this issue for both national and local level. This may be related to limited capacity of regional level planning institutions in terms of finances and human resources practically restricting any monitoring activities in regional level except statistics collected both at national and local level.

2. Environmental governance monitoring audit: local municipal level

Environmental monitoring indicators across various municipalities within Latvia indicators are categorized under key areas such as nature conservation, urban environment, communal services, environmental protection, public health, climate change management,

communication, and environmental governance. Each municipality's progress is assessed through quantifiable measures such as forest coverage, biodiversity protection, waste management efficiency, water quality assessments, renewable energy adoption, and urban development projects. By comparing these indicators across different municipalities, there can be seen the regional variations in environmental efforts and strategic planning. In total, around 200 various indicators have been compiled from the DP of those 7 local municipalities studied but given that many of them are quite the same or similar, there are reviewed around 80-100 comparatively unique indicators in total (in some cases only the scope differs). The municipal DP pay most attention to - length of cycling paths, improvement of municipal areas, energy efficiency of buildings, centralized infrastructure pipeline systems (water supply, wastewater collection, heating).

A notable aspect is the diverse level of data availability across municipalities, where some have detailed monitoring indicators while others lack reported data. For example, Adazi and Ropazi municipalities provide extensive indicators related to nature protection, waste management, and water supply, whereas Salaspils, Olaine, and Marupe have fewer reported metrics in several categories. In the table, Kekava municipality has reported indicators in urban environment, communal services, climate change management, and environmental governance, but lacks data on nature conservation, environmental protection, and health environment. Key focus areas include urban infrastructure, such as public parks and cycle paths, as well as waste management, with indicators on waste sorting and composting areas. Additionally, Kekava tracks water supply and wastewater connections, while its climate change management efforts focus on renewable energy use, public transport availability, and energy efficiency in buildings. This highlights the municipality's emphasis on urban sustainability and infrastructure development, while certain environmental aspects remain unreported. Additionally, climate change management indicators highlight municipalities efforts in GHG emissions reduction, public transport development, and energy efficiency improvements, reflecting their commitment to sustainable urban planning. Furthermore, governance and communication indicators emphasize the role of citizen engagement, digital services, and environmental awareness campaigns. Overall, this table serves as a valuable instrument for assessing and comparing environmental policies and progress at the local government level, helping to identify strengths, gaps, and potential areas for improvement in environmental sustainability strategies.

3. Environmental governance indicators: new sectors practice to be further developed

It is essential to ensure that all municipal environmental goals are measurable, achievable, and aligned with national and EU policies. By bridging the eventual monitoring gap, integrating environmental goals into strategic planning, strengthening public participation, ensuring regulatory compliance, and enabling data-driven decision-making, it would significantly enhance environmental governance and support the long-term municipal sustainability.

As definitively one of the most positive, even not perfect, examples shall be mentioned the full spectrum list of environmental management performance indicators in the DP of Adazi Municipality (RPR). While the number of environmental governance indicators is high (39), without sufficient data collection, monitoring frameworks, and performance evaluations, becomes challenging to assess the actual progress toward environmental goals.

Particularly interesting is to recognize and to follow to the developments of comparatively new environmental governance sectors/fields being in development recently. Here we would like to mention first Governance and Communication sectors of environmental management as to be more and more recognized as sectors to be emphasized out of other more traditional environmental management sectors (water, waste etc.). Also, Climate Change Management sector as developing both with bottom-up interest from municipalities itself, as well as, per growing top-down requirements by national level planning institutions. It is to be mentioned already known for long Environmental Protection sector, but here is to be considered, that municipalities most often still use in practice, so called, Communal Infrastructure sector (traditional and mandatory water and wastewater, waste and heating sectors), but those Environmental requirements being beyond Communal ones are summarized under Environmental Protection. In the Table 1 there is summarized list of indicators of those four above mentioned sectors newcomers as a collection from all 7 municipalities of this study.

The Governance sector focuses on the development and implementation of strategic plans and initiatives that promote sustainable environmental management at the municipal level. Key indicators include creation of thematic and local plans, participation in environmental governance and tidy environment contests, promotion of environmentally friendly companies. Municipal support mechanisms such as co-financing, and electronic services are also emphasized. Civic participation is encouraged through participatory budgeting, citizen initiatives, and neighbourhood organizations. International cooperation and resident satisfaction are monitored to ensure accountability and ongoing improvement in governance quality.

The Communication sector emphasizes environmental information, environmental education, public engagement and pro-environmental behaviour. Indicators track the effectiveness of public awareness efforts, such as environmental education programs, awareness campaigns, and community events. The availability of electronic municipal services is

assessed, along with collaboration with schools and community groups. Clean-up initiatives, eco-contests, and the promotion of environmentally friendly companies further strengthen environmental consciousness. The sector also monitors how well residents understand environmental challenges, helping to shape more effective outreach and educational strategies.

The Climate sector indicators measure progress in reducing greenhouse gas emissions and improving energy efficiency. These include efficiency of heat production, use of alternative energy sources, and energy consumption in public and residential buildings. The sector also evaluates CO_2 emissions, type of fuel used, and share of renewable energy, highlighting sector's integrated approach to mitigating climate change.

The Environmental protection sector monitors the state and protection of natural resources and biodiversity. Indicators include flood risk exposure, water quality, and presence of stormwater systems. Community-based environmental projects, Blue Flag beaches, and urban forests enhance ecological health.

Table 1

Environmental management indicators of the Riga planning region municipalities: four newcomers' sectors

Sector by indicator	***Sector by indicator***
Governance sector indicators 1. Thematic and local plans developed 2. Projects from various environmental governance and municipal competitions 3. Tidy environment contest participants 4. Environmentally friendly companies 5. Land use classification 6. Energy efficiency cost compensation 7. Neighbourhood organizations count 8. Ongoing international cooperation projects 9. Population assessment of territorial development 10. Local government engagement opportunities 11. Municipal co-financing initiatives 12. Number of electronic municipal services 13. Participatory budgeting efforts 14. Citizens' initiative projects implemented annually 15. Resident satisfaction with municipality	**Communications sector indicators** 1. Residents' view of drinking water quality 2. ECO education programs in the municipality 3. Percentage of municipal e-services available 4. Environmental awareness campaigns 5. Environmental events (lectures, discussions) 6. Updates on pressing environmental problems 7. Cooperation with schools and groups on environmental initiatives (contests, events) 8. Community involvement in clean-up activities 9. Projects implemented through competitions 10. Participants in tidy environment contests 11. Number of eco-friendly companies 12. Number of neighbourhood areas organizations 13. Ongoing international cooperation projects 14. Public awareness on environmental issues
Climate sector indicators 1. Heat production efficiency 2. Pro-environmental/alternative energy production 3. Natural gas consumption in municipal buildings 4. Annual primary energy consumption reduction in public buildings 5. Annual greenhouse gas reduction in public buildings 6. Energy efficiency in multi-apartment buildings 7. Emissions from boiler houses and industrial sources 8. Transport infrastructure to prevent traffic congestion 9. Energy efficient municipal and apartment buildings 10. Carbon dioxide emissions (t/year) 11. Type of fuel used for heat production 12. Construction of stormwater drainage systems 13. LED street lighting installations 14. Average electricity and energy consumption in municipal buildings 15. GHG emissions and share of renewable energy 16. Share of low- and zero-emission vehicles in the fleet 17. Co-financing, improving housing energy efficiency 18. Information on energy efficiency and renovations	**Environmental protection sector indicators** 1. Number of people exposed to the floods threat 2. Good water quality (ecological and chemical) 3. Stormwater drainage and treatment 4. Environmental projects in the community 5. Blue Flag beaches 6. Urban and rural forests 7. Nature projects (parks and waterfronts) 8. Nature and recreational trails 9. Publicly accessible areas near water 10. Percentage of afforested land 11. Registered organic farms 12. Natural areas in the city 13. Limited invasive species 14. Growth in sustainable tourism activities

Nature parks, trails, and accessible waterfronts are promoted to foster public interaction with natural environments. The sector also tracks afforestation rates, organic farming, control of invasive species, and growth in sustainable tourism, reflecting commitment to preserving both urban and rural ecosystems.

Together, these four sectors - governance, communications, climate, and environmental

protection - form a comprehensive framework for additional and more sustainable environmental management at the local level as both – really supporting informed decision-making and promote civic engagement, as well as enhance ecological resilience of municipality as socio-ecological system.

4. Comparison of municipal monitoring practices: vertically and horizontally

Environmental monitoring plays a crucial role in assessing progress toward sustainability and ensuring compliance with national and EU. Analysis of key Latvian strategic documents reveals varying levels of attention to environmental monitoring across different sectors. Some indicators are consistently present across all documents, others are fragmented or missing, highlighting potential gaps in environmental governance.

Natural Environment Sector. The natural environment sector is one of the most comprehensively addressed areas in all four documents. A key indicator across all documents is the share of specially protected nature territories, aligning with the EU Green Deal objectives, which aim to increase protected natural areas to 30% of the total land area. This indicator reflects efforts to enhance biodiversity conservation, preserve ecosystems, and protect endangered species. However, while all documents acknowledge the importance of expanding protected areas, specific implementation strategies and monitoring mechanisms vary, particularly at the regional level.

Urban Environment Sector. The urban environment sector plays a crucial role in shaping sustainable and liveable cities, yet its integration across the four documents varies significantly. While some documents emphasize infrastructure development, others focus on mobility, air quality, and urban green spaces. A key indicator in this sector is the development of cycling infrastructure and pedestrian-friendly urban planning, which aligns with broader sustainability goals, including the EU's Green Deal and local climate action strategies. The RPR DP places a strong emphasis on cycling and shared mobility solutions, whereas the LSDS and NDP focus more broadly on urban infrastructure and energy efficiency. The EPG, however, lacks specific indicators on urban development, which may limit the ability to assess the environmental impact of expanding urbanization. Another notable discrepancy is the absence of clear indicators on air quality monitoring in dense urban areas, despite increasing concerns about pollution-related health risks.

Communal Environment Sector. In the communal environment sector, most documents, except for the NDP, emphasize the share of recycled and sorted waste, underlining the goal of increasing waste sorting rates. This aligns with the principles of the circular economy, where waste management is improved through enhanced recycling systems and waste reduction initiatives.

Environmental Protection Sector. The environmental protection sector reveals notable disparities between documents. The EPG includes monitoring indicators for soil radioactivity and seismic activity, ensuring public and environmental safety against potential hazards. Meanwhile, the LSDS highlights the necessity of monitoring nitrogen and phosphorus inflows into freshwater bodies, a critical factor in controlling water pollution and eutrophication. However, the NDP and RPR DP lack environmental protection indicators, leaving a gap in addressing pollution control and ecological risk management. This suggests a need for stronger integration of water quality, air pollution, and soil contamination monitoring across all planning documents.

Health Environment Sector. The health environment sector is the least covered, with monitoring indicators found only in the EPG. Key indicators include premature deaths due to air pollution and the number of residents receiving drinking water of adequate quality. These metrics are essential for assessing the impact of environmental factors on public health, particularly given the increasing risks posed by airborne pollutants such as PM2.5 and nitrogen oxides (NOx). The lack of comprehensive health-related environmental indicators in the LSDS, NDP, and RPR DP suggests that the direct impact of environmental conditions on public health is not sufficiently integrated into broader environmental strategies.

Climate Change Management Sector. Among all sectors, climate change management is the most extensive, featuring the largest number of monitoring indicators. All four documents highlight reducing GHG emissions and air pollution, which aligns with Latvia's commitments under the Paris Agreement and the EU's climate neutrality targets. Additionally, green infrastructure development is a recurring theme. The RPR DP introduces a range of specific indicators, including shared mobility solutions, public transport development, and regional cycling infrastructure, indicating a strong focus on sustainable transportation. However, renewable energy monitoring is only included in LSDS and RPR DP, whereas NDP and EPG lack indicators on renewable energy adoption, a key component in achieving climate neutrality. This suggests that national-level documents should better integrate renewable energy strategies into climate change policies.

Communication Environment Sector. In the communication environment sector, the EPG is the only document that includes a monitoring indicator, specifically related to environmental noise. The aim is to ensure that citizens have access to high-quality information on noise sources and their impact on industrial and urban areas. Given that noise pollution

is an emerging public health concern in urbanized areas, the absence of communication-related environmental indicators in other documents limits public awareness and engagement in environmental issues. Expanding this sector's monitoring framework could help improve citizen participation in environmental decision-making and ensure transparency in policy implementation.

Environment Management Sector. The environment management sector reflects governance and financial aspects of environmental sustainability. The LSDS includes a monitoring indicator for individual e-government usage, reflecting efforts to digitize administrative services and improve public access to environmental information. The RPR DP, on the other hand, includes indicators on basic budget expenditures for municipal environmental management and sustainable energy development strategies. These indicators highlight the role of governance and financial planning in ensuring long-term environmental sustainability. However, the absence of governance-related indicators in the NDP and EPG suggests that strategic financial planning and governance efficiency need further emphasis at the national level.

Analysis of environmental monitoring indicators across key strategic documents highlights both well-integrated focus areas and notable gaps in Latvia's environmental governance framework. While biodiversity conservation, climate change management, and waste sorting receive significant attention, public health, environmental protection, and renewable energy monitoring are inconsistently addressed. Lack of certain indicators in key national documents such as the NDP raises concerns about policy alignment and implementation effectiveness. Strengthening environmental monitoring across all governance levels is essential for achieving Latvia's long-term sustainability goals and fulfilling international environmental commitments. A more harmonized approach across national, regional, and municipal policies would ensure more comprehensive environmental planning, stronger public engagement, and enhanced sustainability outcomes.

5. Municipal environmental monitoring: Kekava local municipality case

Kekava Municipality is in the central part of Latvia, south of Riga, making it an important suburban area within the RPR. Due to its proximity to the capital, Kekava has experienced significant economic and demographic growth, serving as both a residential area and a business hub. The municipality covers an area of approximately 270 km² and has a population of around 24,000 residents, making it one of the larger municipalities in the region. The Daugava River flows through its territory, contributing to its natural and ecological value, while also presenting flood risk management challenges. Budget of Kekava municipality in year 2025 is 99.3 million EUR, including 0.25 million EUR devoted to the participatory budget.

The municipality consists of several towns and villages, with Kekava town as the administrative center. The economy is driven by manufacturing, trade, and logistics, with many businesses benefiting from the municipality's strategic location near major transport routes, including the A7 highway and Via Baltica corridor. Environmental considerations are crucial for municipal planning, as the rapid urbanization poses challenges in waste management, air quality, and green space preservation.

Kekava Municipality Planning Documents. Kekava Municipality Sustainable Development Strategy 2014–2030: This long-term planning document outlines the municipality's strategic vision, goals, and priorities for sustainable development up to the year 2030. It serves as a foundation for all subsequent planning and development activities within the municipality. Kekava Municipality Development Program 2020–2026: This medium-term planning document details specific objectives, tasks, and measures to be implemented between 2020 and 2026. It translates the strategic goals from the Sustainable Development Strategy into actionable plans, focusing on various sectors such as infrastructure, education, social services, and environmental protection. Kekava Municipality Spatial Plan 2019–2031: This spatial planning document defines the municipal land use policies and regulations for the period 2019-2031.

Following the administrative territorial reform in 2021, Kekava Municipality incorporated the former Baldone Municipality. This expansion necessitated updates to existing planning documents to reflect new administrative boundaries and integrate development priorities of the newly included territories. The municipality undertook a comprehensive review and amendment process to ensure that all planning documents accurately represent the expanded municipality's needs and aspirations.

As any municipal DP, Kekava DP have also chapter on DP implementation supervision, including the list of municipal indicators/pointers and, subsequently, **statutory required monitoring reports** measuring the progress made toward the set objectives during the reporting period.

Kekava municipality has good indicators, some directions of activity and monitoring indicators of Kekava municipality coincide with the planning documents of the national level, for example, indicators on forest cover and areas used in organic farming specified in the LSDS nature sector. Kekava municipality has also adapted in the communal sector to the planning documents of the Latvian level, placing emphasis on the share of recycled and sorted waste and paying attention to the reduction of GHG emissions in the climate change sector. Kekava Municipality DP has 4 Medium-term priorities with 2-6 Directions of

Actions; the following recommendations have been developed for their monitoring indicators:

1. Monitoring of natural resources and public outdoor space using the environment planning (EP) approach.
2. Extended monitoring of the social environment can be implemented by monitoring public order and accessibility of the environment.
3. Development in engineering infrastructure and business environment would be more valuable to monitor using target values or to carry out a percentage assessment of progress.
4. Indicators for monitoring governance and communication should be complemented by indicators indicating private sector involvement, citizen satisfaction and the quality of planning documents.

Monitoring program guidelines for Kekava municipality. The table below presents proposals for improving environmental management indicators in DP of Kekava Municipality, integrating new indicators to enhance sustainability and public engagement.

A significant improvement is the inclusion of **public monitoring indicators,** allowing for greater citizen participation in environmental data collection and, potentially, after monitoring communication and discussion and impact ok decision making. These include inventorying rare and protected species, monitoring invasive species, and tracking bird populations in urban areas. The urban environment sector emphasizes better park maintenance, dust reduction on streets, and improving accessibility for people with functional impairments.

In the communal sector new indicators address water quality monitoring, illegal waste dump tracking, and public satisfaction with waste collection services.

The environmental protection sector now includes tracking contaminated and revitalized sites and assessing water body quality.

The health environment sector introduces air pollution monitoring, while climate change management expands to measure GHG emissions from companies, and public transport improvements in both urban and rural areas. Additionally, communication and governance indicators promote environmental awareness campaigns, eco-school initiatives, and direct citizen communication with local authorities. Governance improvements emphasize citizen participation in advisory councils, thematic planning, and international cooperation on environmental projects. These updates aim to strengthen environmental sustainability efforts, increase transparency, and improve overall quality of life in Kekava Municipality. The proposed improvements to environmental management indicators in the Kekava Municipality DP reflect a more comprehensive, data-driven, and participatory approach to sustainability.

The proposed improvements to environmental management indicators in the Kekava municipality DP reflect a more comprehensive, data-driven, and participatory approach to sustainability (Table 2). By integrating public monitoring initiatives, the municipality enhances citizen engagement in environmental stewardship, fostering a more inclusive and transparent governance model. The expanded indicators also ensure better tracking of waste management, climate change mitigation, biodiversity conservation, and air and water quality, aligning with national and EU environmental policies. These additions will not only improve environmental sustainability and resilience but also contribute to a higher quality of life for residents, reinforcing their role as for the forward-thinking, environmentally responsible Kekava municipality.

Table 2

Proposals for improvement of development indicators of environment management in the development program of Kekava municipality, PM – public monitoring

Existing indicators	***Additional/proposed indicators***
Sector 1. Nature protection environment	
1. Area of forests owned by the municipality(ha) (% of total forest area) 2. Number of registered organic farms in the county	1. Specially protected nature territories in a favourable conservation state 2. Natural capital & ecosystem services, provision 3. PM- Inventory of rare and protected species 4. PM - Deposits of invasive species 5. PM Birds in feeders, public outdoor space 6. PM Accounting for Great Trees
Sector 2. Urban environment	
1. Public parks in each county town (Baldone, Balozi, Kekava) (number)	1. Public parks in towns permanently managed 2. At least conceptual plans have been developed for all public parks 3. Street and road maintenance measures to reduce dust 4. Program implementation to improve apartment buildings courtyards 5. Satisfaction of residents with urban amenities 6. The length of bicycles in towns and outside towns 7. Length of sidewalks, cycle paths for people with functional impairments

Sector 3. Communal environment	
1. Number of connections to the centralised water supply system 2. Connections to centralised wastewater system (Nr.) 3. Waste separation (Nr.) 4. Share of sorted waste (%) 5. Composting areas (Nr.)	1. Amount of composted waste 2. PM - number of illegal waste dumps 3. Composting municipal vegetation waste 4. Results of analyses of water intended for human consumption 5. Results of analyses of treated wastewater 6. Population satisfaction with waste points, quality of service 7. Population satisfaction: centralized water supply and sewerage systems
Sector 4. Environmental protection	
No indicators assigned	1. Nr. of contaminated and potentially contaminated sites, degraded areas 2. Recultivated, purified, revitalized objects (Nr.) 3. Proportion of good and high-water quality water bodies
Sector 5. Health environment	
1. Suitable different types of active recreation opportunities	1. Results of analyses of water intended for human consumption 2. Analysis/monitoring of air pollution (SO2, NO2, PM2,5, PM10, C6H6)
6. Climate change management	
1. Public transport routes (Nr.) 2. Renewable energy resources-based boiler houses (Nr.) 3. Electricity consumption per household (kWh/year) 4. Municipal buildings energy consumption (kWh/m2/y) 6. Length, cycle paths (km) 7. SEG emission	1. Renewables yearly percentage - primary energy consumption sources 2. Greenhouse gas emissions (CO2, CH4, N2O, SF6, HFC, PFC) 3. Greenhouse gas emissions per capita 4. Amount of greenhouse gases sequestered 5. Public transport routes in cities (Nr.) 6. Public transport routes in rural areas (Nr.) 7. GHG emissions from companies 8. Climate change adaption practice developments (to account and specify, e.g. free public access drinking water station/network spread etc.)
7. Communication environment (information, education, participation, pro-environmental behaviour)	
No indicators assigned	1. Environmental awareness measures (lectures, seminars, info days) 2. Energy efficiency projects: private (esp. multi-apartment) properties 3. Number of eco-schools 4. Application for direct communication with local government regarding objects that require attention, number of users and applications in it
8. Management environment	
1. Neighbourhood organizations (Nr.) 2. International cooperation projects (Nr)	1. Neighbourhood organizations in environmental management (Nr.) 2. Number of projects aimed at environmental development in the county 3. Developed thematic plans, number of concepts 4. Number of local government local plans and detailed plans developed 5. Activity and involvement of inhabitants in citizens' advisory councils 6. Citizens' satisfaction with environmental management

The proposed improvements to environmental management indicators in the Kekava municipality DP reflect a more comprehensive, data-driven, and participatory approach to sustainability. By integrating public monitoring initiatives, the municipality enhances citizen engagement in environmental stewardship, fostering a more inclusive and transparent governance model. The expanded indicators also ensure better tracking of waste management, climate change mitigation, biodiversity conservation, and air and water quality, aligning with national and EU environmental policies. These additions will not only improve environmental sustainability and resilience but also contribute to a higher quality of life for residents, reinforcing their role as for the forward-thinking, environmentally responsible Kekava municipality.

The findings across the academic and practice literature suggest that municipal environmental management indicators are most effective when not only tailored to local governance territorial SES, structures and participatory processes specifics, but also being as wide and coherent possible aligned, as first, horizontally both with own socio-economic sectors and also indicator systems of neighbouring municipalities, and secondly, vertically with all above

administration-management levels and up to also international ones. Furthermore, historical and contemporary best practice case studies highlight that consistent application practice and institutional support are key to transforming chosen indicators into actionable instruments for sustainable management.

Building environment governance in Latvia, based on these international perspectives, it was important to evaluate how effectively such approaches and principles are reflected in Latvia's own indicator frameworks at national, regional and, particularly, municipal levels, since being theoretically known worldwide in academia for a good while, but still not fully became everyday management practice due to limited capacity of financial and human resources, also limited general public awareness that might require monitoring of specific environmental indicators.

This was recognised also in Latvia, being still in the municipal environmental governance improvement process as due to administrative-territorial reform in 2021 reducing number of local municipalities from 119 to 43 and, subsequently, requesting design and preparations of new statutory municipal development planning Documents – long term Sustainable Development Strategy, mid-term (7 years) Development Program (incl. 1-3 years Action Plan and Investment Plan) and Spatial Planning Program as new opportunities for environmental innovations planning. Actually, 3-4 former neighbour municipalities were aggregated into one, what considerably increased monetary and institutional capacities, also environmental capacities, including, finally, establishing Environmental Protection-Management institutional division. Also, some previous positive environmental management traditions and experiences from separate municipalities were now brought together into the new aggregated municipality.

Current study of all the seven municipalities revealed in total almost 200 environmental management indicators from the statutory DP. However, due to logic overlapping objectives and similar methodologies, the number of accounted unique indicators is estimated to be below 100, with differences mainly in scope rather than distinct monitoring categories. This number of various indicators options do serves as very wide optional indicator experience practice data bank to be communicated between closest neighbours and within their planning region with own specifics, as well to all local municipalities and also above administrative levels, what, unfortunately, is still barely communicated, mutually studied and implemented, so indicators being shared in practice are just most traditional environmental management sectors.

The Communal Environment Sector and Climate Change Management sector are the most thematic spectrum-wide and detailed monitored sectors, with 54 and 50 indicators, respectively. These sectors obviously demonstrate strong continuity with higher-level planning documents, and good horizontal relationship between municipalities. This indicates that local governments have continued to prioritize traditional communal sectors of waste management, water and wastewater, also energy/heating management, actually as prescribed by Local Government Law. Newly developing Climate Change Management sector have been now rapidly expanding. Municipalities are ensuring that these two sectorial monitoring systems, and to some extent also traditional Nature Protection/biodiversity sector, do align with broader regional, national and international sustainability goals.

Although GHG emissions reduction, air pollution control, and green infrastructure development are included in all planning documents, municipalities in the RPR stand out by integrating mobility-focused indicators, such as car-sharing, public transport development, and cycling infrastructure expansion.

Also, particular detailed analysis of the chosen 1 of 7 municipalities of studied of RPR, being traditionally well pro-environmental, the Kekava local municipality's statutory planning documents, besides comparatively high number (18, as recently there were municipalities with 3-5 environmental indicators) and above average thematic spectrum of environmental indicators, also highlighted some gaps in Environmental Governance sectorial monitoring. There are missing indicators related to Environmental health, also Environmental protection and even traditional Urban environment sectors. Also, several other sectors require further refinement and standardization to provide a more accurate and comprehensive picture of environmental conditions. The sector importantly lacks sufficient indicators to assess environmental governance administrative and communication sectors, which are crucial for ensuring transparency, public engagement, and institutional accountability in environmental decision-making. Particular sectoral indicator recommendations (44 new eventual indicators) were prepared to improve monitoring systems for both Kekava municipality and, indirectly, to Latvian municipalities in general, emphasizing the need for more structured and data-driven environmental governance sector indicators.

There was also seen, that RPR development planning documents take a more holistic approach, especially, to sustainable mobility and urban planning, ensuring that climate action efforts extend beyond emissions reduction to include transport behaviour and infrastructure improvements.

This study highlights the importance of improving environmental monitoring systems across municipalities, ensuring that key sustainability goals are effectively tracked and that municipal policies are better aligned with national and regional strategies. While some sectors, such as climate change management and communal environment, already show strong integration, others require significant

improvements to enhance monitoring quality and policy coordination.

Conclusions

This study analysed key statutory overall development and environmental planning documents at national level, development programs (DP) at regional level for chosen Riga Planning Region (RPR) and all the 7 local municipalities in the RPR. The goal was to assess municipal monitoring developments and alignment between municipal and higher-level planning frameworks, identifying gaps and looking for new sector developments in monitoring, also proposing recommendations to enhance particularly municipal environmental governance monitoring.

1. Alignment of indicators across vertical governance levels. The key national planning documents as well as those of RPR and municipal DP do share a number of common environmental governance indicators. Not all the key and main sectorial indicators due to some objective reasons of data availability, but also due to subjective decision-making, are available and consistently integrated across those 3 governance levels, leading to gaps in monitoring, reporting, comparison and decisions.

2. Continuity of indicators in key sectors. The vertical analysis demonstrated strong continuity in Nature Environment, Communal Environment, and Climate Change Management sector indicators across 3 governance levels. However, general Environmental Management, Health Environment, Communication, and newly developing Environmental Protection sector indicators require both further horizontal and vertical cross-level integration development to ensure complementary and effective tracking and evaluation.

3. Municipal environmental development monitoring priorities. The greatest attention in municipal DPs is traditionally given to urban territory improvements, energy efficiency in buildings, and centralized utility systems, but recently also more for cycling infrastructure. While these priorities contribute to sustainable urban development, they do not comprehensively address all aspects of core environmental management, as even biodiversity conservation, climate resilience, and pollution control often remaining poorly monitored.

4. Local monitoring limitations due to national and regional planning. The inclusion of environmental quality and management indicators in municipal DPs is often restricted by the presence or absence of related criteria in national and regional planning documents. The lack of consistent data collection and reporting systems makes it difficult for municipalities to develop also comprehensive risk and resilience strategies.

5. Gaps in the new environmental health, communication, environmental protection sector indicators. In general, for municipal level, there are missing or inadequately defined indicators in the Health Environment, Climate Change Management (besides Energy sector), Communication Environment, and Environmental Protection sectors.

6. Limited public information, public and private sector involvement. The weakest areas in municipal DPs are public information dissemination, citizen engagement, private sector involvement, and environmental data collection in general. Households and businesses have significant impact on greenhouse gas emissions, but municipalities lack access to essential data regarding heating technologies, emissions from private sources, and other key environmental indicators. Without better cooperation between municipalities, private sector stakeholders, and national institutions, local governments remain limited in their ability to develop effective environmental and climate policies.

7. Detailed monitoring and upgrade planning for piloted municipality. Environmental management sector in the Kekava municipality have long standing positive development practice, including for development of professional environmental governance capacities. However, this does not match with actual DP prescribing now comparatively limited its implementation monitoring and insufficiency of having the whole spectrum of environmental indicators, also for assessing governance, communication, and public engagement. Interesting that some other RPR municipalities having less environmental capacities, but indicator lists are more comprehensive, however also still incomplete.

8. Administrative and financial capacities for municipal monitoring. When planning the introduction of new indicators and more comprehensive indicator systems, municipalities must evaluate their administrative capacities, technical expertise, and, particularly, also limited financial resources to support long-term environmental monitoring, data collection and data analysis. Obviously, effective monitoring requires many and various resources – **municipal capacities building is the key precondition** as well as overall cross-level monitoring system un the country.

9. Role of public involvement and participation in environmental monitoring. Given the financial and administrative constraints of local governments, municipalities should increase public participation in environmental monitoring to reduce costs and improve data availability. Citizen science experience develops already various multi-thematic monitoring initiatives, but even mono-thematic ones as monitoring water clarity with Secchi disks, tracking algal blooms, or reporting air pollution changes and more sophisticated ones could provide valuable environmental data at minimal cost. Also well-developed network of Green Flag/Eco-schools in Latvia may be first assistance.

10. Municipal indicator systems building and managing. The focus should be on expert and public collaboration un selecting meaningful indicators with balanced coverage across all environmental management sectors and links to socio-economic development,

potentially ensuring alignment with regional, national and EU planning levels. However, a unified mandatory core (and voluntary) indicators for cross-sectorial and cross-vertical monitoring system development in the country is required. This may save various resources, also financial ones, and strengthen environmental governance systems in Latvian municipalities. This **administrative system precondition** as well as **participatory precondition**, based on public monitoring, participation, and improved coordination are essential for driving measurable, data-based sustainability decisions.

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LOCAL ENVIRONMENTAL GOVERNANCE IN DVIETE RIVER BASIN: PARTICIPATORY WATER GOVERNANCE TARGETING

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Abstract
The study explores challenges in Latvia's environmental, particularly water governance system, including limited institutional capacities and resource constraints at all administration levels in parallel with comparatively low levels of stakeholders'/public engagement and collaboration, but exceptionally growing valuable elements of bottom-up participatory management. The EU HORIZON 2020 project BETTER LIFE based case study aims to explore current small river basin governance and practice management situation using a collaborative qualitative research approach (e.g., developing socially engaged research practice elements) within a research-and-development framework. Dviete River Basin (250 km^2) case study area possessing Natura 2000 site and known by especial long-term spring flooding, was investigated using case study research methodology for performing environmental governance and communication audit, management monitoring evaluation, also stakeholder mapping and building a stakeholder consultation and collaboration platform, all assessments based on complementary document and data resources studies, site visits with photo documentation, semi-structured interviews with representatives of all main stakeholder groups. Results show that river basin management system has been not built and is very fractured content-wise with limited horizontal and vertical integration, and insufficient management instrumentation, and also, stakeholder groups are still in the self-establishment process and rarely interact or collaborate within and between the groups and with management. However, there are voluntary experienced non-governmental co-management deeds towards nature and also water management to be studied and disseminated. Three bottom-line preconditions for the participatory co-management are recognized: a complex environmental communication system; a set of national and local acknowledgement and support instruments; development of horizontal collaboration instruments group.
Keywords: local river basins, participatory governance, communication, upgraded Helix stakeholders' model.

Introduction

Contemporary water governance internationally faces ongoing complexity, with some uncertainty and conflict at its basis, and scholars are again emphasizing that the core problem is exactly governance itself – the water governance process, institutions, and stakeholders. Mentioned is prompting again and again, mainly known for its approaches and that have been in place for a good while, but still have not finally led to their successful implementation, actually, **two key governance instruments – integrated water resource management (IWRM) and stakeholders' involvement and participation**.

For over two decades, Latvia's river basin governance system, according to the EU Water Framework Directive (WFD) goals, was initially established and based on focused planning (less management) on the four largest river basins, and with limited resources and capacities available, has achieved certain positive National monitoring and planning results. While **smaller river basins remain un-planned and under-managed due to limited capacities** at all three administration levels in the country – national, planning regions, and local municipal one. Improving general environmental management, e.g., including also surface water status, definitely requires stronger local stakeholders' engagement (e.g., farmer- and NGO-led initiatives) and socio-ecological system (SES) based cross-sectoral and co-management based and integrated basin-level governance system nationally and, especially, locally (Ernsteins et al., 2017b; Konkovs et al., 2022) with clear management responsibilities and capacities.

However, according to various scholars, **IWRM implementation has not been sufficient,** even in Europe after WFD since 2001, and this principle has been known for several decades, requested and promoted, and purposely communicated by various governmental and non-governmental international institutions and platforms; the results world-wide are limited. Also, those diverse success stories in Europe could be widely and target-oriented disseminated, and different other instruments employed.

Unfortunately, also the 2nd water governance key instrument mentioned has not been sufficiently implemented - **public participation in river basin planning and management has been minimal** even across most of Europe, with limited communication and little impact on environmental outcomes (Rimmert et al., 2020), but also citizen science is not sufficiently explored, particularly for multi-thematic monitoring, etc. Public activists could address key challenges of adaptive management by monitoring and stakeholder engagement, improving environmental management (Aceves-Bueno et al., 2015; Halbe et al., 2013). Again there is growing amount of research exploring participation potential to drive transitions toward more sustainable ecological, social, and political regimes (Von Korff et al., 2012).

Similarly, community-based conservation faces a crisis of identity due to weak participatory processes and limited attention to empowerment, but a slow shift toward participatory, collaborative approaches offers promise for linking environmental protection with stronger local institutions (Mulrennan et al., 2012). Various approaches and studies are growing

and recommendations are being designed, e.g., elaborated IUCN Natural Resource Governance Framework principles oriented towards inclusive, equitable, and locally devolved decision-making (Springer et al., 2021)

Environmental governance.

There are existing scholarly proposals as many as diverse for environmental governance defining, but within this paper framework, here shall be stressed first the following keywords to operate with: **systems, processes, institutions, stakeholders, and decision making/implementing, plus also instruments,** etc., as specifically necessary. Environmental governance could refer to the systems of rules, institutions, and practices that enable political stakeholders to shape environmental actions and outcomes (Lemos & Agrawal, 2006). More broadly, the processes, institutions through which society makes decisions affecting the environment (deLoë et al., 2009).

Our approach is comparatively quite similar (Ernsteins, 1999) as understanding environmental governance via governance process (cycle) and a **triple-dimensional governance (TDG) framework system** - governance stakeholder groups (who), governance thematic issues/sectors (what), and governance instruments (how), and all three as a complementary dimension system (Ernsteins et al., 2017b). TGD model, subsequently, is based on the following **three key mandatory principles:**

- applying socio-ecological systems – **SES principle;**
- all stakeholders' involvement and participation towards the **collaboration principle;**
- a whole set of instruments application – **complementary instrumentation principle.**

This applied governance model has been successfully serving in the studies for decades and for both structured governance situation analysis at the municipal and other territorial structures or organizational types and levels, including also state, NGO, business institutions and companies, as well as for elaborating action policies and practice recommendations and guidelines, and their testing/evaluating (Ernsteins et al., 2017a,b; Konkovs et al., 2022; etc.) as often working with research-and-development studies frameworks. Subsequently, we are looking for the process, where governance dimension systems interact inside and outside, and complement, to ensure a balanced governance approach to environmental protection, climate change, and sustainable development.

Governance target/interest groups/stakeholders. This approach (Ernsteins et al., 2017b) presents a hierarchical framework for all interest groups for necessary collaboration among all 5 **stakeholder groups-built governance segments**. The model is identifying and detailing the following stakeholders' interest groups into their related aggregation forms: state/national level organizations as ministries, agencies, etc., municipalities, businesses, society in general/households, and nowadays especially and importantly also mediators as actually influential stakeholders – media; formal & non-formal educators; legal and non-formal NGO's, community groups and opinion leaders etc; science/academia, consultancies etc. and particularly locally/regionally.

Governance content. Traditionally, environmental governance relied on a sector-specific approach basically focused on environmental infrastructure and nature protection sites etc. Recent research shows the limits of this approach when used alone. A shift toward new appearing sectors/issues and integrated governance sector models now aligns the environmental dimension with social and economic dimensions up to the fourth governance dimension of sustainable development, using a socio-ecological systems approach. Environmental sectors studies nowadays shall include necessary linkages and eventual integrated planning with health, education, agriculture, forestry, tourism, culture, and other sectors governance, promoting sustainability.

Governance instruments. In 2001, the EU adopted the Water Framework Directive (WFD) requiring the establishment of a river basin management system in the countries mandatorily applying integrated water resource management (IWRM) and necessary public participation, followed in 2004 by guidance on participation implementation. Subsequent reports reveal cultural, historical, and other social etc. aspects in both requirements to implement integrated river basin management and participation across Europe and highlight conditions for social learning and effective WFD implementation. They show that institutional, legal, cultural, geographical, and physical factors must be considered (Pahl-Wostl, 2004). Our study links these factors to **the whole set of governance instrument groups:** infrastructure-technologies, economic - financial mechanisms, communication, institutional - administrative frameworks, planning methodologies, and political-legal regulations (Ernsteins et al., 2017b). Within this framework, particular importance lies in the branch (also, nowadays disciplinary environmental sector (Ernsteins et al., 2017a) of environmental communication instruments, whose effectiveness in action-**oriented collaborative communication model** depends on four mutually reinforcing components, actually, instrument groups complementary necessary: information, education and training, public involvement-participation, and pro-environmental behaviour (Ernsteins et al., 2017a).

Towards water governance: an integrated and participatory system.

There is available wide range of scholar studies in particularly on the comparatively resent concept of water governance, actually starting widely this century and possessing various approaches, definitions, applications, etc. As just one of the most active and impactful actors here could be mentioned OECD,

having elaborated principles on water governance and implementation strategy. OECD is stating that 12 designed principles provide the must-work list for governments to design and implement 'effective, efficient and inclusive water governance systems', and for implementation, there was developed also water governance indicator framework, a water governance assessment guide, and a implementation handbook.

12 principles obviously do include innovative governance, monitoring, stakeholder participation, and all main governance principles, mentioned above, also some basic governance approaches as transparency, legal, etc. aspects. Finally, OECD defines **water governance refers to the political, social, economic, and administrative systems that influence water's use and management,** apparently using the UN Sustainable Development tripple-bottom line and later added political/governance dimension. Also, there can be seen elements of listing some governance instruments and transferring this eventual approach to our set of six governance instruments groups mentioned above, we may also get the following water governance framework definition: political and legal, institutional, planning, economic and financial, infrastructure, and communication systems, complementary used for water governance.

Effective water governance in river basins requires both institutional capacity and a nuanced understanding of stakeholder roles. As shown in research (Hong et al., 2024), stakeholder engagement frameworks offer tools for assessing systemic and structural strengths and gaps. Social network mapping approaches have proven valuable for identifying collaboration gaps, bridging processes, actors, and isolated stakeholders in conservation and water management networks (Vance-Borland & Holley, 2011). Integrating these insights with the mentioned triple-dimensional governance model perspectives as covering sectors, stakeholders, and instruments it enables more holistic and comprehensive planning, coordination, and adaptive management of water resources, balancing ecological protection with socio-economic needs (Konkovs et al., 2022), as for any socio-ecological system as lakes, river basins, etc.

Also, participation could be seen as shaped by three dimensions (Hofer & Kaufmann, 2022): actors (citizens, NGOs, institutions), arenas (spaces for decision-making), and aims (desired outcomes). These dimensions also show that participation occurs in both formal consultations and informal grassroots initiatives. For our governance studies in Latvia, we used a partially similar model (Ernsteins, 1999) with the already mentioned three interrelated governance dimensions - studying and managing these dimensions complementarily, practically enables vertical integration across levels, horizontal integration across sectors, and broad multi-stakeholder collaboration (Ernsteins et al., 2017b).

Various models and practice applications of governance have been outlined in environmental theories, including municipal, governmental, also business etc., governance, then the civil society model - also referred to as the **bottom-up (also participatory community-based, etc.) governance approaches,** emphasising public involvement (but not only) in environmental decision-making. Within this model, change occurs through dialogue and negotiation, placing priority on local interest group engagement. (de Loë et al., 2009). The public takes an active part, participating in discussions with different societal groups before final decisions are reached by communities, civil society representatives, and interest groups (de Loë et al., 2009; Sendzimir, 2013). However, **public participation shall be present at all stages of decision making** and together with all main and local stakeholder groups - **all the governance process cycle stages** (Ernsteins et al., 2017b):

- preparation process for decision making, a particular stage for cycle success (situation analysis);
- decision-making process itself (policy planning);
- planning process to implement (action planning);
- implementation process of decisions (management);
- assessment process of implementation (monitoring);
- concluding decision stage – process evaluation and replanning/preparing next cycle of decision making.

This process enhances responsibility and raises awareness, but it could also be an important contribution to the growth of participatory environmental (also, water, nature, etc.) management capacities and, importantly, in the local areas.

As highlighted in **participatory research models,** societal actors, especially now including all types of mediators, are no longer passive recipients of innovation and management, but active co-creators shaping research agendas and development solutions. In studies related to governance and innovation development, a comparable yet structurally distinct and differently emphasised stakeholder model is utilised – the Helix model of innovation management. The Quadruple Helix and particularly Quintuple Helix model offers a valuable management perspective (Schütz et al., 2019; Varmland County Administrative Board, 2019), expanding the basic traditionally applied Triple Helix framework – focused on necessary collaboration between academia, government, and industry – by including two additional components: civil society and the media.

This broader model emphasises the importance of knowledge exchange, innovation driven by a diverse range of societal actors (Morawska Jancelewicz, 2021), aligning well with the multi-stakeholder approaches needed for inclusive, adaptive governance. Building on this Helix-based conceptual approach, we combined the mentioned stakeholders' five segments model with the Helix approach, transformed the Quintuple Helix model, for a particular case, into the

Stakeholders Constellation Collaboration Model (Figure 2), designed to illustrate Helix-type stakeholders' necessary stratifications in environmental governance and communication.

This ongoing study's goal for the first research stage is to explore current river basin governance and practice management situation using a collaborative qualitative research approach to study conditions and perspectives for building up a still and crucially missing environmental, esp. water and nature protection sector management capacities, in particular, via a bottom-up participatory governance approach.

Materials and Methods

The current bottom-up participatory governance research case study, elaborated by the EU Horizon BETTER LIFE project, consisted of several research steps and stages with correspondingly chosen methodological approaches and related methods.

To enable analysis for bottom-up participatory governance and its management phase implementation practice, the first phase of the project studies included an overall assessment of the whole cycle of the environmental governance and communication processes, particularly water and nature protection governance in the territory of the Dviete river basin, as well as stakeholder mapping and consultation process with all stakeholder groups, described here below.

1. Projects and partners-based studies frame.

The EU Horizon project BETTER LIFE (BLIFE) coordinated in Latvia by Daugavpils University, have been studying and developing methodological frameworks on research cooperation, named **socially engaged research (SER)**, between life sciences scholars and various societal interest groups, basically including general public interest representatives, entrepreneurship, local and national governance institutions. The SER approach was used to establish the necessary framework and elaborate content and instruments for this particular selected study, summarized in this paper.

Also, scholars from the University of Latvia, in research partnership work with the Daugavpils University specialists, contributed substantially to the current BLIFE project study design, detailed elaboration, and implementation. In the same time, the BLIFE project case study territory chosen for bottom-up governance research case was the same Dviete river basin territory as has been used already for water retention studies and river basin situation modelling case by another EU Horizon project OPTAIN, realized by Daugavpils University. Part of the general data used for this paper was gathered within the initial stage of the OPTAIN project – particularly, implementation work of the multi-actor reference group (MARG).

2. EU BLIFE Project frame and realisation.

The project 'Bringing Excellence to Transformative Engaged Research in Life Sciences through Integrated Digital Centres – BETTER Life' is implemented in line with SER's mission to foster public engagement in co-creating knowledge and to ensure that life sciences research becomes more impactful, inclusive, and aligned with societal needs. The project aims to bridge the gap between researchers and non-academic sectors by developing tools, standards, and collaboration frameworks implemented at local and regional levels, as well as by building communities of practice to maximize the societal impact of research. It is grounded in the 5x Helix approach, bringing together academia and researchers, industry and business sector, policymakers and public administration, civil society and NGOs, and media and communication channels, ensuring their involvement in pre-research, research, and post-research phases. This approach was the basis for BETTER Life's decision to select the Dviete area as the OPTAIN case study site, where the creation of a MARG (Multi-Actor Reference Group) and the participation of key stakeholder groups were planned from the outset of the Horizon project, combining academic and practical knowledge to co-create sustainable solutions.

3. Case studies research: Dviete River Basin case.

The Dviete River basin was chosen as the study area due to its unique nature-culture and bottom-up experience characteristics. The Dviete River Basin covers a catchment area of 254 km², with an annual runoff of 0.057 km³. The total length of the river is 37 km, with a riverbed slope of 4 m/km in the upper reaches and 0.2 m/km in the lower reaches (Nature Conservation Agency, 2018). The Dviete floodplain experiences extensive spring flooding lasting 1 to 3 months, caused by extensive inflow of the main national river, the Daugava River. Flooding contributes to positive water dilution and natural cleanup processes, but it also affects the local population and economic practices.

The Dviete River Basin has a strong historical memory and lifestyle footprint that must be considered. This natural floodplain territory was extensively meliorated in the 1930s and later for intensive agriculture, shaping a long-standing agricultural tradition for several generations. However, this development also contributed to agricultural pollution of the main national river, the Daugava, and further into the Baltic Sea. Even today, accumulated pollution remains an issue, including within the Natura 2000 site.

After regaining national independence in the 1990s, step-by-step nature protection initiatives began, leading to the establishment of Natura 2000 in 2004. However, the site still lacks an administration, a supervising board, or a broader, stable platform or network. Many national and international projects have been implemented on about 20% (5000 ha) of the river basin, while growing EU environmental legislation affects the rest of the basin. Changes continue to conflict with some agricultural stakeholders and locals.

4. Case study design and implementation planning.

A socio-ecological system (SES) based research-and-development (R&D) framework approach was incorporated into an **integrated case study research**

methodology chosen for BLIFE project, utilising various and complementary realised research methods, including governmental and municipal, as well as research data basis and document studies, local related site visits and photo documentation, and conducting deep semi-structured interviews with key representatives of all stakeholder groups. Also, further elaboration of results from the OPTAIN project performed stakeholders mapping and consultations, and also, multi-stakeholder collaboration platform MARG establishment and running, now for three consecutive years. BLIFE Project research case consisted of the following **subordinated steps of the Dviete river basin case study research:**

- an environmental governance audit,
- an environmental communication audit,
- municipal monitoring audit in the river basin,
- stakeholder mapping and consultations (OPTAIN),
- stakeholder-based MARG process (OPTAIN).
- deep semi-structured interviews with representatives of all stakeholder groups (helixes) recognized, mapped in the Dviete river basin case, done as overall framing and complementary analysis of all steps done before.

5. Case study's research steps implementation.

The first research steps of the current study for the BLIFE project were environmental governance and communication audits of the Dviete River Basin developments. Initially, governmental, municipal, and research data bases were searched, particularly river basin management research, monitoring, and planning developments, with limited information available. Further studies were based on case territory-oriented document analysis, and legal, policy, and planning frameworks were examined at all three governance levels (national-regional-local municipal) in Latvia.

Under the Local Government Law, municipalities are responsible for 22 core (autonomous) functions, including waste disposal, heating supply, water management, sanitation, and resource conservation, while also supporting climate adaptation and mitigation initiatives. The Land Management Law designates municipalities custodians of inland public waters within their jurisdiction, excluding those in national parks, reserves, and other protected sites, which remain under national administration.

The Dviete River basin forms part of the Daugava River Basin, one of four major basins in Latvia, established under the EU Water Framework Directive (2000/60/EC). The Dviete Floodplain Nature Park, established in the delta region of the Dviete river is governed by a Nature Conservation Plan (2020–2032). Particular emphasis was laid upon local municipality development, everyday practice framing **statutory and voluntary documentation studies.** Initially, analysis of the all-statutory municipal planning documents (Sustainable Development Strategy, Development Program, Spatial Plan) and other related documents was performed for the former local Ilukste municipality, as it territorially covered most of the Dviete river basin, but then the municipality was administratively incorporated into Augsdaugava local municipality following national territorial-administrative reform in 2021. Particularly, **monitoring documentation studies** included the Environmental Report, the Monitoring Report for the Ilukste Territorial Plan (2019–2030) developed under the Strategic Environmental Assessment (SEA) Law requirements, and other documents. The same and more varied documents were studied for the newly expanded Augsdaugava municipality. All document studies were complemented by stakeholder interviews.

6. EU OPTAIN Project frame and realisation.

The Dviete River basin was also the selected study site, where an EU Horizon 2020 project initiative, 'Optimal strategies to retain and reuse water and nutrients in small agricultural catchments across different soil-climatic regions in Europe (OPTAIN)', focuses on conserving and reusing water resources within small agricultural basins (<250 km^2) throughout multiple European locations and countries, having 14 case studies altogether in EU countries.

The primary objectives of the OPTAIN study were to identify, engage, and manage consultation with all relevant stakeholder groups, like farmers, tourism companies, NGOs; furthermore, the research sought insights from local government officials, environmental specialists, and local practitioners, aiming to gather academic and practical knowledge on implementing water conservation, reuse practices, and general management in the Dviete basin. A thorough evaluation of these potential water retention measures, along with related modelling at farm and basin levels, will lead to the creation of science-based recommendations for Latvian organisations at different administrative levels, together with policy-focused reviews prepared with the EU project consortium for European partners. The project tasks, local adaptations, earlier research & development models, and existing traditions (Ernsteins et al., 2017b) have been completed.

7. EU OPTAIN studies results evaluation.

Initially the overall situation with all main and most active stakeholders around the case area was considered. **Stakeholder mapping and consultations** (series of short-timing express interviews) were carried out using a design by the University of Latvia (Ernsteins et al., 2017a, b) - **Quintuple Helix Stakeholders Constellation and Collaboration Model** (autonomously designed and tested stakeholders grouping model, being transformed as a revised version of the traditionally known Quintuple Helix model) to identify and detail each of the 5 stakeholders' interest metagroups or stakeholder groups' formed segments (Ernsteins et al., 2017a, b). A total of 50 stakeholders' representative organi-sations were mapped: state (8), municipalities (10), businesses (6), society (5), and mediators (21). Based on audit results, the specifics and importance of each sub-group's involvement in the project were assessed,

guiding the involvement activities for the MARG platform and selection for deep interviews.

Following, the **stakeholder engagement process** was studied and co-organised, being structured through the mentioned **MARG collaboration platform**, established by the OPTAIN project and aimed at strengthening local and regional water retention evaluation & planning in the Dviete River Basin. To date, three annual MARG meetings have been held, with representatives from all target groups, with 10-12 participants per meeting - working with planning and reviewing OPTAIN project progress, analysing the current tasks, and discussing future research directions as in relations to the stakeholders practice interests and perspectives. **Action research approach** elements-based investigations and developments were applied.

8. Complementary stakeholders' interviews.

Finally, but complementary to all above mentioned studies of Dviete case, both for BLIFE project-based list of studies and the OPTAIN project-based produced information, in total 21 **deep semi-structured interviews were conducted.** Interviews were realized mostly in person with representatives of all stakeholder groups as for revised Quintuple Helix Stakeholders model- from state agencies (3 persons), municipalities (5), businesses (3), society (2), and joint group of mediators, including NGOs (2), media (1), educators (1), and academia (2 persons).

Results and Discussion

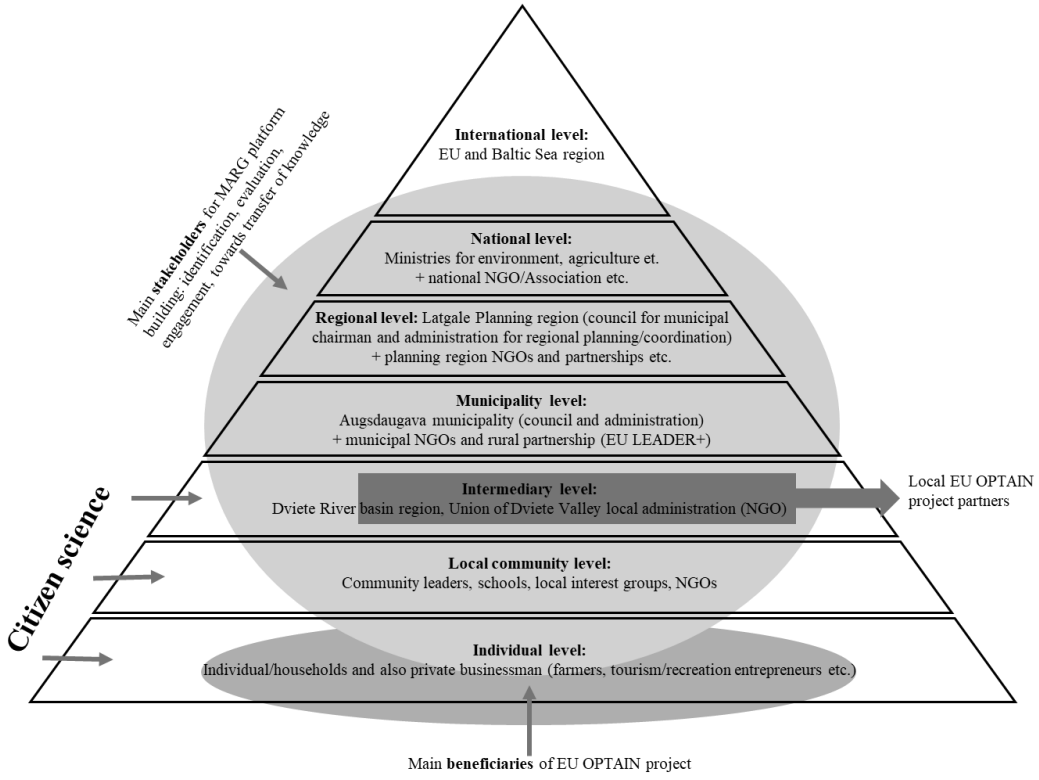
In the results section, we will review the research conducted in the first phase of the study, including all the steps mentioned un methodologies chapter. The results of conducted a whole set of deep semi-structured interviews with representatives of all stakeholder groups (helix) has to be integrated in all research steps realized.

1. Environmental governance audit

At the start of the project, one of the first tasks was to conduct an environmental governance situation analysis within the basin area. This analysis was carried out using **three dimensions of environmental governance: instruments, target groups, and content** (thematic sectors related). The primary focus was on three sectors: water resources, environmental protection, and socio-economic aspects, ensuring a comprehensive assessment of the region's environmental governance and sustainability challenges. A comprehensive approach is adopted, **integrating all groups of management instruments**, namely: Policy and legislative tools; Institutional and administrative mechanisms; Planning strategies; Economic and financial instruments; Infrastructural and technological solutions, and Communication instruments, complementary, emphasising information, education, participation, and environmentally responsible behaviour. Successful environmental and socio-economic projects require a structured, multi-level governance system (Figure 1) as applied for the current study.

Figure 1

Dviete river basin stakeholders: Vertical integration approach for governance levels and towards horizontal integration for governance sectors (Ernsteins, et. al. 2024).



The model links international (EU), national (ministries, NGOs), regional, municipal, and local actors through vertical coordination, while horizontal integration ensures cross-sector cooperation in nature protection, environment, forestry, eco-tourism, agriculture, and socio-economic development.

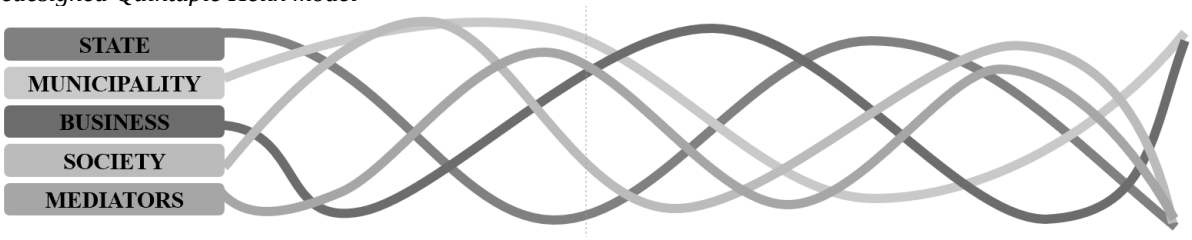
The framework includes all major stakeholders: municipalities (four levels), state and regional bodies, corporate sector, households, and citizens. It also stresses the role of mediators - NGOs, media, educators, and research institutions - in knowledge transfer and engagement. The model ensures direct benefits for individuals and communities, while local partners strengthen citizen science, collaboration, and sustainable decision-making (Figure 1).

An in-depth assessment of target groups was carried out for this case study, and representatives for detailed interviews were selected using a modified five-spiral collaboration model, which organises interactions within five governance sectors: state, municipal administration, businesses, society, and mediators. This method creates a structured system for examining and defining stakeholder engagement, grouping them into five interconnected collaboration spirals. These spirals illustrate evolving, interlinked relationships, forming a hierarchical cooperation structure that improves governance efficiency (Figure 2).

Unlike Helix models that consider public authorities as a single unit, this framework separates state administration (which includes various, often competing, national-level sectors, e.g., ministries, their agencies, etc) from municipal governance, along with regional administrations and planning bodies in Latvia. Although municipalities officially belong to the broader state administration system, real-world observations reveal that these two groups frequently operate with different information, perspectives, and priorities in various contexts. Consequently, distinguishing these stakeholder categories is crucial. Additionally, mediators play a critical role in governance and communication, divided into four sub-groups: media, educators (both formal and informal), NGOs (including professional and society-based organisations), and the academic/scientific sector. This model illustrates both the vertical and horizontal dimensions of stakeholder interaction, emphasising the necessity for collaboration to create a fully integrated and complementary nationwide governance system. To ensure effective environmental governance is to be required: engagement across five key segments is state administration, municipal governance, individual/household participants, corporate entities, and mediators. Achieving a balanced and interactive relationship among these sectors is essential for a well-functioning and sustainable governance framework. A variety of instruments are applied in managing the Dviete River basin, supporting efficient governance and long-term sustainability. Regulatory and political measures include the Dviete Nature Park conservation plan, as well as other legislative directives that regulate land use and regional growth. Administrative and institutional mechanisms consist of municipal environmental specialists and natural resource departments, overseeing land management and pollution control, alongside state agency divisions tasked with supervision and inspections across Jekabpils and Augsdaugava municipalities. Planning instruments play a key role in strategic development, with documents such as the Development Program, Ilukste Municipality Territorial Plan (2019–2030), and the Sustainable Energy and Climate Action Plan (until 2030) guiding long-term initiatives. Financial and economic instruments support environmental protection through project funding for conservation efforts, particularly in the Dviete Nature Park, as well as investments in infrastructure improvements. Infrastructure and technological instruments include drainage and stormwater systems, water supply, and wastewater management facilities, ensuring ecological stability. Lastly, communication instruments enhance public awareness and engagement, including the Dviete Valley Information Centre ‘Gulbji’, tourism guides, and educational activities such as environmental classes, fostering knowledge-sharing and sustainable practices.

Figure 2

The Constellation collaboration model of the main stakeholder groups (Ernsteins, 1999) – represented as redesigned Quintuple Helix model



The primary environmental management sectors within the Dviete River basin have been thoroughly examined. In the environmental protection domain, pollution control was evaluated, leading to the identification of potentially contaminated sites across the region. A total of 14 locations with possible pollution issues were discovered, including former landfills, warehouses, and fuel storage facilities.

Additionally, flood-prone zones and high-risk areas within the basin were mapped, with the Pilskalne administrative territorial unit of municipality at risk from Daugava River floods and the Dviete administrative territorial unit of municipality impacted by Dviete River overflow.

In current conditions as **positive characteristics** shall be mentioned the following territorial development aspects - belonging to the NATURA 2000 network, unique habitats, rich cultural history as one of Latvia's oldest inhabited areas, ecotourism potential, active NGO involvement, and community support for participatory governance. But as negative ones - outdated water and sewage systems, poor waste management and drainage infrastructure, limited National financial support, agricultural pressures, potential pollution sites, weak transport connections, and insufficient intersectoral communication. Also climate change impacts such as ecosystem degradation and increased flood risks, demographic decline due to rural depopulation, and vulnerabilities in agriculture linked to changing climate conditions.

The environmental governance audit in the Dviete River Basin revealed that the necessary better environmental and water governance is currently missing and requires a multi-level governance system - both vertical and horizontal—as well as coordination across sectors such as environment, agriculture, tourism, and socio-economic development. The audit emphasised that under these conditions, the importance of a bottom-up approach is especially widely applicable (besides Dviete Valey municipal society). In terms of water management, the audit found limited planning, technical, and administrative capacities. Although the area is part of the Natura 2000 network and should be actively managed, due to these limited capacities, a local NGO has taken on this responsibility. The audit also highlighted the necessary strengthening of environmental communication.

2. Environmental communication audit

The environmental communication action-oriented model (Ernsteins et al., 2017a) applied, consists of four mutually complementary instruments – environmental information, environmental education, public engagement, and pro-environmental behaviour actions. The audit conducted in the Dvietes River Basin revealed the need to strengthen communication among stakeholders. While environmental information is shared through various channels, there is considerable potential to enhance collaboration. Effective bottom-up communication depends on strong engagement, which is currently underdeveloped in the region. Systematic planning and sustained efforts, beyond the voluntary work of NGOs, are required to improve environmental communication, emphasising its crucial role in fostering understanding and cooperation. The environmental communication audit in the Dviete River Basin, based on the action-oriented communication model (Ernsteins et al., 2017a), identified the need to reinforce cooperation and information flow among stakeholders through four key complementary communication dimensions. The audit stressed that strengthening community involvement beyond the voluntary efforts of a few NGOs requires systematic, continuous planning, even though there is no real coordination or work capacity, is to be taken by municipal administrative-territorial units of particular territories and/or knowledgeable local NGOs supported by local communities.

Environmental information includes municipal websites, e-encyclopaedia, dvietespaliene.lv (LIFE+) and the OPTAIN project, as well as the Dviete Nature Park tourism plan (2009) and recent guides (Augsdaugava 2024, cycling, water tourism, surroundings). Information is provided on stands about the park, restoration works, birds, wild horses and cattle, corncrake habitats, and directional signs. Additional materials include articles, videos, and features on the floodplain and cultural heritage. Information points are provided by the 'Gulbji' centre, Daugavpils tourism centre, Dviete municipal union, the Nature Conservation Agency, and the Regional Environmental Board.

Environmental education is carried out by the 'Gulbji' centre, which organises ecotourism, exhibitions, monitoring, consultations, public education on natural values and lifestyle, and provides a children's classroom. Events include Birdwatching Days, open-air activities, landscape and lichen hikes, and the youth hike 'We Go into Nature!'.

Public participation is reflected in park management with local involvement. The Dviete municipal union works on biodiversity and heritage protection, implementing the park's conservation plan, promoting ecotourism, and preserving the rural landscape.

Pro-environmental behaviour is expressed through conservation and restoration plans, meadow restoration, floodplain management, and aquatic plant studies. Actions include corncrake habitat restoration, improving birdwatching, and reducing human pressure. Tourism and education cover the floodplain development plan, water tourism during low water, and equipment for the nature classroom. The OPTAIN project targets reduced water and nutrient runoff.

Overall, the audit emphasises that enhancing environmental and nature communication of both outer and especially inner as within stakeholder groups and between them, is crucial for fostering collective understanding, towards collaboration and sustainable action in the region, currently being widely developed and applied. Leading role and general model of NGO Dviete Valey municipal society working for public good shall be further supported, utilised, and possibly multiplied. Environmental communication within the agricultural sector is limited, particularly regarding water retention issues, where available information is minimal and communication is virtually non-existent. In contrast, the Nature Conservation Agency engages

in comparatively extensive communication, facilitated by the implementation of several projects, the placement of informational stands, and targeted interaction with youth audiences. At the same time, prolonged and complex communication processes are ongoing between the Ministry of Environmental Protection and Regional Development, the Ministry of Agriculture, and local activists concerning wild animal populations introduced within the Dviete floodplain area as part of a project. Additionally, the Latvian Environment, Geology and Meteorology Centre conducts water monitoring every six years; however, communication with municipalities and local stakeholders in this context is practically absent.

3. Municipal monitoring in Dviete River Basin

The shortcomings identified in the environmental governance, communication audit revealed significant issues in environmental governance generally. Therefore, this chapter examines the development of monitoring in the Dviete River basin, with focus on water and nature protection, as well as public participation. Until the 2021 Administrative Territorial Reform, the territory of the Dviete River basin was part of Ilukste Municipality (647.5 km²; 7,500 inhabitants), which consisted of 8 local territorial administrative units (parishes). After the reform, Ilukste Municipality was merged with Augsdaugava Municipality (2,523.6 km²; >35,000 inhabitants).

In Ilukste Municipality in 2019, within the previous planning period (2014–2021), territorial development plan (2019–2030) was prepared, which was also reviewed together with the Ilukste Municipality Development Program for the new planning period (2020–2026). According to the national supervision of the former Ilukste Municipality's Territorial Planning (Ilukste Municipality, 2019a), the Environment State Bureau of the Republic of Latvia (ESB) has stated in the Environmental Report that the municipality must submit a monitoring report to the bureau at least twice during the next planning period (in 2020 and 2024), which should be prepared based on the list of specific indicators, which was divided in eight key indicator groups, including surface water and air quality, polluted sites, waste and wastewater management, and protected areas.

However, already the 2020 report (Ilukste Municipality, 2019b) showed major data gaps: several indicators lacked any information (e.g., wastewater management, polluted sites), and other data provided were either outdated or generalized, offering limited insight into specific environmental trends. For example, surface water assessments were based on data from 2013, and there was no information on official swimming areas or degraded land. Additionally, it has been noted that the information provided in the report does not directly correspond to the specified indicators.

Similarly, in this report, based on 2013 data, the water quality of the Dviete River was assessed as medium; however, in the Daugava River Basin Management Plan (2022–2027), the ecological quality of the Dviete River basin is assessed as poor (Nature Conservation Agency, 2018). Furthermore, information on the nature conservation sector in this report is limited.

The Ilukste Municipality Development Program Implementation and Monitoring Document (2020–2026) outlines a total of 72 medium-term development indicators (Ilukste Municipality, 2020). Although these are monitored annually across multiple sectors, none of the 72 indicators fully cover environmental governance sectors, water resource governance, nature conservation governance, or water retention issues. Moreover, the development program (Ilukste Municipality, 2020; 2019b) does not sufficiently integrate the indicators established by the ESB, highlighting a gap between national environmental priorities and local planning frameworks.

Following the 2021 territorial reform, which merged Ilukste Municipality into Augsdaugava Municipality, a new set of general and sectoral development indicators was defined for the newly formed administrative unit. The Augsdaugava Development Program Implementation Monitoring and Evaluation Document (2022–2027) (Daugavpils City & Augsdaugava Municipality, 2021a; 2021b) outlines a total of 85 performance indicators. Of these, 32 are related to environmental governance, though not all environmental sectors are covered. Only two indicators address water management broadly, without directly targeting water governance. In the context of nature protection governance, four indicators are defined, mainly focusing on waste management and invasive species control. Notably, there are no indicators related to water retention. Meanwhile, the new Augsdaugava Territorial Plan and its list of indicators are still in the development phase and are currently unavailable to the public.

Also, the previously required ESB monitoring report was no longer prepared in 2024, as such indicators are not included in the current list for the newly formed municipality, and the Environmental Department in Augsdaugavas municipality is not informed about the need for this monitoring report.

Water retention is not specifically assessed or addressed in key planning documents. Although state-level monitoring of the Dviete River occurs twice every six years, the municipality is unaware of this activity. As a result, the municipal assessment of water quality is rated as 'medium', while the national assessment classifies it as 'poor', indicating a significant gap in information and perception (Latvian Environment, Geology and Meteorology Centre, 2021). The audit highlights the critical need for clearer, more targeted monitoring frameworks that directly address environmental sustainability, particularly water and also nature protection governance, and policy implementation effectiveness in municipal planning, even if municipal capacities are limited – for

this situation, a citizen science approach (local communities-based monitoring) could be widely introduced as such capacities are available.

4. Stakeholder mapping and consultations

During the initial phase of the study, a situational audit of target groups was performed in the Dviete River basin region within the OPTAIN Project frame. The revised upgraded five spiral-type stakeholder grouping recognition and potential collaboration framework functions as a structural model for defining and organising stakeholders, systemically arranging them into five interlinked quintuple Helix spirals (Figure 2). These groups were accordingly classified, segmenting them into five categories: state, municipalities, businesses, mediator groups, and general society.

The state segment includes three ministries: the Ministry of Environmental Protection and Regional Development (with regional environmental boards, the meteorology and geology centre, and the Nature Conservation Agency), the Ministry of Agriculture (forestry, agriculture, fisheries, with regional departments), and the Ministry of Economics (tourism through the Investment and Development Agency of Latvia). These institutions ensure national policy, supervision, and sectoral governance.

The municipal segment consists of Augsdaugava municipality, covering the Dviete river basin and Natura 2000 site, with its institutions and territorial administrations (e.g., Bebrene, Pilskalne, Dviete). It also involves neighbouring Jekabpils municipality. Additionally, tourism centers, development agencies, training centres, and the Latgale Regional Planning Council support local governance and cooperation.

The business segment primarily includes large agricultural enterprises managing this territory, local farmers (livestock, crop, organic farming), and tourism service providers (guesthouses, boat rentals, guiding services). They ensure practical resource management and regional economic development.

The mediator segment is divided into four main sub-segments: media, educators, NGOs, local/regional research-/consultants and wider as academia. During the identification of stakeholder groups, with a particular focus on environment-nature-water-agriculture sector interactions (Nexus approach), a total of eight NGOs were identified as being directly connected to this region. Within this segment, NGOs play a particularly significant role, especially the local 'Union of Dviete Valley Municipalities', which is actively involved in managing the area and contributes to environmental governance and public engagement.

The society segment encompasses informal civic activities, which can be divided into four main categories: Households; Individuals – local activists and opinion leaders; Social and interest groups – representatives of informal initiatives; Local resident/household communities.

Overall, the Stakeholder mapping revealed a wide/sizeable, also complex and diverse stakeholder landscape, but also with very limited interconnections between stakeholders and their groups. This very limited interconnectivity is to be seen in both directions – as was expected between sectors, even in closely linked nexus areas like water–nature–agriculture, but also not very much more within each sector. And, a third direction – inside stakeholder groups, between various group members. The number and type of stakeholders within all five groups are sufficiently good for implementing integrated, cross-sectoral water and environmental governance, but a very selective, careful, and stepwise communication and interaction process is crucially necessary to reach such governance process qualities.

Also, a kind of 'crystallisation points' – such as trustworthy organisations or networks, platforms (including e-ones) – are required for the facilitation of communication and, further on, for collaboration developments. Ideally, there should also be some instruments (also financial, of course) as part of supportive mechanisms/environment from the national level, either directly or via municipalities or municipal planning regions, crucial based on the Nexus approach, emphasising collaboration across environment, nature, water, and agriculture sectors.

5. The stakeholder participation: MARG process

The establishment and operation of the Dviete River Basin management Multi-Actor Reference Group (MARG), realized as part of the OPTAIN Project frame, focuses on engaging all key stakeholders within the catchment area. This includes local governments and their services, regional and national agencies for water and nature protection, farmers, agricultural specialists, and advisors, as well as thematic groups like the tourism sector. More local community leaders, interest groups, NGOs (both professional and public), scientists-experts may play an integral role in MARG. This diverse representation benefits stakeholders by enabling them to influence the OPTAIN Project research process, integrating local knowledge and a shared vision for regional progress. It also creates opportunities to explore innovative methods and techniques for improving water and biogenic management in agricultural landscapes. Moreover, by facilitating engagement between farmers, agricultural advisors, and policymakers, MARG contributes to shaping agricultural policy frameworks.

Initially, the project attracted significant interest, with more than 15 participants representing the main stakeholder groups. However, participation declined in subsequent years, with only 8–12 stakeholders regularly attending. This decrease in engagement can be attributed to several factors. First, water retention was not a priority for local farmers and some other stakeholder groups. Second, the project's focus on modelling water retention, rather than the development of physical infrastructure or pilot cases, did not align with the expectations of many local stakeholders, who understandably prioritised tangible outcomes.

Additionally, several early participants cited scheduling difficulties as a barrier to sustained engagement, as it was challenging to find meeting times that suited all stakeholders. Furthermore, the geographical distance to the Dviete basin centre significantly limited the involvement of national and regional stakeholders. In response, hybrid meeting formats — combining in-person and remote participation — were introduced, which improved stakeholder engagement. This flexible approach reduced the time commitment required for participation, with meetings no longer demanding half a day or more, and thereby facilitated broader and more consistent involvement.

The development of MARG (Multi-Actor Reflective Group) progressed gradually as part of the broader social learning and adaptation process, indicating the potential for such an approach to evolve at the local level. However, this development must be considered in light of the contextual factors and conditions described above. A key enabler of future progress is bottom-up interest — particularly when the issues addressed are concrete and timely for multiple target groups simultaneously. Additionally, top-down support is essential: national and regional institutions in water management, nature conservation, environmental protection, agriculture, and tourism sectors need to actively promote stakeholder engagement, especially through information-sharing and interactive communication tools. Furthermore, a locally recognised organisation, such as the Dviete NGO, could play a central role in coordinating these types of MARG instruments at the grassroots level.

MARG process strengthens bottom-up water and nature protection governance by actively involving local stakeholders—such as farmers, NGOs, experts, and policymakers—in decision-making and research planning. Through inclusive communication and knowledge sharing, MARG can support the development of context-specific, innovative solutions for agriculture and water retention, etc. This participatory approach may improve understanding of regional challenges and enhance the design of effective policies and measures, but ultimately, it fosters collaboration across levels and sectors to build resilience, ensure sustainable water and land management with one main precondition - selfishly bottom-up coordinated and top-down supported.

The case of the first-time also summer floods in 2025 in the Dviete river basin further underscored the need for flexible, locally adapted water governance in small catchments. As recent research also emphasises, effective river basin management must integrate not only environmental content and instruments, but also governance structures that meaningfully engage stakeholders across all levels and sectors (Ernsteins et al., 2017b; Vance-Borland & Holley, 2011). Related approaches, e.g. Natural Resource Governance Framework by IUCN, support this by promoting knowledge co-creation and cross-sector integration as essential elements of adaptive governance.

The environmental governance audit in the Dviete River Basin clearly demonstrates that current governance instruments and mechanisms, particularly in water and environmental management, remain fragmented and underdeveloped. Despite part of the Dviete river basin area being designated a Natura 2000 network, national institutional and technical capacities at the regional/local level are insufficient, also missing permanent administration at the Natura 2000 site, resulting in direct or indirect reliance on local civil society actors, such as NGOs, to fulfil essential environmental functions. Particularly, it is to be mentioned again the leading NGO in the Dviete river basin area –the Union of Dviete Valley Municipalities.

Moreover, the governance audit reveals that weak intersectoral coordination and the lack of strategic communication frameworks hinder effective collaboration among key stakeholders, including also between state institutions and municipal authorities. Compared to the traditional Helix models (Schütz, et al., 2019; Morawska Jancelewicz, 2021), the more detailed separation of stakeholder categories done for these studies, e.g., including four mediator groups – not only NGOs, but also regional/local media, formal/nonformal educators, and particularly local/regional research/expertise (esp. academia, also consultancies etc.) - is particularly relevant in this context, as these groups are critical in facilitating communication, knowledge transfer, and public engagement but remain underutilised in practice.

Additionally, while a wide range of governance instruments are formally present - ranging from legislative instruments to various communication mechanisms - their implementation is uneven, not well coordinated, fragmented, and non-complementary. Notably, not only are water retention practices not addressed in municipal planning documents, but also water resources management and protection are barely mentioned, besides traditional sectors of drinking water and wastewater issues.

The environmental communication audit (incl. information, education/training, participation, and pro-environmental behaviour) in the Dviete River Basin revealed critical gaps in stakeholder collaboration, particularly in bottom-up engagement and systematic planning. Also, not only is environmental communication within the agricultural sector very limited, but also in water governance or the whole environmental governance process, thus reflecting broader governance capacity gaps to be addressed via integrated, cross-sector stakeholder engagement. The action-oriented communication model applied for the audit underscores the need to strengthen and complementarily employ all four communication dimensions - information, education, engagement, and

pro-environmental actions - especially beyond the voluntary work of NGOs. A more coordinated approach, supported by municipalities and informed local actors, is essential for fostering sustainable cooperation in the region.

The municipal monitoring system continues to be gradually improved, particularly following the administrative-territorial reform in 2021, when smaller municipalities were merged, which also increased the environmental management capacity of local governments. However, municipalities still lack the resources and capacities to develop and, more importantly, implement a fully functional and sufficiently detailed indicator system - especially in the domain of environmental governance. Environmental governance in contemporary always expanding understanding is still not a priority for municipalities, besides traditional statutory household services as waste, heating, water (supply/wastewater) sectors, even though public interest in environmentally friendly actions is gradually increasing.

Similarly, in the field of water resource management, municipal monitoring of the sector's diverse aspects remains very limited, even though the national river basin management planning system has already been in place for three cycles of seven-year planning. Yet even at the national level, management capacity remains insufficient. For more than two decades, river basin planning in Latvia has prioritised large basins, while small river basins like the Dviete river basin (250 km2) have been largely overlooked due to capacity constraints - both at ministerial and its regional levels, as well as also municipal level, traditionally not involved in river basin monitoring and planning. Also, EU Water Framework Directive-based Consultation Councils, including representatives of national/regional NGO's, are being established at each of the four existing national river basin districts, are financially strictly bound, looking for additional actions and innovations. As a result, this eventual NGO bottom-up impact is clearly limited too.

In this broader context, there is a particular need for bottom-up governance - namely, local community-based co-governance and the development of forms and opportunities for public monitoring. In the studied case of the Dviete River basin, such opportunities can be supported by the local NGO Union of Dviete Valley Municipalities, as well as by the MARG collaboration platform established within the Horizon 2020 project OPTAIN, which shows potential for further participatory governance development.

The stakeholder mapping revealed a wide but weakly connected network across five key stakeholder groups. Despite sufficient existing diversity for cross-sectoral governance, collaboration is limited both between and within sectors. Strengthening communication through trusted actors or platforms and providing supportive instruments - especially at the national or regional level - is essential for enabling effective water-nature-agriculture nexus-based governance. This aligns with broader theoretical models of environmental governance that emphasise inclusive participation, co-creation of solutions, and decentralisation of authority (de Loe et al., 2009; Lemos & Agrawal, 2006).

The development of the Multi-Actor Reference Group (MARG) in the Dviete River basin has shown that stakeholder involvement in water and nature governance can grow gradually – provided local interest and institutional support align. Initial enthusiasm was high, but participation declined due to the limited relevance of water retention for some stakeholders, lack of visible infrastructure outcomes, and logistical challenges. Hybrid meeting formats improved accessibility, and discussions led to clearer shared recommendations. While the MARG approach has not yet fully matured, it shows potential to evolve into a local coordination instrument. The MARG working sessions contributed directly to research prioritisation, indicator selection, and feedback on proposed water retention measures.

While there is interest in joining MARG, more regular, targeted communication and practical support, such as consultations or training, are needed, as the strictly scientific nature of the OPTAIN project limits local participation despite generally positive perceptions. MARG participants want practical projects like river cleaning and tourism improvements, local activism remains limited, being outside project-based and with very limited state and regional support due to low local management capacity—especially for the NATURA 2000 area, still voluntarily managed by a local NGO with limited municipal assistance.

The issue of water retention has so far not been widely addressed or practically implemented at the municipal level. Water retention is not integrated into municipal strategic and action planning or international and national support programs. Still limited are the communication on retention possibilities and mechanisms, gains, and practice examples available for farmers. Similarly, public awareness of water retention opportunities is very limited or almost non-existent. Additionally, there is a lack of effective monitoring and evaluation systems. Both municipalities and local NGOs lack sufficient capacity to systematically and sustainably address this issue.

This situation began to change in the Dviete region with the launch of the OPTAIN project in 2021, which encouraged local stakeholder groups to recognise the importance and potential of water retention. The project-initiated discussions raised interest in the topic, but significant progress has still not been achieved. Having within the OPTAIN project several diverse and practically working demonstration (piloting) sites would have facilitated the encouragement process, as it was mentioned by almost all stakeholders. However, the availability of governmental financial support programs would still be still limiting factor.

Conclusions

1. The environmental governance audit in the Dviete River Basin highlights major challenges - pollution from particularly wastewater treatment systems, annual long-term flooding, intensive agriculture, Nature 2000 territory management as left for voluntary locals, and water governance (management) process, in general. While various **governance measures exist, they are fragmented and uncoordinated** - stressing the need for a balanced adaptive governance frame.
2. The Dviete river basin, as a socio-ecological system, faces its primary challenge in governance, with insufficient horizontal (cross-sector) and vertical (multi-level) integration – necessary application of **water–nature-environment-agriculture-tourism sectors nexus approach** and strengthening content-wise coordination across stakeholder levels.
3. **A structured, multi-tiered local governance approach** is required, potentially including a three-dimensional governance model. Stakeholders, un general, acknowledge support for step-by-step bottom-up management further implementation, developing trusted platform and supportive institutional mechanisms, which can facilitate collaboration and improve water management, nature and environmental protection, local socio-economic development.
4. After the 2021 territorial reform towards municipal aggregation, water management and environmental governance **municipal monitoring in the Dviete River Basin remains limited**, with virtually no state-based oversight. The lack of local and national-regional multi-thematic data adds uncertainty, making strengthened environmental monitoring, including citizen science approaches and targeted water indicators, essential for stakeholders and informed decisions for sustainable vertically and horizontally integrated water resource management.
5. **A comprehensive set of governance instruments** – policies and legislation, planning, institutional and administration, economic-financial, infrastructure and technology, and all four complementary communication instruments – should be better integrated and applied in a complementary way to enhance practical effectiveness.
6. The environmental communication audit revealed a need for better information sharing, education, public engagement and pro-environmental behavior. **Strengthening this action-oriented environmental communication** is key to improving understanding, encouraging participation, and supporting more effective stakeholder collaboration and governance.
7. Interactive inclusion of all **key stakeholders – especially mediators -** can significantly strengthen collaboration and engagement. Applying the modified five-spiral collaboration model helps structure interactions and align priorities across governance levels, potentially improving overall efficiency.
8. **The bottom-up approach is still weak** and relies too heavily on NGOs, with conflicting views among interest groups. But there was general stakeholders' interest - especially if bottom-up engagement is sustained and complemented by top-down support, targeted communication, and the active involvement of trusted local actors like the NGO Union of Dviete Valley Municipalities.
9. The establishment of the **Multi-Actor Reference Group (MARG)** in the Dviete River Basin has proven essential for, first, just for non-traditional gathering and meeting option of diverse stakeholders, and second – starting information and experience sharing and discussion. The third - integrating diverse stakeholder perspectives into the project OPTAIN, as for research project planning. By engaging local authorities, farmers, experts, NGOs, etc., MARG fosters eventual collaboration across sectors and scales, enhancing policy dialogue and supporting the co-development of context-specific solutions.
10. There could be recognized **three main instrumental preconditions for bottom-up participatory management** development:

- **Environmental** (nature, water etc.) **communication** precondition - the targeted systemic development and coordinated implementation of all four complementary groups of communication instruments.
- **Acknowledgement and support instruments** precondition, to be developed by national, regional and local governments, for bottom-up and co-work developments, particularly, for Nature2000 and river basin areas missing any administration – various types of instruments, including the existing examples of statutory delegation of management functions, co-financing mechanisms etc., actually all selection of support instruments from each of environmental governance instruments list.
- **Collaboration instruments** precondition, complemented by comparatively new and horizontal type of overlapping instrument's group as such instruments could come from each, several and all existing instruments groups.

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HOUSEHOLD PRO-ENVIRONMENTAL BEHAVIOR DEVELOPMENTS: LOCAL PRACTICE LIMITATIONS AND PERSPECTIVES IN MUNICIPALITIES

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Abstract
After an initial national-level representative household survey was conducted to study pro-environmental behaviour (PEB) developments in Latvia, a directly related representative local household survey was performed in two chosen township municipalities. The survey was combined with deep semi-structured interviews of selected households and selected experts/specialists aiming to study backgrounds of existing PEB practices in local municipal socio-ecological systems. Survey scope included not only the basic environmental thematic sectors, but, also non-traditionally, sustainable consumption clusters-based sectors, as well as, considering the governance stakeholders PEB situation and governance instruments applications (Triple Governance Dimensions model frame). The study complementary included also PEB related territorial observation studies, analysis of municipal data, statutory and voluntary documents as for Case Study Research methodology application. The Research-and-Development framework approach was used and pre-planned research collaboration started not only with both municipalities, but also with local Eco-schools as introducing the Socially Engaged Research frame too, involving school students into the research process. Similar to the national survey, most of households consider themselves as at least PEB-oriented, although it does not always translate into PEB practice – known value-action gap was seen as caused by various barriers, actually, recognizing a set of barriers and their direct correspondence to the whole list of PEB governance instrument's groups - regulatory, institutional, planning, economic, infrastructure, and communication barriers limiting PEB instruments. Upgrade and systemic development of PEB governance instruments are required, and especially, in partnership with mediators the complementary development of communication instruments - information, education/training, involvement/participation, and practical PEB demonstration use.
Keywords: governance dimensions, sectors, instruments, stakeholders, communication, socially engaged research.

Introduction

Promoting sustainable consumption in society is the basis of the sustainable development concept and is one of the long-term development priorities of the European Union. Accordingly, the long-term National Sustainable Development Strategy in Latvia also provides for the practice of a sustainable lifestyle in society. Housing is the first provision for human life. Individual can take initial responsibility for reducing environmental management practice problems by maintaining their home in an environmentally friendly way practicing a pro-environmental behavior (hereinafter – PEB) and lifestyle.

A grand prerequisite towards achieving sustainable development goals is the practice of PEB by all types of organizations - institutions, interest groups, communities and individuals in everyday life. The main consumption sectors that have the greatest impact on the environment, assessed both by the ecological footprint and the amount of greenhouse gas emissions generated by households, are food, housing, and transport. The loads created by other sectors, such as communication, education, and financial services, are much smaller.

To promote PEB, it is necessary to achieve a balance between economic growth, social development and environmental conservation, as well as to achieve the development of the attitude and behavior of the population in the context of sustainability on a global, national and local scale, as well as in households, respectively in household environmental management (hereinafter – HEM), as the hitherto under-estimated and purposefully updated, truly the lowest and closest level of environmental management to the population (Stern, 2000; Ernsteins, et al. 2011).

Efforts to define a sustainable lifestyle are a complex process, as they include different understandings of each individual and the entire society as a whole about what is the environment and the actions and behavior that are friendly to it. The definition proposed by the UN Commission on Sustainable Development states that a sustainable lifestyle is a pattern of consumption and behavior that satisfies basic human needs; ensures a better quality of life; reduces the use of natural resources; emissions of waste and other pollutants throughout the product's life cycle and does not threaten the needs of future generations. In turn, the Latvian Sustainable Development Strategy for 2030 defines it as a healthy and environmentally friendly lifestyle, which includes: a careful attitude towards the environment and nature, remembering the needs of future generations; thoughtful decisions and reasonable actions, creating the best possible life for oneself and children. The concept of PEB is closely related to the concept of environmentally significant behavior found in the literature, the validity of which can be defined by the impacts on the environment created because of a specific behavior (Stern, 2000). Paul Stern classifies the manifestations of PEB into two groups: 1) actions that are oriented towards intentions (actions that the person acting considers to be environmentally friendly); 2) actions that are oriented towards impacts.

PEB and lifestyle are a set of important factors and actions that strengthen the concept of a resilient community and promote sustainable development. The sectors of separate waste collection, energy, transport and food are those in which PEB has been popularized to the greatest extent in Latvia so far. In general, it must be said that an environmentally

friendly lifestyle has not become widely popular although individual PEB actions have taken root, which have most often been related to financial or accessible infrastructure aspects. Ensuring the development and practical application of environmental communication (Ernsteins, et al. 2017a), in general and specifically HEM, in all its complementary instruments, is essential to promote individual awareness (Ernsteins, et al. 2017b).

The aim of this paper is to account and system-based assess PEB activities and its background settings in Latvia's households based on the results of national and local sociological surveys, and complementary case study research methods, paying special attention to the two key approaches.

Initially, a three-part set of factors that explain the most important factors determining our behavior: individual (skills, values, knowledge), social (social and legal norms), material (infrastructure, technologies, products and delivery systems) (Blake, 1999; Entwistle et al., 2015).

Also, another three-part set of complementary governance dimensions approach being seen as potential PEB governance dimensions framework (Ernsteins, et al., 2017b) - PEB sectorial thematic content, related to each interest group's role and behavior, as well as, PEB barriers overcoming governance instruments.

1. Frameworks for environmentally friendly actions

In the context of the environmental management process, PEB can be defined as actions motivated by the environmental awareness of society and the individual, which are manifested in professional and everyday activities and whose goal is the identification and resolution of environmental problems (Ernsteins, 1999). They are manifested as individual and collective actions aimed at the conservation and development of natural capital: reducing resource depletion and pollution, increasing ecological capacity and preserving and developing ecosystem services.

According to the motivation for action, PEB can be divided into unconscious, impact-reduction-motivated and intention-motivated actions, which do not necessarily provide significant environmental benefits. The proportion of motivated (conscious) and unmotivated (unconscious) actions in the PEB of an individual and a community indicates the sustainable behavior of an individual or a community.

The practice of PEB in everyday life is influenced by a number of factors. These are environmental values, which are based on personal orientations towards the environment. Namely, people with a greater set of eco-centric values tend to be proactive in reducing environmental pressures. At a basic level, the availability of environmentally friendly goods and services (infrastructure) is crucial. Social factors largely help us to differentiate people according to their level of PEB, and relate not only to people's demographic profile, but also to structural features (e.g., waste sorting capabilities) and situational factors (e.g., knowledge of environmental problems and opportunities to solve them) (Steg & Vlek, 2009). Theories explaining behavior vary, but in this case, we will use both above mentioned three-part sets of:

- factors as un individual, social and material context approach that determines our behavioral habits;
-governance dimensions as structured into communication contexts and socio-ecological systems governance context approach, that necessarily emphasize PEB encouragement and step-wise establishment, as well as governance framework.

1.1. Individual context

Individual factors can include, for example, personal values, attitudes and skills, as well as rational considerations that a person makes before acting, including the assessment of personal benefits and costs. However, recent research has shown that making choices is largely based not on pragmatic calculation, but on basic heuristics, generalizing from accumulated experience and emotional events.

How people feel about something – their emotional response – is another aspect of their behavioral choices (e.g., fear, kindness, or apathy). Some theories contrast spontaneous, emotion-based decisions with pragmatic, rational choices. This distinction is often related to a person's self-control and self-confidence in their ability to complete a behavior. A person needs skills to know to perform an action, including knowledge of a procedure (e.g., the skills of driving a vehicle in an energy-efficient manner) (Shove et al., 2012). Habit is a behavior that is performed automatically and frequently, usually at the same time and place. It can also be understood as a routine. The range of factors influencing behavior shows that human behavior is not always conscious and rationally balanced.

1.2. Social context

Opinion leaders can be considered people who have a strong influence on others, for example, in the formation of social norms. In social networks, these people can be nodes in a network that connects many. Also, institutions influence the behavior of groups of individuals when they participate in specific activities or interact with other people. Institutions can be formal (such as the normative framework established by the government) or more informal (such as family life). In both cases, there is a specific behavior that is expected of participants. People's perceptions of how other people evaluate their behaviour have a strong influence on the decisions they make. People in society play different roles (mother, employee, football fan, etc.), which determine a person's different patterns of behavior and attitudes. A related concept is identity, which is a person's 'inner' sense of who they are (e.g., being a good person or identifying as 'green'). The web of relationships between people, characterized by mutual acquaintance, trust, and interaction (sometimes called 'social capital'). Social networks can help explain how ideas, innovations, and behaviors spread (e.g., growing your own food).

1.3. Complementary communication context

Various research done in recent years are characterising both the sector-based behavioural aspects or more engagement-based practices, but all together coming to some emerging patterns or another PEB development contexts, particularly, stressing communication process, content and instruments (Ernsteins, et al., 2017a) towards carefully studied and selected stakeholder sub-groups and well-planned governance frameworks (Brizga & Ernsteins, 2016).

The model of action-oriented collaboration communication (Ernsteins, 1999; Ernsteins et al., 2017a) emphasizes that the full-scale communication process is realized as a result of the sequential and mutually complementary use of the four dimensions or instrument groups – information, education-training, involvement-participation and PEB development and demonstration, subsequently step-wise with usage of each next instrument, are acquiring knowledge, experience, understanding, skills, attitude, motivation and, most importantly, not only readiness for specific action, but also the practice of self-experience of each specific thematic action. Further ok leading to the formation of a specific thematic environmental awareness and, in the context of repeated cycles, a gradually integrative environmental awareness is possible (Ernsteins, 1999). Accordingly, the PEB is viewed as a motivated action of society in general, various interest groups and stakeholders, and everyone in their professional and everyday life activities.

Research indicates that individuals with high self-efficacy, civic engagement, and those in rural areas are more likely to engage in environmental co-production - compatibility between local services and citizen needs also plays a crucial role (Alonso et al., 2019). A study on household recycling practices found that reputational concerns, as avoiding shame, significantly influenced PEB. This highlights the role of social esteem in driving environmental actions (Alpizar & Gsottbauer, 2015). Researchers found also a positive relationship between personal values (egoistic, altruistic, biospheric) and pro-environmental attitudes, which influence waste sorting and sustainable consumption, stressing the importance of fostering responsible consumption (Majumder et al., 2023). Personal and social norms, and perceived behavioural control are major factors influencing waste separation behaviour (Goh et al., 2022). The environmental knowledge and values were found to positively correlate with efficient household water consumption (Sarpong et al., 2022).

There could be recognized certain emerging patterns arising from scholars made studies, just to mention some key characteristics:

- Information and education: effective communication and education are crucial complementary communication instruments for overcoming barriers to PEB and motivating sustainable practices (Ernsteins, 1999; Sarpong et al., 2022). Empowering individuals through training and resources enhances their ability to adopt sustainable behaviours (Majumder et al., 2023; Alpizar & Gsottbauer, 2015).
- Participation and PEB actions/demonstrations: suggesting interventions as possibly collaborative should aim for socially rewarding PEB actions as own participation and publicly available PEB practices can motivate pro-environmental behaviour (Majumder et al., 2023; Esfandiar et al., 2021; Brizga & Ernsteins, 2016; Alpizar & Gsottbauer, 2015).
- Policy and public support: inclusive and collaborative policy frameworks are essential for successful environmental governance, considering demographic engagement towards collaboration (Alonso et al., 2019; Alpizar & Gsottbauer, 2015).

1.4. Socio-ecological system governance context

The development of the household environmental management (HEM) focuses on two basic aspects: improving the living environment inside the dwelling and enhancing cooperation with other households in the outside/public environment. This includes promoting and influencing the availability of external conditions for environmentally friendly management of the dwelling. The work does not analyze the consumption approach separately, but by looking at the most important consumption clusters, namely housing, food and mobility, an integrated approach is developed to include info HEM all three clusters. When formulating the content structure of HEM, it is necessary to supplement it with a description of the development of HEM processes, namely, HEM includes the entire environmental management cycle from situation assessment and environmental policy development to action planning for practical implementation and later monitoring in the management of housing and its internal and external environment.

Clusters and sectors of the HEM dimension.

The division of HEM sectors according to the European Topic Centre on Sustainable Consumption and Production (ETC SCP) is three consumption clusters: housing and building; food and drinks cluster and mobility/transportation cluster. However, such an approach in the context of HEM does not fully cover all elements of the HEM functioning as socio-ecological system (SES); therefore, we offer a modified SES-based three-cluster model for HEM: natural, engineering and built environment as infrastructure cluster; social, cultural and economic environment as lifestyle cluster; separately also management and communication environment as stewardship cluster (Ernsteins et al., 2011).

Subsequently, the following list of thematic sectors needs to be built to be considered for adequate HEM sector-wise implementation. The **HEM Infrastructure cluster** may include 5 sectors: Nature environment (including external environment with land resources); Built environment; Energy; Water and Waste. **The HEM Lifestyle cluster** would consist of

also 5 sectors: Environmental health; Food consumption; Consumption of household products, objects and services; Leisure activity/recreation (including culture environment) and Inhabitants mobility. Finally, the HEM **Stewardship cluster** includes just 2 main sectors: Management sector (including 6 groups of main instruments) and Communication sector (including 4 groups of instruments – environmental information and education, public participation and PEB) (Ernsteins et al., 2011). Those two last sub-sectors of Stewardship cluster are integrative and **horizontally-oriented sectors** compare to **vertically-oriented sectors** for Infrastructure and Lifestyle clusters.

Moreover, besides this governance content basic specifications as governance content dimension there is to be added also governance stakeholders' dimension and governance instruments dimension to be altogether realized as complementary dimensions (who, what and how is realizing governance process). This **Triple-Dimensions Governance framing model (TDG)** potentially are to be seen as PEB governance framework (Table 2).

Materials and Methods

To assess the household's environmental management (HEM) and their related PEB, the National research grant-based project study used both quantitative and qualitative sociological research methods and there were two research stages – national level overall PEB study in Latvia and municipal level study in two chosen township municipalities.

National household's PEB survey: realization.

Initially, the national household PEB survey questionnaire was developed (R. Ernsteins, J. Brizga, J. Kaulins) and implemented (number of respondents sufficiency: n = 1009; confidence interval: 3%) in the frame of the national research grant project SUSTINNO (2015-2019). The survey, using stratified random multistage sampling and face-to-face interviews in the places of residence of respondents overall in Latvia, was conducted by the permanent national network of interviewers as for this data gathering there was commissioned sociological consultancy company TNS (Latvia). Realization of the questioner filling-based interview requested from interviewer and respondents 45 – 60 minutes. Results of this survey are published (Brizga et al., 2017)

Municipal household's PEB survey: introduction.

Following, the next project stage was realized: in-depth studies of household PEB practice at the local municipal level in Latvia, and chosen two township municipalities - Liepaja and Valmiera (Table 1).

Both municipalities are statutory orienting their development planning documents and implementation process towards Green Municipality perspective (Valmiera have the voluntary Environmental Declaration (2015) approved by the City Council) and are municipal environmental governance forerunners in Latvia. During previous years both municipalities have developed both top-down and also bottom-up based various municipal administration and main local stakeholders PEB oriented activities.

Table 1

Characteristics of both pilot areas

Indicators	***Liepaja***	***Valmiera***
Number of residents	67 398	22 811
Area (km^2)	68.02	19.36
Population/people per km^2	1 313	1 221
Households, thousand	32.6	9.9
Average household/persons	2.04	2.26

Source: (Central Statistical Bureau, Latvia, 2025).

They are having different basic statistics (Table 1) and located in different ethnographic and planning regions of Latvia, also having comparatively different development histories previously, even both being also actively supporting industrial developments. Liepaja (about 75,000 inhabitants) as costal town at the Baltic Sea is located in Kurzeme region, western part of Latvia. Valmiera (about 25,000 inhabitants) is spreading at both coasts of Gauja river, located in Vidzeme region, north-east part of Latvia. Both cities can be characterised comparatively similar – regional, industrial and transportation hubs, green, recreation, sport, education and culture centres.

The study in both municipalities was aiming to assess background settings of existing municipal PEB practice situation and existing/required pre-conditions, households' motivation, limitations barriers, existing and to be developed whole set of governance instruments and, particularly, communication instruments (Ernsteins et all., 2017a) (Table 2).

Research-and-development (R&D) framework.

R&D was functioning towards also enhancement of PEB policies and its implementation qualities locally as project was realized in close partnership in regular communication and various seminars, knowledge exchange with both municipalities, as well as, in research partnership with local Ecoschools as for students' research involvement.

Case study research (CSR) methodology.

CSR was implemented complementary combining various sociological research methods. Initially, municipal and other data, along with statutory and voluntary municipal planning, regulations and other related documents, were studied. This was combined with related territorial and process observation studies un relation to PEB practice by various stakeholders.

To evaluate the data obtained in the national questionnaire and further on to test and adapt national questionnaire to the particular municipal level, before the local survey began, 10 in-depth semi-structured household interviews were conducted Valmiera and 14 in-depth interviews were conducted in Liepaja. The interview averaged up to 1 hour, as the interviews had the same questionnaire as the national (and later also

local) survey. Interviews were oriented to go into the detail of reasoning behind households PEB contexts, decisions and behaviors in all environmental infrastructure - lifestyle - stewardship clusters, also stakeholders' participation and their PEB, barriers recognized and instruments used, altogether as of Tripple Governance Dimensions model (Ernsteins et all., 2017b) as PEB governance framework (Table 2).

Also, after conducted surveys in both municipalities, an in-depth semi-structured interviews based on survey's thematic blocs and environmental governance dimensions was realized (up to 1 hour in length) with two groups of specialists – with three environmental issues related specialists in Valmiera municipal administration and four similar specialists in Liepaja administration, as well as, with three academic experts with extended research and practice collaboration experience in municipal environmental governance and PEB.

Socially Engaged Research (SER).

The studies in both municipalities were conducted with extended element of SER. The results of these local in-depth interviews as well as results of the national questionnaire were presented and discussed in focus group interviews with main stakeholders invited in both municipalities of Liepaja and Valmiera. Later, survey results and focus group results were presented to representatives of local governments at the Liepaja City Council's Environmental Commission and at a roundtable discussion with municipal specialists and experts in Valmiera municipality (no existent municipal Environmental Commission etc. alike).

All results and local recommendations from the discussions were used to adapt the national questionnaire for local municipalities. While the same structure and questions were kept, some recommended local specifics were added, particularly questions about residents' satisfaction with the environmental services provided by their municipalities.

SER approach application, involved establishing a partnership not only with municipal administration and its specialists, but also full-scale research cycle involvement of local Eco-schools (Green Flag schools). The planning and management process of the survey implementation in both townships included several necessary collaboration steps with participating schools. These steps were: introducing results of the national survey and main concepts and models behind the studies, presentation and discussion of the local survey questionnaire, training students and teachers, supervising the survey process, gathering results, evaluating and discussing findings. Volunteering students were assigned to particular districts of the city and as prescribed were visiting households there and conducting questionnaire-based interviews. Finally, students made practical recommendations for municipal administration.

Municipal household's PEB survey: realization.

To assess in-depth HEM and PEB, a local household survey was conducted with necessary representation: in Valmiera with n = 373; in Liepaja with n = 361; and confidence intervals - 5%. Table 1 represents the main quantitative characteristics of both pilot territories. The survey in municipalities was practically conducted by Eco-school students, primarily from secondary schools, being supervised by teachers/Eco-schools coordinators. The processing of the questionnaire data done by company TNS was financially supported by both municipalities.

The structure of the questionnaire was based on designed 3 thematical PEB management clusters described above and consisted of 5 thematical parts, including more than 40 questions (Brizga et al., 2017):

1. general SES-based characteristics of the household,
2. household environmental pressures - assessing all traditional environmental sectors one-by-one in detail (infrastructure cluster),
3. household consumption pressures - assessment of all goods and services used, mobility (lifestyle cluster),
4. household environmental values, participation and overall management (stewardship cluster),
5. household PEBs and their motivations.

The research covered the entire municipal environmental governance process, including evaluations of all the process cycle stages from situation analysis, policy design, planning, till implementation management and monitoring (Ernsteins et all, 2017b) and, covering three governance dimensions – governance sectors, stakeholders and instruments (Table 2).

Table 2

Case study research frame: three governance dimensions

***Sectors** (extended)*	***Target groups***
Nature/biodiversity	State/National government
Land resources	Municipal government
Water resources	Entrepreneurs/bussines
Energy	Society/households
Air protection	Media
Waste	NGOs
Building/housing	Educators (non/formal)
Transport/mobility	Science/Academia
Food & drinks	**Instruments**
Other products/resources	Political and regulatory
Recreation/culture	Institutional/admin
Environmental health	Planning
Household stewardship	Financial/economic
Communication sector	Infrastructure/technologies
Climate change	Communication

Source: (Ernsteins et all., 2017b).

Results and Discussion

Municipal case study research

This paper mainly reflects and analyses the results of local municipal level surveys, Limited number of interviews and municipal data and document analysis, but the national survey data is used only for comparison and could be followed separately as partially published (Brizga et al., 2017).

1. Environmental sector problems around the house

Respondents in the cities of Valmiera and Liepaja are recognizing various environmental problems in traditional urban environment thematic sectors (Figure 1). Dust was most frequently mentioned as a permanent or frequent environmental problem near their home by both respondents in Valmiera (29%) and Liepaja (49%). The second most frequently mentioned environmental problem is noise, which was mentioned by 37.3% of respondents in Liepaja and 28% in Valmiera. Polluted natural waters were mentioned the least (6.8% in Liepaja, 4.3% in Valmiera).

Respondents in both cities are mostly satisfied with the quality of many environmental and other services available at and near their homes - the proportion of very satisfied and satisfied respondents is in the range of over 50% to 80%. At the same time, it should be emphasized that the lowest satisfaction applies to very important sectors – preschool educational institutions and children's playgrounds. Although the differences in the overall satisfaction of respondents (very satisfied + satisfied) are small in both cities, the number of respondents who answered very satisfied is lower in Liepaja city.

Figure 1

Environmental problems near the home that respondents mentioned as constant or frequent (%)

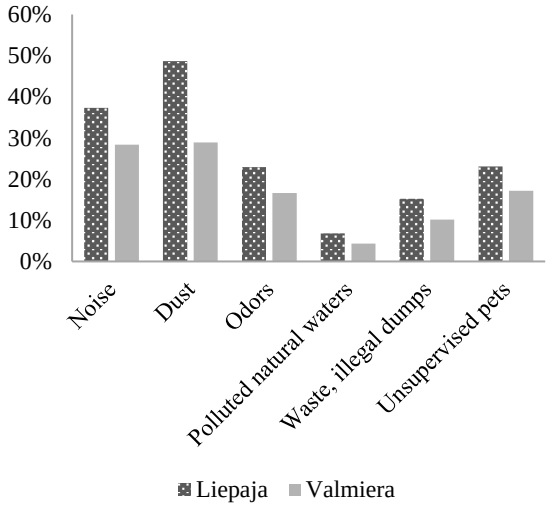
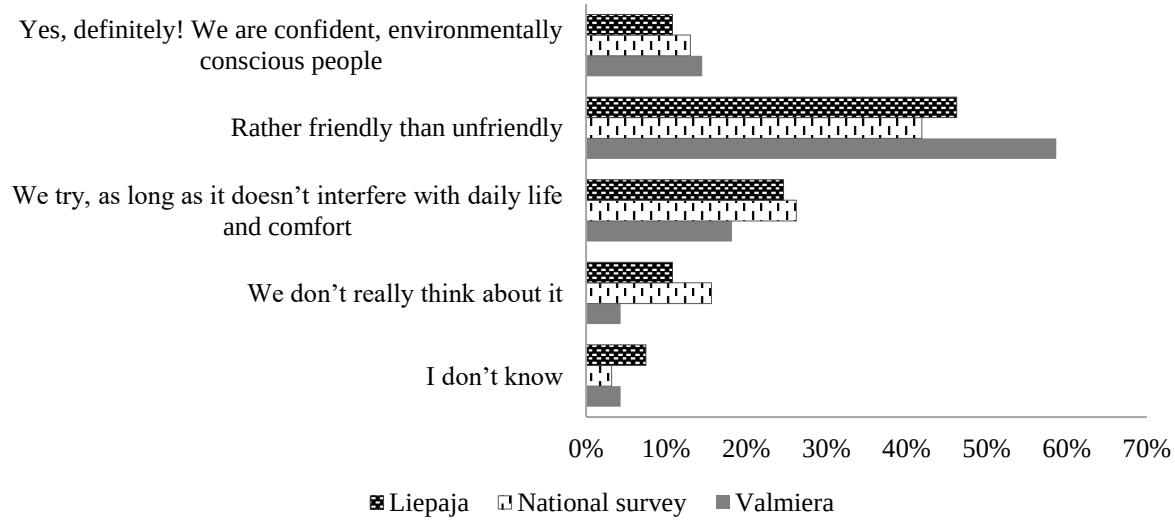


Figure 2

Overall, how would you rate whether your household is environmentally friendly?



50% of respondents in Valmiera and 35% in Liepaja consider the environmental quality of their home surroundings to be good or very good. However, there are also relatively many people in Liepaja (11%) who consider the environmental quality of their home surroundings to be poor.

2. Integrative assessment – PEB in general

The national survey shows that environmental protection is very (40%) or quite important (49%). Only 2.9% of respondents consider it not very important, and 0.5% - not at all important. Similar, but even much higher positive scores are also found in Valmiera and Liepaja: in Valmiera, 89% of respondents, but in Liepaja, 82%, believe that environmental protection is very or quite important to them (Figure 2).

Most respondents consider themselves to be committed to being green, or rather, environmentally

friendly. 13% of respondents in the national survey consider themselves to be convinced green-minded. The residents of Valmiera (15%) consider themselves to be more 'green' (Figure 2) as in Liepaja (11%).

To the question 'Which of these areas do you think the municipality should improve so that residents can live a 'greener' lifestyle?' respondents from both Valmiera (51%) and Liepaja (53%) most often answered that by providing better infrastructure. The ability to monitor how we consume resources more and stimulate change was mentioned much more by the residents of Valmiera (46%) than by the residents of Liepaja (25%). By way of example, the municipality implementing sustainable consumption, supporting those who want/do it, was mentioned by almost half of the respondents in Liepaja (49%), but only a fifth in Valmiera (21%). The public transport planning and communication, informing residents was similarly rated by respondents in both cities.

From the interviews taken there was affirmed quite radical PEB change to more environmentally friendly household behavior after a child is born in the family or in cases of changing a number or type of inhabitants of particular household. Three of the respondents interviewed had children who were a few months old. The birth of a child in these families has increased consumption, both in terms of the child's clothing, furniture, belongings (toys, diapers, etc.) and food purchases, as well as mobility and health care. However, on the other hand, families with newborns are starting to pay more attention to the use of environmentally friendly detergents and a healthier, more environmentally friendly diet etc.

So, changes in consumption habits usually occur when people's living conditions change, e.g. several respondents pointed to the following relationships:

• the widow claimed that she started buying fewer, but better-quality goods; goods in smaller packages;

• the young family, in turn, pointed out that the need for transportation, health care and food consumption habits have also changed.

Interviewees who pay increased attention to chemicals in household admit that they sometimes encounter resistance and disinterest in their families, which hinders their PEB, because people do not want to conflict with their loved ones.

Often, several generations live in one household, with different environmental awareness and environmental values. These differences also hinder the implementation of PEB. It is interesting to mention several examples regarding the use of cleaning products, which were indicated by the respondents:

(1) one of the respondents resided with her in-laws. Although she is concerned about the impact of household chemicals on the environment and their children's health, since living together she has started using environmentally friendly cleaning products less often, because her in-laws do not trust them and do not consider it necessary;

(2) one of the respondents, answering the question about the use of natural cleaning products (lemon juice, vinegar, soda, etc.), indicated that it is stagnant and a tradition of the socialist era, when people did not have access to modern cleaning products;

(3) there are also respondents who without any problems admit that they use vinegar or soda to clean surfaces. People also indicate that they choose environmentally friendly cleaning products and organic food in cases having allergies in the family.

3. *PEB awareness: most to least popular behaviours*

Local surveys also show which actions people in the PEB are already implementing and which they would not be willing to take (Figure 3). One of the most popular actions is the use of cloth shopping bags (62% in Valmiera, 63% in Liepaja). Respondents claim that they already sort waste (63% of respondents in Valmiera, 31% in Liepaja), eat organic food (37% in Valmiera, 39% in Liepaja), live in insulated housing (35% in Valmiera, 24% in Liepaja) and use public transport (34% in Valmiera, 36% in Liepaja).

However, there are also actions that people would not be willing to take. A large proportion of people (41% in Valmiera, 46% in Liepaja) would not be willing to reduce the consumption of animal-derived food products, reduce indoor air temperature (39% in Valmiera, 52% in Liepaja), cooperate with neighbours, friends, share household electrical appliances, cars, etc. (38% in Valmiera, 47% in Liepaja) and use electrical appliances less (29% in Valmiera and 38% in Liepaja). The use of an energy-efficient car is also unpopular in the PEB (in Valmiera, only 7%, in Liepaja, 8% of respondents would be willing to do so). Many of these actions appear on both lists, namely people who would never be ready to give up meat in their diet, but would gladly reduce the amount of waste, and vice versa (Figure 3). Some respondents emphasise that they would never be ready to reduce the indoor air temperature or give up their car but would consume organically grown food daily. In the in-depth interviews, people also indicate that there are things that they simply cannot change, for example, the heating system or the energy resources used if they live in an apartment building connected to the city's centralized heating. At the same time, the study revealed a significant problem: people are reluctant to be more actively involved in environmental protection, to invite others to act for PEB, or to actively educate themselves about environmental issues.

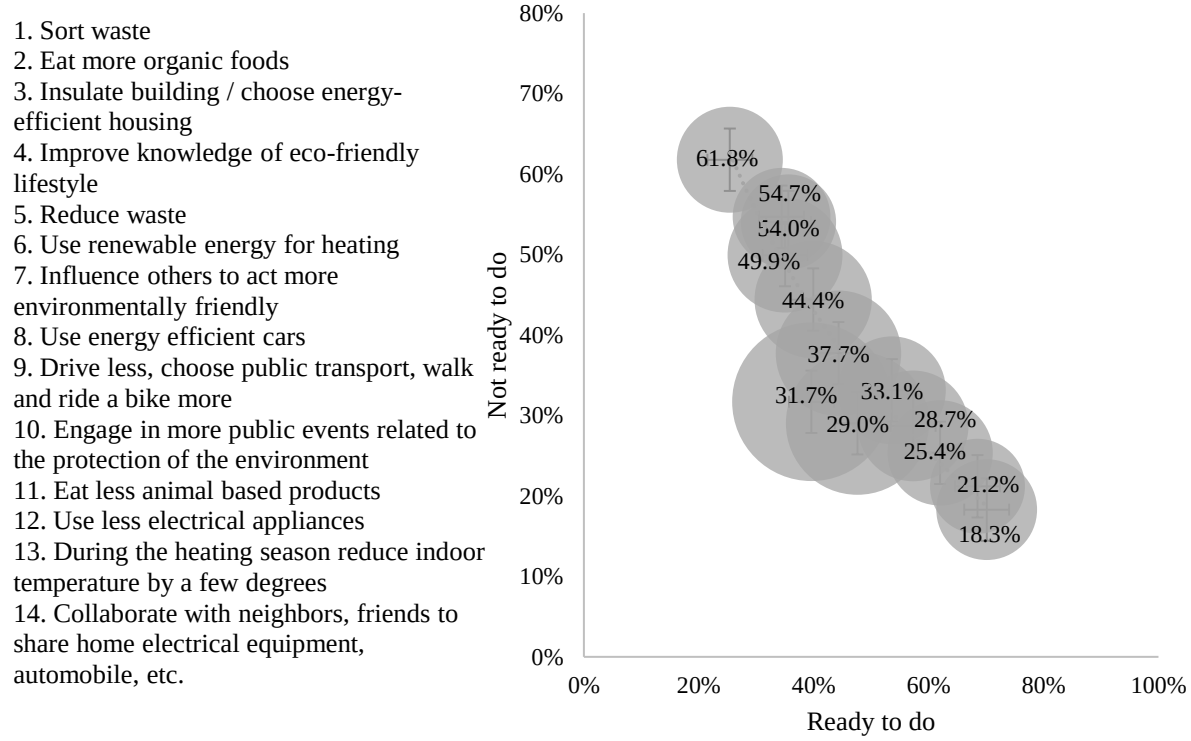
As the main reasons that slow down and reduce people's desire to act environmentally friendly in their everyday lives, respondents usually mention indifference and laziness (66% in Valmiera; 63% in Liepaja), unwillingness to reduce the existing level of comfort/sacrifice personal comfort (43% in Valmiera; 44% in Liepaja), an unsatisfactory level of personal well-being (28% in Valmiera; 27% in Liepaja), as well as ignorance. As the most frequent reasons that contribute to people's desire to act environmentally

friendly in everyday life, the respondents mentioned the values prevailing in the family and caring for their child. The values prevailing in society, the example of other people and a satisfactory level of personal well-being were also often mentioned.

However, respondents assess that the bad example and information about environmental problems do not appeal to them. At the same time, only 54% of respondents in Valmiera and 40% in Liepaja believe that they have full or partial access to information about environmental problems and their solutions. A significant proportion of respondents also mention ignorance and lack of information (36% in Valmiera; 38% in Liepaja).

Figure 3

Towards Environmental Awareness: most to least popular behaviours



4. Barriers to PEB developing and governance instruments for interventions

Results of survey and interviews with households and environmental experts and specialists suggest that PEB is undergoing an evolving and uneven process across different lifestyle domains and economic sectors. Even although a wide spectrum and diversity of types of PEB is already practised, most respondents acknowledged the existence of numerous obstacles hindering the fuller integration of such behaviours into everyday life. As with PEB itself, these barriers are varied in nature. Some necessitate behavioural change not only at the household level but also within private and public organisations, including municipalities, national agencies, and non-governmental organisations (NGOs). Nevertheless, both individual and institutional actors are engaged in positive initiatives, ranging from internal organisational PEB reforms to public-facing environmental activities.

In Liepaja, a principal impediment to PEB progress is perceived to be the limited cooperation between various target groups, even municipality has developed Environmental protection and public participation unit, expanding communication activities to all groups and also having long term support mechanisms for NGO's. Comparatively, in Valmiera, the main challenge lies in the fact that, although the existing municipal institutional framework, even without Environmental unit, functions quite effectively, actually supported by the high environmental awareness of a number of senior specialists, but existing system possibly has reached its developmental limit. The establishment of a formal environmental governance structure within the municipality is now next stage necessity as mentioned especially in interviews.

A notable constraining factor is the detachment of national/regional institutions from local environmental policy. **The notion that exactly traditional financial constraints present a major obstacle is seldom** expressed in Valmiera. To some extent, the state of PEB is shaped less by the degree of formal institutional organisation and more by the **general level of environmental awareness within society and the intensity of communication between groups**. While financial resources are not the primary determinant of PEB adoption, significant infrastructure requirements and the need for additional human resources underscore their relevance. The creation of a coherent

organisational structure and coordination mechanism for environmental governance should therefore be regarded as a priority.

Barriers to PEB implementation identified in survey and particularly discussed during the interviews in both municipalities can be described as well overlapping by general-type of activities, however, obviously, having specifics due to biogeographical, economic and also some social and culture-historical differences. All in all, barriers recognized could be grouped into **six barrier's categories,** what actually is directly aligned with the same number and type of **six environmental/governance instrument's groups**, subsequently, the most relevant for addressing them and to be integrated into municipal statutory planning documents. Here is represented a short summary of most mentioned typical barriers and to be taken into account by municipalities first of all.

1. Regulatory barriers. National level possess two types of regulatory constraints as were identified. Firstly, certain statutory limitations, particularly affecting state/regional agencies, resulting into reduced capacity and instrumentation to address environmentally harmful practices effectively. Also, excessively rigid regulatory frameworks or their over strong application. Municipal regulations basically cover most of environmental and, directly, PEB needs, but implementation with supervising/controlling capacities are still limited and barely covered by communication means.

2. Institutional barriers. Within municipalities, institutional constraints are most often linked to limited capacity, resulting in an inability to prevent or penalise environmentally damaging behaviours such as littering, graffiti, and other offences. Enforcement mechanisms to maintain environmental cleanliness are underutilised; those who already act responsibly continue to do so, whereas offenders not always are affected either by administrations and/or by limited awareness campaigns, for example, the absence of a dedicated environmental education coordinator.

3. Financial and economic barriers. Funding shortages affect both the recruitment of necessary personnel and the maintenance and expansion of infrastructure. Residents often lack the means to renovate internal utility systems or improve energy efficiency, particularly in multi-apartment buildings. Funding constraints limit the ability to support all proposed community clean-up projects. As a result, events that should be held regularly often occur only sporadically, especially in waste management and environmental cleanliness initiatives and dome, even popular, recreation areas may suffer from under-management.

4. Infrastructure-related barriers. These are often linked to financial and economic constraints but can also occur independently. Waste sorting was a recurring theme, frequently discussed in contradictory terms. Some argued that sorting was being introduced too rapidly, outpacing both infrastructure development and public awareness. Others contended that low levels of participation were due to insufficient sorting infrastructure. Additional issues include the absence of a municipal composting facility for organic waste.

5. Planning process and documents-related barriers. Municipalities themselves or regularly encouraged by national/regional authorities traditionally are oriented first of all towards environmentally non-friendly processes and activities, but PEB type activities, even well-known, are lacking behind – not well discussed and planned during municipal planning processes of statutory documents (traditionally once in seven years of development planning cycle) as competing also with prioritized social and economic work directions. Subsequently, the statutory documents as main 7 years municipal Development Program have very limited number of PEB activities being integrated, besides general environmental infrastructure activities as being mandatory for municipalities – being so seen even for pro-environmentally oriented municipalities. This directly leads to the interconnected municipal budgeting. Outside project-based funding becomes the main PEB developments resource.

6. Communication barriers – complementary informational, education, participation and PEB design/demonstration barriers. Incorrect waste sorting was often attributed to insufficient or unclear information, lack of training activities and practical demonstration cases. These primarily relate to inadequate information exchange between stakeholders, notably between waste management providers and households. Municipal overall engagement with both the media and the public is improved especially in social media, but positive developments receive not adequate coverage, leaving little room for positive, educational, or instructive stories. Environmental topics are also irregularly featured and are often lost amid other content. Lack of environmental NGO's, even some other sector NGO's do perform also some environmental activities. The most persistent obstacles are behavioural, rooted in established habits and reluctance to compromise personal comfort. Attitudes towards environmental cleanliness and waste sorting vary by neighbourhood, often correlating with education levels and the prevalence of harmful habits. Deliberate damage to public infrastructure were reported more in disadvantaged areas.

As mentioned above, both national and local questionnaires show that most respondents consider themselves to be more or less environmentally friendly. However, this high environmental awareness does not always translate into PEB and a number of barriers do exist as well as governance instruments to overcome them.

Most respondents consume animal products in their daily lives, as this is common practice, and often travel by private car, as it is more convenient to get to the desired place, while often the public transport is used

by those who cannot afford private transport. But the most common PEBs do not always ensure sufficient reduction of environmental loads. People's actions are embedded in existing social norms and infrastructure - survey show that people are generally satisfied with the quality of these centralized services. For example, supply systems and infrastructure (traffic, food and heat supply) largely determine people's behavioral habits. In Liepaja, where public transport is more developed, more people use it; in Valmiera, more people live in insulated apartment buildings and sort waste, because the Vidzeme region has a much more developed waste sorting etc. waste infrastructure as regional municipalities were establishing a joint municipal company (ZAAO, located un Valmiera) for waste management, performing also waste communication function for different groups of inhabitants, what altogether strengthens waste sorting in daily practices and social norms.

Waste-related actions are also some of the most popular PEBs mentioned by respondents, such as using shopping bags and sorting waste. There is a belief that such small PEBs can lead to environmentally friendly behavior on a large scale, but there is a lack of evidence for this. Studies (Austin et al., 2011) have shown that there is no correlation between whether people undertake one PEB or several. Although PEB helps people feel more environmentally friendly, research shows that the idea of being green in relation to a specific, often relatively simple action can give individuals a sense of having done their bit for society and thus justify other non-PEB actions.

One of the biggest challenges is to find the most optimal way to promote positive changes in the daily behavior of individuals and households, making it more environmentally friendly and sustainable. Influencing behavior is a key task of public policy.

In recent decades, factors influencing behavior have been widely analysed and decision-makers should take this research into account, because changing behavioral habits can be a good tool to promote, for example, such important PEBs as waste sorting, use of public transport or a vegetarian diet. Policies aimed at behavioral changes can also be financially effective.

One of the main tasks of most policies is to achieve behavioral changes. To do this, several strategies can be used. The most common governance instruments are regulations that can set different norms of behavior. This approach is often effective, but it is very expensive and may be inappropriate in many situations. Therefore, decision-makers are increasingly using other, less regulatory, but often very effective methods. For example, those that incentivize the choice of certain behavioral habits (e.g., excise tax on fuel) or inform (e.g., public health guidelines), as well as sophisticated communication techniques.

However, it should be noted that existing instruments, such as economic and information, are not always effective, because they are based on the assumption of rationality of decision-making - if carrots and sticks are provided, together with clear information, people will weigh the costs and benefits of their actions and act rationally. Unfortunately, research shows that human behavior is not always perfectly rational, and knowledge does not always lead to action.

Our study shows that respondents do not consider environmental information to be a significant incentive for environmentally friendly behavior (Figure 4). Other studies (Oullier & Sauneron, 2011) also confirm that the statement informed people make the right choices does not hold true in practice. A large amount of information can sometimes even reduce people's ability to make the desired choice (Ölander & Thøgersen, 2014). However, it is information campaigns that are often used to promote behavioral change. Information campaigns can be significantly improved if the latest findings about human behavior are considered:

• Previous experience, emotional associations (e.g., a strong desire to avoid losses), habits and routines have a very strong influence on behavior, especially that which is repeated semi-automatically in everyday life.

• The amount of information and the relative importance assigned to it are important in deciding. However, the effectiveness of information depends on how, when and by whom this information is presented. So, it's necessary to combine the content and process of information, actually communication.

• People are strongly influenced by the actions of those around them (Figure 4), but people act in ways that make them feel better about themselves.

• People often go with the flow and stick to familiar choices anchoring to cope with the complexity of choices (Oullier & Sauneron, 2011).

• People discount the future – they place greater value on the immediate future and do not consider future costs or savings,

• People are attracted to new and seeming appropriate.

• Complexity can lead to avoidance of decision-making and sticking to current practices.

Therefore, an approach that focuses on changing the context – the environment in which we make decisions and respond to cues – has the potential to produce significant changes in behavior at a relatively low cost. Designing policies closer to our innate responses to the world offers a potentially powerful way to improve individual well-being and social well-being. Therefore, it is important not only to inform people about PEB, but also to show good examples, encourage and educate, involve and create various incentive mechanisms and eliminate the most harmful actions with the help of rules and restrictions.

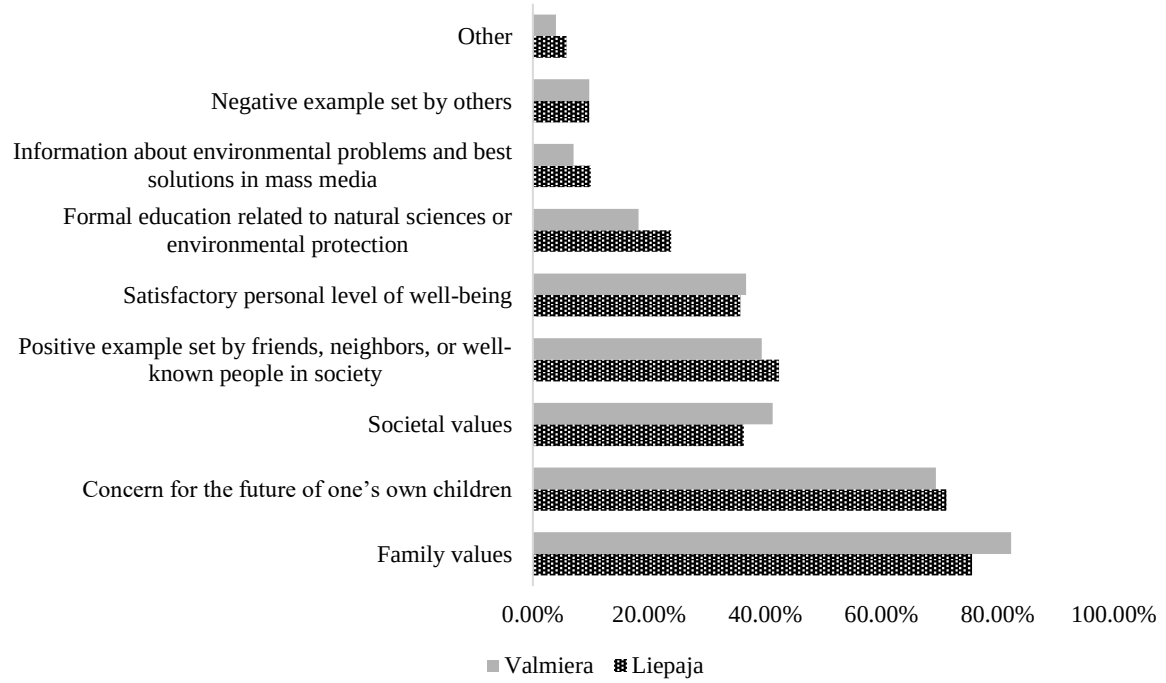
Research shows that behavior based on routines and cultural habits (e.g., high meat consumption, transportation habits, or waste management habits) can be associated with various biases and selective perception: people select information that confirms their preferences and ignore information that does not

match their habits (Steg & Vlek, 2009; Gifford, 2011). This is a significant challenge in the development of PEB. Although many respondents say that in the future, they would be willing to reduce their consumption, use private cars less, or learn more about sustainable lifestyles, there is no certainty that people will be able to break out of their usual routine and translate their good intentions into action.

The study also reveals that the desire to protect or improve the environment is rarely the primary motivation for people's PEB but can reinforce it. Several PEBs appear to be motivated by the desire to save money, improve health, clean up the environment, increase property value or gain recognition from others. However, the costs of PEBs are also relevant issue in Latvian society, since the income of most of the population could be a limiting factor as well.

Figure 4

What, in your opinion, encourages people for PEB in their daily lives? (3 possible answers)



There is also the free-rider problem – the behavior of those members of society who benefit from the environmental protection actions of others but are not prepared to pay for it themselves. This can lead to ignoring unpleasant environmental considerations.

Since an individual's behavioral habits depend on both the individual himself and collective practices, norms, technologies and infrastructure, etc., PEB management must take place at both the individual and community levels. Efforts to change behavior should not only focus on the psychological and functional needs of a person but should also consider the social and symbolic value of a modern lifestyle.

The physical environment can play a significant role here, for example, infrastructure and supply systems that form social norms can play a decisive role in the development of PEB. The issue of infrastructure is particularly relevant in the areas of waste management, transport and energy supply. In turn, supply systems (people mostly shop in supermarkets) determine the range of available products, design, packaging, etc. Consequently, as supply systems become more sustainable, wider opportunities for PEB open.

PEB should be strengthened in society's everyday practice, promoting:

• a decrease in consumption volumes in population groups with higher incomes;

• changes in the structure of consumer spending, redirecting spending to consumption sectors with lower environmental impact and promoting the availability of PEB oriented (eco-efficient) sustainable products and services on the market (technological solutions, delivery systems and infrastructure);

• decommercialization of meeting the needs of the population, developing product sharing, intensification of use and reduced use;

• development of sustainable value orientation in society, strengthening a non-materialistic lifestyle.

Conclusions

The results of the municipal household PEB questionnaire and in-depth interviews in Valmiera and

Liepaja cities allow us to draw certain general PEB **research-and-development conclusions.**

1. While the two cities studied are really different as a complex socio-ecological systems, except that both have a pro-environmental orientation inclination, most of the **PEB basic sector characteristics are similar** or with similar tendencies, **except for lifestyle cluster.** Basic infrastructure cluster sectors, where clearly understandable differences are due to the town's size and type, settlement structure, etc., both cities are facing first of all main typical urban environmental issues – dust, noise, odours, unsupervised street pets, but already much less waste, water, heating related ones as statutory municipal responsibility.

There are real PEB differences, as per the answers provided by respondents – newly introduced/accepted non-traditional environmental sectors and sustainable consumption clusters-oriented sectors (lifestyle cluster) as being not system-based developed yet and definitively less or/and differently approached.

2. There is to be necessary further and selectively detailed PEB governance improvement of traditional environmental sectors, but, particularly, **both newcomer-PEB sectors of municipal governance – new environmental and consumption clusters' sectors,** having high climate impacts e.g., households' lifestyles, mobilities, food & drinks consumption. This requires interest groups-based interactive governance process in the municipalities, what have been really recognized in post-research period in both municipalities - including **PEB step-wise integration info all and each of governance processual cycle stages**, particularly for necessary well-designed SES-based monitoring stage, what could be well used also for public monitoring involvement, including participating Eco-schools as discussed by them too.

3. The assignment of traditionally used governance instruments – such as regulatory and informational ones - is clearly not enough to succeed with PEB. **A whole set of complementary governance instruments is necessary for the PEB governance framework.** The proper and selective considerations of design and implementation quality of this set of instruments and their intercommunication are the main success precondition. Policy and regulatory, institutional and administrative, planning, economic-financial, infrastructure and technological ones, as well as, set of communication instruments, are forming the **PEB governance framework.**

4. Even though in both cities as similarly in the national PEB survey done before, most households consider themselves almost or directly environmentally friendly, but this **high environmental self-evaluation does not always translate into PEB.** This internationally known value-action gap is traditionally explained by the psychological, social, and physical barriers that limit the development and spread of PEB in society**.** Our PEB studies revealed a more detailed list of barriers.

5. Traditional and well-known PEB barriers as infrastructure, economic, information, education (incl. psychological, social, etc), etc., are just a part of those recognized during PEB studies. The **whole set of PEB barriers**: **policy and regulatory, institutional and administrative, planning, economic-financial, infrastructure and technological, and, set of communication barriers** are responsible for limiting PEB developments in the municipalities studied. It's understandable, but still encouraging that this set of six main groups of PEB barriers directly comes together with the same set of governance/PEB instruments.

6. Some of the PEB actions are more attractive than others for citizens, also for municipalities and other actors, so that one person or organization can easily accommodate parallel environmentally damaging and sustainable behavior. The motivation to protect or improve the environment is rarely the primary motivation for people's PEB, but it can reinforce it. **PEBs are often motivated by the desire to save money, improve health, increase property value, or gain recognition from others.** Much more attention should be paid to the socio-psychological factors of people's decision-making (feelings, desires, social pressures and norms) – actually, for all communication instrument's orientation and selective usage.

7. Even further developing and also use of non-traditional information instruments its insufficient for changing behaviour. A complementary set of action oriented and collaboration development instruments should be more developed and applied - our environmental & PEB communication collaboration model (Ernsteins, 1999) includes, **besides information also education & training instruments, involvement & participation instruments, and PEB practice demonstration instruments,** which all are to be complementary and adjusted to the societal groups.

8. Household behaviour is driven by a complex set of factors and they vary depending on the different interest groups of society. First, we recognize five main and wholly complementary societal stakeholder groups or governance segments: **households-inhabitants, governmental and also municipal segments, business-entrepreneurs segment and nowadays also mediator's segment too.** Further on, we shall consider various and very many specific interest groups within those governance segments and within various socio-ecological systems those particular groups live and perform. We should consider this societal heterogeneity very carefully and not only around interests, but also taking into account behavioral history, traditions, age, family types etc., when planning the PEB communication process and instruments - very selectively targeting and performing for this **high societal diversity and applying related complementary communication instruments.**

9. Pro-environmental behavior should be strengthened in overall municipal planning and management practices by facilitating a tailored PEB policy

approach to bridge behavioural gaps and overcome PEB barriers. Those and other PEB weaknesses shall be **regularly monitored and appropriately integrated into the entire municipal development (and environmental) governance process,** including integration into each of all the process stages from situation analysis, policy design, planning, till implementation management and monitoring. Importantly, the key PEB success **precondition** is recognition and application of **all three complementary governance dimensions** – Tripple - Dimensions Governance **(TDG)** framework model as also PEB governance framework - governance sectors, governance stakeholders, and governance instruments.

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EVOLUTION OF WATER LEVELS IN THE RIVER LIELUPE: A PERSPECTIVE FOR JELGAVA CITY

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Abstract
The River Lielupe is a critical hydrological and ecological resource for Jelgava City, significantly influencing agricultural productivity, urban development, biodiversity, and disaster risk management. However, long-term fluctuations in water levels pose pressing challenges, particularly increased flood risks during wet periods and more severe low-flow conditions during droughts. This study undertakes a comprehensive analysis of multi-decadal daily water level data recorded at the Jelgava gauge station, employing robust statistical approaches to identify clear patterns and trends. By systematically examining seasonal and annual variations and investigating potential climatic and anthropogenic drivers, our results reveal significant increases in both mean and minimum water levels, accompanied by a discernible decline in maximum levels. These shifts indicate evolving hydrological dynamics, likely driven by changing precipitation regimes, increasing land-use intensification, alterations in upstream land management practices, and ongoing river regulation efforts. The findings underscore the growing urgency for adaptive water resource management strategies tailored specifically to the basin. Recommended actions include the development of advanced flood protection infrastructures, sustainable water-use frameworks, comprehensive ecosystem-based planning, and strategic and well-informed policymaking. These strategies are essential to enhance the long-term resilience, sustainability, and ecological functionality of the Lielupe basin amidst ongoing climatic variability, urbanization pressures, and broader environmental change.
Keywords: hydrology, flood risk, adaptive management.

Introduction

The River Lielupe is considered a vital environmental and socio-economic resource for Jelgava City. Its water levels are influenced by factors ranging from agricultural activities and urban infrastructure planning to flood control measures and drought mitigation strategies (Krapesch et al., 2011; Miller et al., 2014). Over time, its hydrological regime has been modified by natural variability, climatic shifts, and human interventions (Itoshiro et al., 2021; Guo et al., 2022).

Variations in river form are quantified, and the factors influencing channel and valley responses to extreme floods, such as gradient, channel and floodplain morphology, and sediment availability, are analysed. These insights are essential for understanding the impacts on the river's hydrological regime (Bertoldi et al., 2010; Krapesch et al., 2011; Saha et al., 2019). Accurate hydrological simulations and river flow forecasts are recognised as key tools for managing water resources, assessing water demand, and planning irrigation (Ge et al., 2018; Guo et al., 2022).

The effects of climate change and human activities, including urbanisation and dam construction, on river hydrology have been widely studied (Allen & Pavelsky, 2015; Zhang et al., 2016; Feng et al., 2020). Structural and non-structural measures, such as flood-limited water level operations, are explored to mitigate extreme weather impacts and support sustainable water management (Li et al., 2012; Wei et al., 2016).

Large dams, such as the Three Gorges Dam on the Yangtze River, have significantly impacted downstream hydrology and river ecosystems (Zhang et al., 2016). Channel modifications for flood control have also been shown to harm freshwater ecosystems and associated species (Usuda et al., 2010; Wu et al., 2018).

Long-term hydrological data analysis is regarded as critical for identifying trends and understanding processes driving water resource changes (Krapesch et al., 2011; Miller et al., 2014). These assessments provide essential guidance for developing evidence-based water management and climate adaptation strategies (Itoshiro et al., 2021; Guo et al., 2022).

This study examines historical water level data from the Jelgava gauge station on the River Lielupe. Trends, seasonal and annual patterns, and climatic and anthropogenic factors influencing the changes are investigated (Bertoldi et al., 2010; Saha et al., 2019). The findings aim to inform urban planning, agricultural management, flood risk reduction, and environmental conservation in the Lielupe basin (Ge et al., 2018; Feng et al., 2020).

The aim of this study is to analyse historical water level records from the River Lielupe at Jelgava, to identify long-term trends and the driving processes, and to apply these insights to project future conditions, thereby supporting sustainable water resource management and policy development within the basin.

Materials and Methods

Daily water level measurements recorded at the Jelgava gauge station were utilised to generate key metrics, including daily maximum, mean, and minimum levels. Seasonal patterns were characterised by aggregating data by month to identify intra-annual variability, while annual statistics enabled the detection of long-term trends.

Linear regression and the non-parametric Mann–Kendall test were applied to assess trend significance and direction. The resultant findings were visually represented through time-series plots, boxplots, and other graphical tools, enabling straightforward interpretation of temporal variability. Collectively,

these methods ensured a rigorous and transparent approach to identifying and understanding underlying hydrological patterns.

Results and Discussion

Seasonal water level variability

Distinct seasonal patterns emerged from the analysis, revealing the natural hydrological cycle of the River Lielupe (Figure 1). Peak water levels occurred in March and April, primarily driven by snowmelt and spring runoff from the catchment. In contrast, the lowest water levels were observed in July and August due to lower rainfall, higher evapotranspiration, and increased agricultural water use.

During autumn, partial recovery in water levels was noted, with secondary peaks in November and December. This recovery is attributed to enhanced precipitation and storm runoff during this period. The cyclical nature of these seasonal variations underscores the predictable nature of hydrological changes in the River Lielupe basin.

Pronounced seasonal peaks during March and April have been confirmed, primarily influenced by snowmelt and spring runoff from the catchment area. A sharp rise in the seasonal component has consistently been observed during this period, thereby highlighting the dominant role of snowmelt processes in shaping river discharge.

Figure 1

Seasonal decomposition of Maximal water levels in the River Lielupe at Jelgava

The seasonal decomposition of water level data isolated these recurring patterns and confirmed the dominant role of snowmelt processes in shaping river discharge during spring. A sharp rise in the seasonal component was consistently observed during March and April, emphasizing the influence of catchment hydrology. Conversely, prominent seasonal lows in July and August, driven by reduced precipitation and heightened evapotranspiration, underscore the predictable nature of low-flow conditions during summer. The partial recovery in autumn reflects enhanced rainfall and storm-driven runoff, contributing to secondary peaks later in the year.

In addition to seasonal cycles, the decomposition analysis isolated long-term trends in water levels. These shifts correspond closely with the overall changes in mean, maximum, and minimum water levels discussed in Section 3.2. By disentangling seasonal influences from longer-term drivers, the underlying processes governing water level fluctuations have been more clearly delineated.

This integrated approach highlights the complex interplay between seasonal hydrological dynamics and long-term environmental trends, providing a comprehensive understanding of water level variability within the River Lielupe basin.

Yearly trends

Annual trend analysis revealed several significant changes (Figure 2). An upward trend was observed in the mean water levels ($\tau = 0.381$, $p < 0.001$). This suggests a consistent increase in baseline water availability over the studied period, which may indicate long-term hydrological or climatic changes impacting the region. The increasing mean levels

could contribute to enhanced ecosystem stability and resource availability.

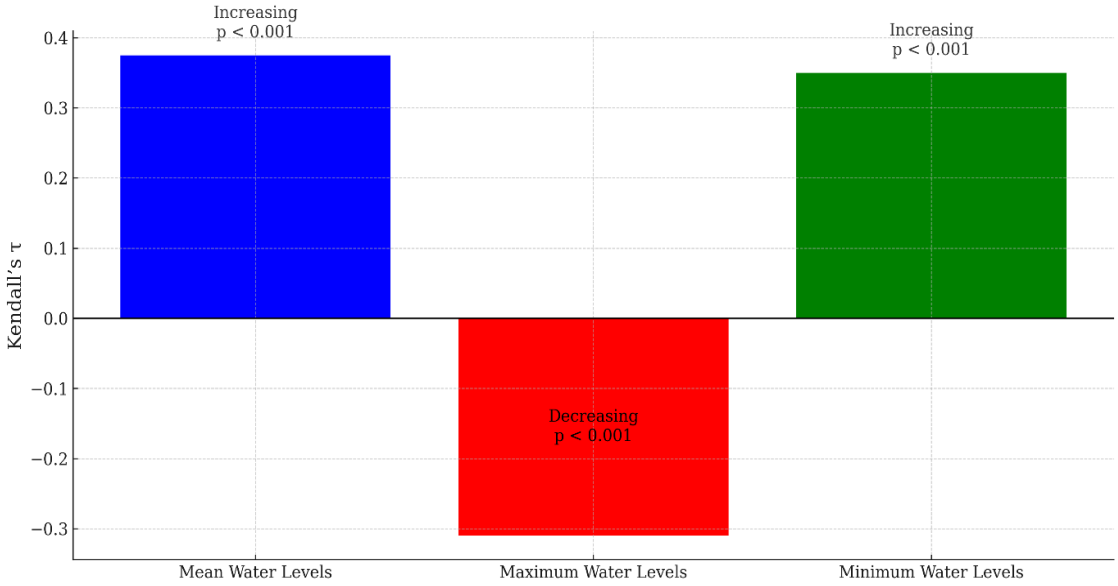
A declining trend in maximum water levels was identified (τ = -0.307, $p < 0.001$). This reduction in extreme flooding events suggests improved flood management practices, potential changes in precipitation patterns, or other environmental factors mitigating peak water flows. While the decline in maximum levels might reduce flood risks, it is essential to monitor these trends for their implications on floodplain dynamics and habitat maintenance.

A significant increase in minimum water levels (τ = 0.356, $p < 0.001$) was observed, indicating improved resilience of the river system during dry periods. Higher minimum levels are beneficial for maintaining ecological functions, supporting biodiversity, and ensuring water availability during droughts. This trend reflects positive changes in catchment area management, groundwater recharge, or seasonal flow regulation.

These findings underscore the importance of continuous monitoring and adaptive water management strategies to address both natural variability and anthropogenic influences on the River Lielupe's hydrological regime.

Figure 2

Long-term Trends in Water Levels for the River Lielupe at Jelgava



Factors influencing water level changes

The observed trends in the water levels of the River Lielupe are likely shaped by multiple climatic and anthropogenic factors (Krapesch et al., 2011; Miller et al., 2014). Regional climate change, characterised by modified precipitation patterns, rising temperatures, and altered snowmelt timing, is believed to exert significant influence on river discharge (Itoshiro et al., 2021; Guo et al., 2022). Hydrological responses are further modified by land use changes, urban expansion, intensified agriculture, and river regulation through dams and weirs, with impacts observed on both seasonal flow distribution and long-term water availability (Bertoldi et al., 2010; Saha et al., 2019).

Broader global changes, including sea-level rise and evolving atmospheric circulation, are also thought to interact with local watershed processes, potentially amplifying or dampening existing trends (Ge et al., 2018; Feng et al., 2020). The relative contributions of these various drivers must be understood to support the development of effective water resource management and climate adaptation strategies (Allen & Pavelsky, 2015; Zhang et al., 2016).

The impacts of climate alteration and human activities on the hydrological regime of the River Lielupe have been quantified to assess water demand, plan irrigation, and implement measures for flood control and drought mitigation (Li et al., 2012; Wei et al., 2016). Strategies for flood control, both structural and non-structural, alongside the dynamic operation of flood-limited water levels, have been explored to mitigate the effects of extreme weather events and to ensure sustainable water resource management (Usuda et al., 2010; Wu et al., 2018).

Critical insights for urban planning, agricultural management, flood risk reduction, and environmental conservation within the Lielupe basin are expected to be provided by this study. The findings are intended to contribute to the development of strategic, evidence-based policies and adaptation strategies to address the evolving water-related challenges faced by Jelgava City and the surrounding region.

Implication for future projections

The patterns observed in the water levels of the River Lielupe highlight several critical trends. A decline in maximum water levels has been identified, potentially reducing the severity of large-scale inundations. However, an upward trend in mean and minimum

water levels suggests a more stable baseline water supply, which could support agricultural productivity and reduce drought vulnerability (Krapesch et al., 2011; Miller et al., 2014). Despite these benefits, localised flooding events driven by short-duration, high-intensity rainfall remain a significant concern (Itoshiro et al., 2021; Guo et al., 2022).

Seasonal variations have also been emphasised, with peaks in water levels occurring during spring due to snowmelt and secondary peaks in autumn attributed to enhanced precipitation. Meanwhile, summer months are marked by low-flow conditions caused by reduced rainfall and increased evapotranspiration. These patterns underscore the importance of managing seasonal water availability to mitigate risks and optimise resource use.

The implications of these hydrological changes extend beyond water supply and flood control. Urban infrastructure, including drainage systems and water treatment facilities, may come under increased pressure due to more frequent heavy rainfall events.

Agricultural practices could be both positively and negatively affected, with improved baseline water availability offset by challenges posed by unpredictable rainfall patterns and localised flooding.

Ecosystem health within the Lielupe basin is also likely to be impacted. Reduced maximum water levels could alter floodplain dynamics and wetland ecosystems, while higher minimum levels may enhance the resilience of aquatic habitats during dry periods. The interplay of these factors must be carefully managed to maintain ecological balance and biodiversity.

Regional climate change, when combined with local land use practices and river regulation, can intensify or reduce observed hydrological trends. Modified precipitation patterns, rising temperatures, and urban expansion have all been identified as key drivers of hydrological variability (Ge et al., 2018; Feng et al., 2020). These influences must be considered in both short-term planning and long-term adaptation strategies.

To address the challenges and opportunities posed by these trends, several actionable strategies are recommended:

1. To enhance flood management, structural and non-structural measures should be revisited to prioritise the mitigation of rapid-onset flood events, particularly those triggered by intense localised rainfall. Dynamic operation of flood-limited water levels can be optimised to account for evolving rainfall patterns, ensuring that localised flooding risks are minimised (Allen & Pavelsky, 2015; Zhang et al., 2016).
2. Urban infrastructure, including drainage and water supply systems, should be retrofitted or redesigned to accommodate increasing hydrological variability resulting from climate change and land use dynamics. Investments in resilient infrastructure, such as permeable surfaces and retention basins, can reduce the impact of flash floods on urban areas (Usuda et al., 2010; Wu et al., 2018).
3. Improved sustainable agricultural practices should make use of better water availability during dry periods to increase irrigation efficiency and crop yields. At the same time, it is important to prepare for the risks of irregular rainfall and localised flooding.
4. Integration of climate and hydrological model outputs can improve the accuracy of seasonal and annual flow forecasts, supporting better water resource planning and risk management. These forecasts can inform resource allocation, flood preparedness, and long-term water management policies (Forzieri et al., 2013; Borgomeo et al., 2015).
5. Long-term water policies and governance frameworks should aim to balance water use across sectors, promote efficient management practices, and strengthen the resilience of water systems to climate variability. Collaborative governance frameworks involving local authorities, stakeholders, and scientists are essential to implement these strategies effectively (Hansen, 2013; Zarafshani et al., 2016).

Conclusions

1. This study provides a detailed assessment of long-term water level fluctuations in the River Lielupe at Jelgava City, revealing increased mean and minimum levels alongside declining maxima. These findings underscore the complexity of hydrological responses to changing climate regimes, land use practices, and water management strategies. Although reduced flood extremes may alleviate certain historical challenges, shifting hydrological dynamics have the potential to alter floodplain processes, sediment transport, and wetland ecology.
2. The documented variability emphasizes the necessity of adaptive and forward-looking approaches in urban development, agricultural production, and ecosystem conservation. Infrastructure must be designed and maintained to withstand localized flooding, while farming practices should be flexible to capitalise on a more reliable water supply. Future work should integrate socio-economic considerations and advanced modelling techniques to develop a holistic understanding of the river's evolving behaviour.
3. In essence, the observed changes in the River Lielupe water levels reflect broader climatic and anthropogenic influences impacting river systems worldwide. Ongoing monitoring, coupled with proactive adaptation and policymaking, will be essential to maintain ecological integrity, ensure sustainable water resource use, and support socio-economic vitality under increasingly dynamic environmental conditions.

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CALIBRATION AND VALIDATION OF A CONCEPTUAL HYDROLOGICAL MODEL IN SWAMPY RIVER BASINS OF LATVIA

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Abstract
In this study, the conceptual rainfall-runoff model METQ2007BDOPT was evaluated through detailed calibration and validation procedures carried out in five Latvian river basins, each characterised by diverse natural, topographical, and climatic conditions, including notably swampy areas with complex hydrological dynamics. Long-term observational runoff data covering a fifty-year period (1956–2006) were rigorously utilised to assess the model's overall performance and robustness. Satisfactory to good agreement was achieved between observed and simulated daily discharges across all tested basins, with correlation coefficients (r) ranging from 0.77 to 0.88 and determination coefficients (R^2) varying from 0.60 to 0.78, indicating reliable predictive capabilities. The strongest performance was recorded for the Malta River at Viļāni, reflecting highly consistent simulations of runoff patterns, whereas comparatively weaker but still acceptable results were observed for the Malmuta River at Kažava, likely due to more intricate swamp hydrology. These findings clearly confirm that the METQ2007BDOPT model can be effectively applied under varied environmental and hydrological conditions, particularly demonstrating its strength and adaptability in swamp-dominated river basins. Special emphasis was placed on refining key swamp-specific parameters within the model structure, effectively representing subtle yet crucial hydrological processes often overlooked or inadequately represented in conventional hydrological models. Such focused refinement enhances the model's precision and practical utility for hydrological forecasting and water resource management in complex landscapes.
Keywords: rainfall-runoff modelling, calibration and validation, swamp hydrology.

Introduction

Hydrological modelling is widely recognised as essential for understanding and managing water resources in regions characterised by complex hydrological dynamics, such as swampy river basins (Guo et al., 2017). These basins are defined by the presence of extensive wetlands, floodplains, and intricate interactions between surface water and groundwater (Spence et al., 2011). The accurate modelling of hydrological processes in these environments is considered crucial for applications such as flood risk assessment, water resource management, and ecosystem conservation (Merz et al., 2011).

The hydrological modelling of swampy river basins is associated with significant challenges, which are attributed to their unique and complex characteristics. These include notable spatial and temporal variability, limited data availability, and intricate hydrological interactions. Processes such as surface water-groundwater exchanges, evapotranspiration, and water storage dynamics exhibit high variability, complicating their representation within models (Koçyiğit et al., 2017). Additionally, the availability and quality of essential hydrological data, such as streamflow, groundwater levels, and precipitation, are often restricted, further impeding the calibration and validation of models (Vervoort et al., 2014). The representation of wetlands and floodplains also presents difficulties, as these features display non-linear and dynamic behaviour that is challenging to incorporate into hydrological frameworks (Spence et al., 2011). Furthermore, the complexity of these basins contributes to high levels of uncertainty and equifinality, where multiple parameter sets yield similar outputs, thereby complicating model reliability and interpretability (Alwan et al., 2016).

To address the unique challenges posed by swampy river basins, various approaches to hydrological modelling have been developed. Integrated surface water-groundwater models, such as MIKE SHE and ParFlow, are frequently employed to capture the interactions characteristic of these environments (Thirel et al., 2015). Wetland-specific models, including the Wetland Water Budget Model (WWBM) and the Wetland Hydrological Model (WHM), have been designed to represent the distinct hydrological processes within wetland ecosystems more effectively (Spence et al., 2011). Distributed hydrological models, such as the Soil and Water Assessment Tool (SWAT) and the Hydrological Simulation Program-FORTRAN (HSPF), are utilised to account for the spatial variability of hydrological processes across swampy regions (Zhang et al., 2013). The integration of remote sensing data, such as satellite imagery and soil moisture observations, with hydrological models has been demonstrated to improve the representation of these processes, particularly in data-scarce areas (Renard et al., 2010). In addition, uncertainty, and sensitivity analyses, including Monte Carlo simulations and Bayesian inference, have been applied to quantify and reduce the uncertainty associated with modelling these systems (Yin et al., 2016). Collectively, these approaches have been shown to enhance the accuracy and reliability of hydrological models in swampy river basins.

Earlier applications of METQ and its variants (e.g., METQ2007BDOPT) in Latvian basins have demonstrated overall effectiveness in simulating discharge under varying conditions, including forested and agricultural landscapes (Ziverts & Jauja, 1999; Bakute et al., 2015; Grinfelde & Bakute, 2017). However,

swamp-dominated basins present unique difficulties owing to prolonged wetness, variable soil moisture regimes, shallow groundwater tables, and intricate groundwater-surface water exchanges. These conditions necessitate parameterisation that differs substantially from that used in more conventional terrains.

The aim of this study is to assess the performance of the METQ2007BDOPT model, with a specific emphasis on its application in swampy areas. By calibrating and validating the model in five Latvian river basins, this research seeks to evaluate its ability to simulate daily discharges under complex hydrological conditions characteristic of swampy environments. Additionally, the study aims to identify the model's strengths and limitations and propose enhancements to improve its effectiveness in representing the unique dynamics of swamp-dominated basins.

Materials and Methods

Study area and data

Five river basins - Imula, Iecava, Pērse, Malta, and Malmuta - were selected to represent a broad range of hydrological and geographical conditions, including swampy areas (Table 1). These basins exhibit varying levels of forest cover, agricultural activity, and topographical features, thereby providing a suitable test of the model's performance across multiple environmental settings.

The swampy nature of certain basins, particularly Malmuta and Malta, introduces added complexity. High forest coverage (e.g., Pērse basin, 47%) and flat, low-lying areas (e.g., Malmuta basin) influence runoff patterns and water storage. Long-term runoff data (1956–2006) were used for calibration and validation. Local meteorological records complemented these hydrological datasets.

Methods

The METQ2007BDOPT model employed in this study is a conceptual rainfall-runoff framework designed to simulate daily river discharges by incorporating key hydrological processes such as precipitation, evapotranspiration, and soil moisture dynamics. The calibration procedure aimed to align model parameters with observed discharges, while validation was undertaken using independent datasets to ensure that the model could reliably predict runoff patterns without overfitting to the calibration period.

Table 1

Characteristics of the studied river basins and hydrological stations

River	***Hydrological Observation Station***	***Catchment Area (km²)***	***Avg. Annual Precip. (mm)***	***Calibration Period***	***Validation Period***
Imula	Pilskalni	263	650–700	1956–1990	1991–1994
Iecava	Dupši	1166	650–730	1956–1990	1991–1994
Pērse	Usiņi	329	680–800	1956–1990	2001–2006
Malta	Viļāni	876	650	1976–1990	1991–1994
Malmuta	Kažava	192	650	1980–2000	2001–2006

Detailed basin-specific parameters were applied, particularly for the Malta and Malmuta basins, to capture the unique hydrological characteristics of swampy regions (Table 2). The key model parameters basically are the same as in the METQ98 (Ziverts & Jauja,1999). These parameters enhanced the model's capacity to simulate processes such as groundwater-surface water interactions, soil moisture variability, and snowmelt dynamics. Regarding Imula, Iecava and Pērse, we did not allocate swamp basin-specific parameters. Special consideration was given to swamp-related parameters, ensuring that the patterns of water storage and release in poorly drained soils were accurately represented. These parameters were calibrated to reflect distinct soil, groundwater, and climatic conditions.

Calibration focused on adjusting parameters to minimise discrepancies between observed and simulated discharges, thereby improving the model's accuracy ʻFigure 1'. To maintain objectivity, non-overlapping calibration and validation periods were used. Performance was evaluated using statistical metrics, including correlation coefficients (r) and determination coefficients (R^2). The correlation coefficient assessed the linear relationship between observed and simulated values, while R^2 quantified the proportion of variance in observed discharges explained by the model.

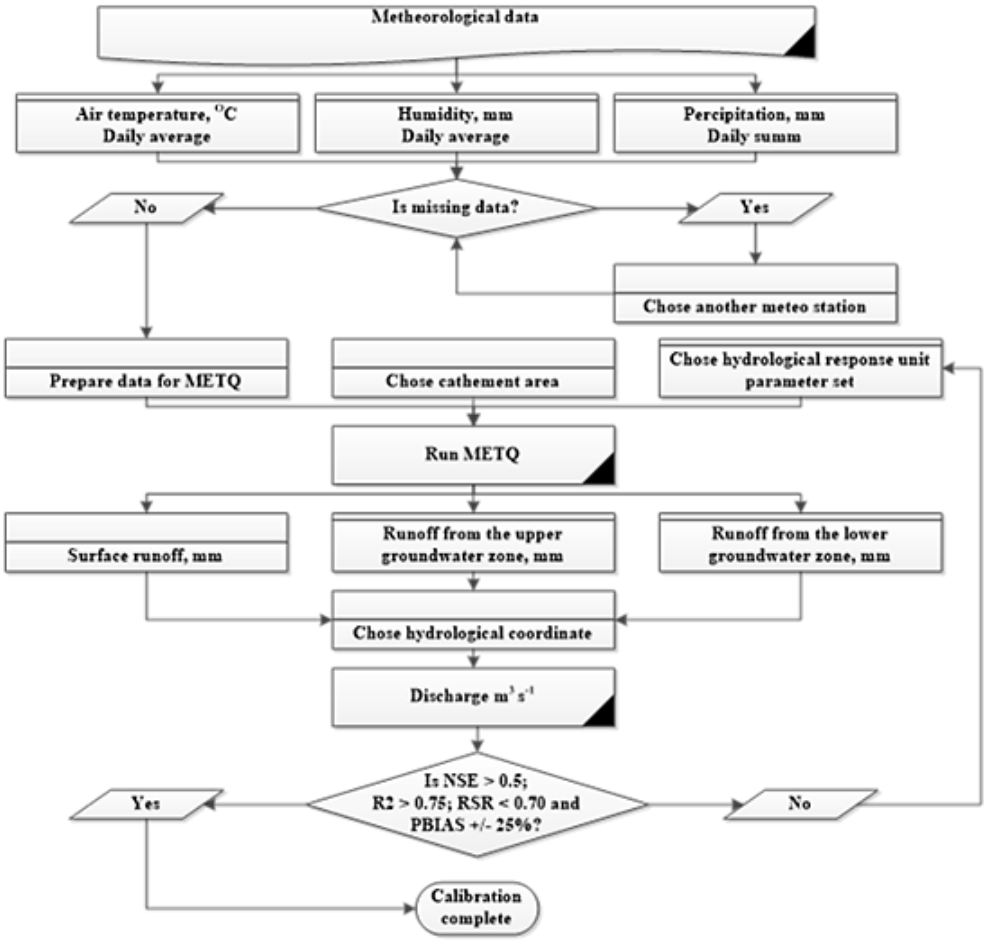
Table 2

Key model parameters for Malta and Malmuta Basins

Parameter	***Malta***	***Malmuta***
WMAX (mm)	30	20
ALFA	0.124	0.2
ZCAP (cm)	130	80
CMELT (mm/day)	3	2.5
PZ (cm)	305	60
RCHR	48	25
AMELTK	0.05	0.07

Attention was given to basin-specific parameters that allowed for the improved representation of swamp-influenced runoff processes, especially in the Malta and Malmuta basins. Parameters such as ZCAP, RCHR, and CMELT were critical for capturing soil moisture retention, groundwater recharge, and snowmelt dynamics, respectively. These parameters enabled the model to better account for hydrological complexities often associated with swampy and low-lying regions.

Figure 1
Calibration steps of the model METQ for the hydrological response unit



The study examined multiple river basins with varying climatic and physiographic conditions. Calibration and validation periods were determined by data availability: Malta (1976–1994), Pērse (1956–2006), Iecava (1956–1994), Malmuta (1980–2006), and Imula (1956–1994). This multi-basin approach ensured that the model could be tested under a range of conditions and that its performance could be more comprehensively evaluated.

Addressing the challenges inherent in swamp modelling required a careful approach. High spatial variability in swamp hydrology was tackled by using high-resolution precipitation and topographical data, allowing for a more accurate representation of localised swamp processes. The study did not employ proxy or remote sensing data (such as satellite-derived rainfall estimates) to compensate for sparse monitoring networks, focusing instead on refining the model's inherent process representations. Efforts were made to incorporate feedback mechanisms characteristic of swamp ecosystems, including prolonged surface water retention in depressional areas and gradual groundwater release. These processes, which have often been neglected or underrepresented in previous modelling attempts, were integrated to improve the reliability of the METQ2007BDOPT model's simulations, particularly in environments shaped by complex swamp hydrology.

Results and Discussion

The performance of the METQ2007BDOPT model was evaluated during both calibration and validation phases across all five basins (Table 3). The results indicated variable performance, reflecting the influence of basin-specific characteristics and swampy conditions. For the Imula Basin, moderate performance was achieved during calibration (R^2 = 0.66), whereas validation results showed weaker

explanatory power (R^2 = 0.43). The correlation coefficient (r) during calibration (0.77) suggested a strong linear relationship between observed and simulated discharges, which declined somewhat during validation (r = 0.70), indicating a reduced yet still acceptable linear relationship.

Similarly, the Iecava Basin exhibited moderate calibration performance (R^2 = 0.66), followed by a diminished fit during validation (R^2 = 0.44). Although the R^2 value declined, the correlation coefficient (r) remained relatively robust, decreasing only slightly from 0.82 to 0.79. This finding suggests that while the proportion of explained variance was reduced, the overall linear association between observed and simulated values remained comparatively strong.

In contrast, the Pērse Basin performed well under both calibration (R^2 = 0.65) and validation (R^2 = 0.68) conditions. The correlation coefficient (r = 0.85) was consistently strong across both periods, indicating stable and reliable simulations of daily discharge. This stability implies that the model's parameterisation was particularly suitable for the Pērse Basin's hydrological characteristics.

Table 3

Calibration and validation performance of the METQ2007BDOP model

River Basin (Station)	***Calibration R^2***	***Calibration r***	***Validation R^2***	***Validation r***
Imula–Pilskalni	0.66	0.77	0.43	0.70
Iecava–Dupši	0.66	0.82	0.44	0.79
Pērse–Ūsiņi	0.65	0.85	0.68	0.85
Malta–Viļāni	0.78	0.88	0.69	0.87
Malmuta–Kažava	0.52	0.65	0.60	0.78

Among the studied basins, the Malta Basin at Viļāni achieved the highest overall performance. An excellent calibration fit was indicated by R^2 = 0.78, while a strong validation result of R^2 = 0.69 confirmed the model's robustness. Correlation coefficients remained high (r = 0.88 during calibration, r = 0.87 during validation), marking the Malta Basin as the benchmark for model adaptability and precision, as reflected in the performance metrics (Table 3).

The Malmuta Basin presented the greatest challenges. Although calibration performance was comparatively weak (R^2 = 0.52), a slight improvement during validation (R^2 = 0.60) suggested that the model's predictive capability increased over time. The correlation coefficient improved from 0.65 to 0.78, indicating that while initial parameterisation may not have been fully optimised for swampy conditions, certain aspects of the model configuration proved more effective under validation (Table 3).

Overall, the Malta Basin consistently outperformed the others, reflecting the model's adaptability to its specific hydrological conditions, whereas the Malmuta Basin posed significant challenges, highlighting the need for further refinement in swampy and low-lying terrains. Stable performance was demonstrated in the Pērse Basin, suggesting a strong suitability of the model's parameterisation for its environmental setting. Validation metrics generally showed slight declines or maintained consistency relative to calibration, indicating that while the model exhibited a robust predictive capacity, further enhancements could be implemented to improve accuracy and applicability across all studied basins.

The METQ2007BDOPT model has been demonstrated to perform strongly in simulating discharge patterns in swampy and variable basins, achieving high correlation coefficients (r = 0.77–0.88) (Guo et al., 2017). This indicates that the complex hydrological dynamics observed in these environments have been accurately replicated. The incorporation of swamp-specific parameters has been identified as a key factor in enhancing the model's capacity to represent these intricate systems (Guo et al., 2017).

Parameters such as WMAX, ZCAP, and RCHR have been found to play a critical role in capturing essential hydrological processes within swampy basins, including soil water storage, capillary rise, and groundwater recharge (Guo et al., 2017). Through the accurate representation of these processes, biases have been reduced, and the simulated runoff dynamics have been brought closer to the observed data (Guo et al., 2017). The importance of incorporating appropriate parameters and process representations when modelling hydrological systems with significant wetland and floodplain components is thereby highlighted.

The careful calibration of snowmelt parameters (CMELT and AMELTK) has further improved the model's capacity to depict seasonal transitions, particularly during periods when frozen conditions give way to thawed states (Guo et al., 2017). This has been deemed essential in Northern European climates, where snowmelt processes exert a critical influence on the overall hydrological regime (Guo et al., 2017).

The model's strong performance in swampy and variable basins has been attributed to its ability to capture the complex interactions between surface water, groundwater, and snowmelt processes (Guo et al., 2017). This contrasts with many traditional

hydrological models, which often struggle to represent the unique characteristics of these environments with sufficient accuracy (Spence et al., 2011). Hydrological modelling includes various challenges, e.g., setting appropriate geomorphic boundary conditions, account for river channel dynamics, etc. (Swinnen et al., 2021). In addition, there does not exist a one-size-fits-all model, and it is important to improve performance of hydrological models (Mozafari et al., 2023).

The findings of this study underscore the importance of developing and applying specialised hydrological modelling approaches that are tailored to the specific challenges posed by swampy river basins (Merz et al., 2011). By incorporating appropriate parameters and process representations, researchers and water resource managers are better equipped to improve the understanding and management of these complex and ecologically significant systems (Koçyiğit et al., 2017).

Future research is recommended to continue exploring advanced hydrological modelling techniques, such as integrated surface water-groundwater models, wetland-specific modelling approaches, and the integration of remote sensing data, in order to further enhance the ability to simulate and predict the behaviour of swampy river basins (Vervoort et al., 2014). In addition, rigorous uncertainty analysis and sensitivity analysis techniques are necessary to quantify and mitigate the uncertainties inherent in hydrological modelling of such complex environments (Alwan et al., 2016).

When compared to other conceptual rainfall-runoff models, the METQ2007BDOPT framework has demonstrated strong competitiveness, particularly in swampy environments (Thirel et al., 2015). This can be attributed to the model's adaptability, which is underpinned by its basin-specific parameterisation (Thirel et al., 2015). Such a robust foundation provides opportunities for future refinements and broader applications to a wider range of catchment types (Thirel et al., 2015).

The reliability of the model in accurately simulating discharge patterns within swampy basins suggests that it can be effectively utilised for a variety of critical applications, including climate change scenario assessments, sustainable water resource planning, and integrated catchment management strategies (Thirel et al., 2015).

The insights derived from this study are expected to contribute to the development of improved modelling frameworks capable of better accommodating the complexities of wetland and swamp systems (Thirel et al., 2015). By advancing the understanding of critical hydrological processes in these environments, researchers and water resource managers will be better positioned to make more resilient and sustainable decisions regarding water resource management.

Conclusions

1. Through calibration and validation conducted across five Latvian river basins, the suitability of the METQ2007BDOPT model under swampy and variable conditions was confirmed. Robust results at Malta–Viļāni (R^2 = 0.69, r = 0.87) demonstrated the model's capability, while challenges at Malmuta–Kažava highlighted areas for improvement.
2. Incorporating basin-specific parameters significantly enhanced the model's capacity to capture the unique hydrological dynamics of swamp-dominated basins. Future efforts should focus on refining parameter estimation techniques, integrating finer-resolution data, and considering additional hydrological processes, such as biogeochemical cycles and vegetation-hydrology feedbacks,to produce even more accurate and ecologically relevant simulations.

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FORECASTS OF WASTE DYNAMICS IN LATVIA IN THE CONTEXT OF EU WASTE MANAGEMENT POLICY

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Abstract
Latvia faces growing waste challenges due to urbanization and consumption. Aligned with EU goals, it aims to cut landfill waste to 10% by 2035 through prevention, reuse, and recycling. This study assesses the dynamics of waste volume and flow in Latvia from 2018 to 2023, evaluating current waste management performance and forecasting future trends. The research is based on historical data from public databases and the regional waste management company SIA 'AAS Piejūra', analyzing various waste fractions. Results reveal a consistent increase in total waste volumes, rising from 3,439 tons in 2018 to 11,877 tons in 2023, with a notable spike in 2020 (10,220 tons). Key recyclable waste categories demonstrated significant growth: glass recycling increased from 277 tons in 2018 to 2,399 tons in 2023, and cardboard and paper from 264 tons to 1,739 tons in 2020. Mechanical waste processing remained the dominant category, peaking at 7,223 tons in 2023, indicating robust material recovery performance. Results reveal a consistent increase in total waste volumes, rising from 3,439 tons in 2018 to 11,877 tons in 2023, with a notable spike in 2020. Glass and cardboard recycling improved, while mechanical processing had the highest volumes. Fluctuations in tires and PET reflect changing infrastructure. Results show progress in recycling and waste processing efficiency. Advancements highlight the need for continued investment in infrastructure and awareness to support Latvia's circular economy. The study aids planning for better recycling, future needs, and EU compliance.
Keywords: waste volume trends, urbanization and waste, public awareness in waste management.

Introduction

The increasing production of waste globally, including in Latvia, is regarded as a pressing environmental and social challenge. This phenomenon is primarily attributed to rapid urbanization, rising consumption, and technological advancements, which collectively exert significant pressure on waste management systems to adapt and evolve. Urbanization, in particular, has been associated with heightened waste generation, as increased population density and consumption patterns in cities result in larger volumes of waste (Ciuta et al., 2015; Burlakovs et al., 2020). The waste generated in urban areas is typically characterized by a significant proportion of organic materials, which are recognized as complicating waste management efforts (Romero-Hernández & Romero, 2018).

In response to these challenges, ambitious waste management policies have been established by the European Union (EU) to reduce landfill dependency, prioritize recycling and reuse, and facilitate the transition toward circular economies. These policies are designed to ensure compliance with international standards for environmental sustainability by member states, including Latvia (Avarand et al., 2023). Emphasis is placed by the EU's Waste Framework Directive on waste prevention and resource recovery, encouraging the implementation of strategies that align with circular economy principles (Avarand et al., 2023).

In Latvia, an ambitious target has been set to reduce landfill waste to 10% of total waste by 2035, demonstrating a strong commitment to sustainable waste management practices (European Commission, 2020). The importance of prevention, reuse, and recycling over traditional waste disposal methods is highlighted by this goal. The transition to a circular economy is aimed not only at minimizing waste generation but also at maximizing the value derived from waste materials, thereby contributing to environmental sustainability and economic resilience (Mihajlov et al., 2021).

The dynamics of waste generation and its composition in Latvia are influenced by multiple factors, including seasonal variations, urbanization, and industrial activities. These elements are recognized as creating a complex landscape for waste management, particularly in coastal regions where seasonal population surges exacerbate existing challenges. An understanding of these dynamics is regarded as essential for the development of effective waste management strategies that align with both local needs and European Union (EU) directives.

Significant fluctuations in waste generation are experienced in coastal regions of Latvia due to seasonal population increases, particularly during the summer months when tourism peaks. This influx of visitors is observed to generate more waste, which can overwhelm existing waste management systems (Burlakovs et al., 2020; Gbolahan, 2023). The composition of waste during these periods is characterized by a notable increase in organic waste from food services and recreational activities (Kubule et al., 2019). Such dynamics are recognized as necessitating adaptive waste management strategies to accommodate varying waste streams throughout the year.

Urban centers in Latvia, marked by dense populations and concentrated industrial activities, are acknowledged as presenting further challenges to waste management efforts. High volumes of waste are generated in these areas, consisting of municipal solid waste (MSW), industrial by-products, and construction debris (Barisa et al., 2015). The diverse

composition of waste in urban settings is understood to require innovative approaches to sorting and processing, as traditional methods are often inadequate for handling the variety of materials present (Grainger et al., 2018). For example, the integration of waste-to-energy technologies has been proposed as a viable solution for converting non-recyclable waste into energy, thereby reducing landfill dependency (Gbolahan, 2023).

Innovative approaches are recognized as essential for addressing the complexities of waste generation in Latvia. Enhanced waste sorting systems, supported by public awareness initiatives, have been shown to improve recycling rates and reduce contamination in recyclable materials. The implementation of deposit-refund systems for beverage containers has been demonstrated as an effective method for increasing recycling participation among residents (Dāce et al., 2013). Additionally, the application of life cycle assessment (LCA) methodologies is acknowledged as providing valuable insights into the environmental impacts of various waste management strategies, guiding policymakers toward sustainable practices (Yay, 2015).

The improvement of waste management infrastructure is identified as critical for effectively managing the dynamics of waste generation in Latvia. Investments in modern recycling facilities and composting systems are considered essential for better processing of organic waste and recyclables (Kubule et al., 2019). Furthermore, public engagement campaigns aimed at educating citizens about waste sorting and recycling are recognized as fostering a culture of sustainability and encouraging responsible waste disposal behaviours (Cantillo & Quesada, 2022).

The dynamics of waste generation and its composition in Latvia are shaped by seasonal variations, urbanization, and industrial activities, presenting unique challenges for waste management systems. Addressing these challenges is understood to require innovative approaches, improved infrastructure, and active public engagement. By adopting comprehensive waste management strategies that consider the complexities of waste generation, Latvia can work toward achieving its sustainability goals and complying with EU directives.

Despite the growing importance of sustainable waste management, there is a lack of comprehensive, data-driven analyses that track long-term waste volume and flow dynamics in Latvia, especially in relation to specific waste fractions and seasonal fluctuations. Existing studies tend to focus on isolated aspects, such as waste composition or public attitudes, without providing integrated assessments over time. Therefore, this research aims to fill this gap by offering a systematic overview of waste generation trends, their alignment with EU policy goals, and implications for future planning.

This study is focused on the analysis of waste volume and flow dynamics in Latvia between 2018 and 2023. Historical data from publicly available databases and SIA ʻAAS Piejūraʼ have been examined to provide a comprehensive evaluation of trends in waste management efficiency and infrastructure development. Special attention has been directed toward the success of recycling programs, fluctuations in specific waste categories, and the factors driving these changes.

The goal of this research is defined as the identification of key trends and challenges in waste management, the assessment of progress toward EU compliance, and the proposal of strategic recommendations for improving recycling efficiency and reducing landfill dependency. By fostering sustainable waste practices, it is intended that a green economy will be supported, environmental impacts will be reduced, and long-term solutions benefiting both society and the environment will be created.

This paper is aimed at providing valuable insights into the evolution of waste management systems in Latvia and offering a framework for addressing future waste challenges. The findings are designed to guide policymakers, researchers, and waste management practitioners in the development of robust strategies that align with EU directives and contribute to a more sustainable future.

Materials and Methods

The research area

The study was conducted in the Piejūra region, located along the western coast of Latvia and managed by the Piejūra Waste Management Association (SIA ʻAAS Piejūraʼ). This region, encompassing municipalities such as Talsi, Tukums, Ventspils, and parts of Jūrmala, is characterized by a diverse mix of urban centers, rural areas, and coastal zones ʻFigure 1ʼ.

A combination of geographic, demographic, and economic factors was observed to shape the waste generation dynamics in the region. Urban centers, including cities like Ventspils and Tukums, were identified as significant contributors to municipal solid waste due to higher population densities and concentrated industrial activities. Surrounding rural areas were noted to produce biodegradable agricultural waste, reflecting the agrarian economy of the region. The Baltic Sea coastline was recognized as an influential factor, with seasonal surges in population during peak tourism periods significantly increasing the volume of waste generated, particularly organic waste from recreational activities and food services. The waste management system in the Piejūra region was observed to operate under an integrated framework, including collection, sorting, and recycling services overseen by SIA ʻAAS Piejūraʼ.

Facilities for sorting and processing recyclable materials, such as glass, paper, and plastics, were reported to align with European Union (EU) waste management directives.

Figure 1
The area of AAS 'Piejūra' waste management services

Seasonal waste management strategies were implemented to address fluctuations in waste volume during tourism peaks, and innovative programs, such as deposit-refund systems for beverage containers and waste-to-energy initiatives, were highlighted as key components of the system. These characteristics were considered essential in contextualizing the waste management challenges and opportunities within the Piejūra region, providing a relevant framework for assessing the effectiveness of sustainable waste practices.

Data collection

The information required for the study was obtained from publicly available databases, including the Central Statistical Bureau of Latvia (CSP), the State Environmental Service (VVD), the Latvian Environment, Geology and Meteorology Centre (LEGMC; in Latvian: LVĢMC), and historical data from the waste management company ʻAAS Piejūraʼ (Limited Liability Company ʻAAS Piejūraʼ, or SIA ʻAAS Piejūraʼ) on waste volumes and flows by fractions from previous years. Regional and national statistical data sources were utilized to analyze changes in waste volumes and composition. Demographic data regarding population changes and lifestyle shifts in the region were also collected and analyzed.

The dataset included specific waste fractions such as cardboard and paper (150101), glass (150107), PET plastic (150102), used tires (160103), household electrical equipment (200136), biodegradable waste (200201), and waste from mechanical processing (191212), among others. Data were collected annually for the period from 2018 to 2023. Descriptive statistical methods were used to evaluate annual changes in total and category-specific waste volumes. These results were interpreted in the context of the European Union's Waste Framework Directive, particularly focusing on the target to reduce landfill waste to 10% of total waste by 2035. The analysis emphasized trends in recycling efficiency, fluctuations in specific waste types, and the capacity of existing waste infrastructure.

Results and Discussion

The table (Table 1) provides a comprehensive overview of annual waste quantities realized from 2018 to 2023, with total, average, maximum, and minimum values presented across various waste categories. Trends, fluctuations, and overall changes in waste management efficiency and practices are reflected over this period. Total waste volumes were observed to increase consistently, rising from 3,439.260 tons in 2018 to 11,877.354 tons in 2023. A significant spike was identified in 2020, during which waste volumes more than tripled compared to 2019, indicating substantial growth in waste collection or processing. Similarly, average annual waste volumes followed an upward trajectory, demonstrating improvements in waste management systems.

Certain waste categories, including cardboard and paper waste (150101) and glass (150107), were found to exhibit significant maximum realized quantities in 2020 and 2023, respectively, indicating the success of recycling programs. Mechanical waste processing (191212) remained the largest category throughout the study period, peaking at 7,223.440 tons in 2023, which reflects the robustness of recycling and material processing activities. In contrast, fluctuations were observed in categories like used tires (160103) and PET (150102), potentially influenced by variations in demand, collection rates, or the availability of infrastructure.

The analysis emphasizes overall improvements in waste management practices, with particular progress noted in the expansion of recycling efforts and processing capacities. These findings underscore the critical importance of maintaining steady investment in waste infrastructure and programs to ensure long-term sustainability and compliance with environmental policies. This evaluation serves as a solid foundation for future strategic planning in waste management, with a focus on improving recycling efficiency and adapting infrastructure to meet evolving demands and environmental targets. The analysis of waste volume and flow dynamics in Latvia from 2018 to 2023 provides critical insights into the evolution of waste management practices and their alignment with European Union (EU) directives. The observed increase in total waste volumes, from 3439260 tons in 2018 to 11877354 tons in 2023, highlights the growing challenges of waste generation driven by urbanization, rising consumption, and technological advancements. This trend reflects a broader pattern seen across many EU member states, where waste generation has been closely linked to economic activity and population growth (Valenćiková & Fandel, 2023). The significant spike in waste volumes in 2020, when waste generation more than tripled compared to 2019, may be attributed to changes in collection or processing

systems, suggesting that waste management practices are becoming increasingly responsive to emerging demands and fluctuations in consumer behavior.

The increase in waste volumes aligns with the EU's New Circular Action Plan, adopted in March 2020, which aims to reduce waste generation while promoting sustainable practices across various sectors, including packaging, batteries, and construction materials (Homenko et al., 2021). This plan emphasizes the importance of adhering to the Waste Framework Directive 2008/98/EC, which established the waste management hierarchy prioritizing prevention, reuse, and recycling over disposal. The implementation of such directives is crucial for countries like Latvia, which are striving to enhance their waste management systems in accordance with EU standards (Kubule et al., 2019).

Moreover, the growth in waste volumes raises questions about the effectiveness of current waste management strategies and the need for continuous improvement. As highlighted by Przydatek (2020), many new EU member states, including Latvia, still face challenges related to high volumes of non-selectively collected waste, which can hinder recycling efforts and increase landfill dependency. This underscores the necessity for Latvia to develop and implement more robust waste management policies that not only comply with EU regulations but also promote sustainable development and resource efficiency.

The findings also suggest that public awareness and engagement play a critical role in improving waste management practices. As noted by Melece et al. (2018), changing attitudes and behaviors among households is essential for achieving recycling targets set by the EU, such as the goal of recycling 60% of municipal waste by 2025 (Melece et al., 2018). Therefore, initiatives aimed at educating the public about waste sorting and recycling can significantly enhance the effectiveness of waste management systems.

Table 1

The realized material in tons from 2018 to 2023

Code	***Realized Material***	***Total (2018-2023)***	***Aver. (2018-2023)***	***(Year) Max.***	***(Year) Min.***
150101	Cardboard, paper waste	6,384.816	1,064.136	2020 (1739.112)	2018 (264.200)
150107	Glass	7,614.990	1,269.165	2023 (2399.460)	2018 (276.720)
150102	PET	435.736	72.623	2020 (146.636)	2023 (0.000)
150102	Film, Big Bag	1,139.042	189.840	2023 (292.760)	2019 (63.169)
150102	HDPE and PP materials	194.863	32.477	2020 (72.897)	2018 (8.520)
150104	Metal packaging	17.770	2.962	2021 (13.380)	2018 (0.000)
200136	Used household electrical equipment	491.155	81.859	2021 (137.240)	2018 (10.620)
200102	Glass (window)	151.740	25.290	2023 (68.980)	2018 (0.000)
200121	Fluorescent lamps	4.800	0.800	2020 (1.720)	2019 (0.000)
160103	Used tires	1,010.560	168.427	2022 (311.600)	2019 (0.000)
200140	Metals	148.751	24.792	2020 (39.973)	2018 (0.000)
191212	Waste from mechanical processing	29,212.020	4,868.670	2023 (7223.440)	2019 (1525.760)
191207	Wood	201.840	33.640	2019 (163.920)	Other years (0.000)
200201	Biodegradable waste (branches)	650.340	108.390	2023 (233.100)	2018 (0.000)

In conclusion, the analysis of waste volume and flow dynamics in Latvia from 2018 to 2023 reveals significant trends that reflect both challenges and opportunities in waste management. The increasing waste volumes highlight the need for adaptive strategies that align with EU directives while addressing local conditions. Continued investment in waste management infrastructure, coupled with public engagement and education, will be essential for Latvia to achieve its sustainability goals and effectively manage waste in the future.

The findings of this research provide a robust foundation for strategic planning in waste management in Latvia, emphasizing the need to improve recycling efficiency, adapt infrastructure to meet evolving demands, and align practices with European Union (EU) environmental compliance goals. As Latvia navigates the complexities of waste generation and

management, it is imperative to address current challenges while leveraging successful initiatives that have emerged over recent years. For instance, the implementation of extended producer responsibility (EPR) schemes has shown a promise in enhancing recycling rates and reducing landfill dependency, as highlighted by Kubule et al. (2019). Such initiatives not only contribute to waste reduction but also foster a culture of sustainability among producers and consumers alike.

Moreover, the transition toward a circular economy is crucial for prioritizing sustainability, resource efficiency, and environmental protection. The EU's Circular Economy Action Plan provides a comprehensive framework that Latvia can adopt to promote sustainable practices across various sectors, including packaging, textiles, and electronics (Gbolahan, 2023). By aligning national policies with EU directives, Latvia can enhance its waste management systems and contribute to broader environmental goals, such as reducing greenhouse gas emissions and conserving natural resources.

To ensure the effectiveness of these strategies, further studies are recommended to explore the long-term impacts of current waste management practices and to refine policies for future optimization. Research focusing on the economic, social, and environmental implications of waste management initiatives will provide valuable insights for policymakers and stakeholders. Additionally, examining the role of public engagement and education in promoting responsible waste disposal behaviors can enhance community participation in recycling programs, as noted by Popova and Sproģe (Popova & Sproģe, 2021).

Furthermore, the integration of advanced technologies in waste processing and recycling, such as artificial intelligence and machine learning, could significantly improve operational efficiencies and sorting accuracy. Investigating the potential of these technologies in the Latvian context will be essential for modernizing waste management practices and achieving sustainability targets.

In conclusion, Latvia is well-positioned to transition toward a circular economy by addressing current challenges in waste management and leveraging successful initiatives. By focusing on improving recycling efficiency, adapting infrastructure, and aligning with EU environmental compliance goals, Latvia can pave the way for a more sustainable future. Continued research and collaboration among stakeholders will be vital for refining waste management strategies and ensuring their long-term success.

Conclusions

1. Total waste volumes increased steadily, from 3,439.260 tons in 2018 to 11,877.354 tons in 2023, with a notable spike in 2020. This trend reflects growing challenges associated with urbanization, rising consumption, and technological advancements. The increasing waste volumes underline the importance of adaptive and innovative waste management strategies to handle the escalating demands effectively.
2. Specific waste categories, such as cardboard and paper (150101) and glass (150107), exhibited significant growth in recycling, demonstrating the success of targeted initiatives. Mechanical waste processing (code 191212) remained the largest waste fraction throughout the study period, with volumes increasing from 1,526 tons in 2019 to 7,223 tons in 2023. This indicates improved material recovery and reflects greater capacity in sorting and recycling systems.
3. Categories like used tires (160103) and PET (150102) displayed notable fluctuations, indicating gaps in collection rates and infrastructure. Addressing these inconsistencies requires further investment in waste sorting systems and expanded recycling capacity to ensure stable and efficient resource recovery.
4. Latvia's progress in improving recycling rates and reducing landfill dependency aligns with the European Union's (EU) circular economy and waste management directives. However, sustained efforts are needed to achieve the ambitious target of reducing landfill waste to 10% of total waste by 2035. In 2023, approximately 49% of municipal waste was still landfilled in Latvia, indicating a significant gap between the current situation and the EU target. Bridging this gap will require accelerated investment in recycling infrastructure and waste diversion strategies.
5. Public awareness and participation were identified as critical drivers for achieving effective waste management. Initiatives like deposit-refund systems have proven successful in increasing recycling participation, but further public education campaigns are essential to foster responsible waste disposal behaviors.
6. Continued investment in modern waste management infrastructure, including advanced recycling facilities and composting systems, is crucial for addressing the growing waste volumes and achieving long-term sustainability. Integrating technologies such as waste-to-energy systems and artificial intelligence for sorting could enhance efficiency.
7. The seasonal surges in waste generation, particularly in coastal regions during peak tourism months, present unique challenges. Adaptive strategies, such as seasonal waste collection schedules and infrastructure expansion, are necessary to address these variations effectively.

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LONG-TERM SPATIAL CHANGES IN AIR QUALITY IN JELGAVA CITY

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Abstract
Air pollution has been identified as a significant environmental issue and a major health threat, particularly in densely populated urban areas. Long-term and spatial variations in air quality across Jelgava City were analyzed using the Air Purity Index (I.A.P.), which is calculated based on the distribution and frequency of sensitive lichen species. Lichens were utilized effectively as biomonitoring tools due to their high sensitivity to air pollutants, their ubiquity, and their cost-effectiveness for detecting pollution trends over extensive spatial scales. Sampling plots were systematically established across various city zones, and comprehensive field data were collected from 1,250 deciduous trees carefully selected for uniformity in age, crown shape, and local growth conditions. The analysis revealed that in 2016, approximately 2.75% of Jelgava's urban area was categorized as high pollution zones, while 44.0% fell into moderate pollution zones, and 53.25% were classified as low pollution zones. Improvements in air quality were predominantly observed in suburban and peripheral areas; conversely, increased pollution was distinctly noted in the city center, correlating strongly with intensified industrial activities, growing vehicular emissions, and traffic congestion. The findings highlight the critical role of urban green infrastructure in mitigating air pollution impacts, particularly in moderate and low-pollution zones, whereas high-pollution hotspots continue to threaten biodiversity, public health, and urban ecosystem sustainability, demanding urgent mitigation efforts.
Keywords: biomonitoring, lichen-based monitoring, Air Purity Index (I.A.P.), urban sustainability.

Introduction

Air pollution has been identified as a pressing global issue, particularly in urban environments where its effects are exacerbated by population density and industrial activities. It is reported by the World Health Organization (WHO) that nearly 90% of the global population is exposed to polluted air, with urban areas being affected most severely due to high levels of vehicular emissions and industrial discharges (Dhimal et al., 2021; Bräuer et al., 2021a). In cities, alarming levels of pollutants such as particulate matter (PM), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) are observed, leading to significant health risks and environmental degradation (Rohde & Muller, 2015; Jennings et al., 2021).

The profound and multifaceted health impacts of air pollution are well-documented. Premature mortality is reported to be significantly contributed by air pollution, with millions of deaths annually attributed to respiratory and cardiovascular diseases (Burnett et al., 2018; Syuhada et al., 2023). For instance, in India, a substantial burden of disease has been linked to air pollution, with increased morbidity and mortality rates observed due to high exposure levels (Balakrishnan et al., 2019; Kumar, 2023). The economic implications are also highlighted; it has been estimated by the Public Health Agency of Canada that CAD 114 billion is lost annually due to health-related issues caused by air pollution (Syuhada et al., 2023). Similar economic burdens are noted in other countries, where a considerable percentage of GDP loss is attributed to health care costs and lost productivity (Balakrishnan et al., 2019; Syuhada et al., 2023).

Urban environments are regarded as particularly vulnerable to the effects of air pollution due to unique geographical and infrastructural characteristics. Stagnated air flow is commonly experienced in high-density areas, exacerbating pollution levels in street canyons and densely built environments (Yuan et al., 2014). Pollutant dispersion is influenced by the configuration of urban landscapes, resulting in localized hotspots of poor air quality (Baró et al., 2014). Additionally, socio-economic disparities in urban settings are noted to disproportionately expose marginalized communities to the brunt of air pollution, emphasizing the necessity of equitable environmental policies (Bräuer et al., 2021b; Jennings et al., 2021).

Mitigation strategies are considered essential to combat the adverse effects of air pollution in urban areas. Air quality improvements are shown to be achievable through nature-based solutions, such as urban forestry and green infrastructure, which enhance pollutant dispersion and absorption (Baró et al., 2014; Menon & Sharma, 2021). Significant reductions in urban air pollution levels are demonstrated by the implementation of green traffic policies, suggesting that positive outcomes can be achieved through strategic urban planning (Qiu & He, 2017). However, the operationalization of these strategies is recognized as requiring time and investment, with their success contingent upon comprehensive policy frameworks addressing both environmental and public health concerns (Gani, 2023).

The monitoring of air pollution is regarded as critical for understanding its impact on human health and the environment. The assessment of air quality is often conducted using bioindicators, particularly lichens. Lichens, which are symbiotic organisms composed of fungi and algae, are recognized for their high sensitivity to air pollution, making them excellent indicators of atmospheric conditions. The absorption of pollutants directly from the air by lichens allows the levels of various contaminants, including heavy metals and other toxic elements, to be gauged by researchers (Pilecka-Ulcugaceva et al., 2022; Pilecka-Ulcugaceva et al., 2024).

The widespread utilization of lichens in biomonitoring studies has been facilitated by their sensitivity to environmental changes. It has been demonstrated through studies that lichen diversity and vitality are significantly influenced by air pollution, particularly in urban areas. It was highlighted by Biase et al. (2022) that lichens are among the most commonly utilized bioindicators for monitoring atmospheric quality, as many species exhibit particular sensitivity to chemical pollution (Biase et al., 2022). This sensitivity has enabled the assessment of the impact of pollutants on lichen communities, which are reflective of broader environmental health.

The transplantation technique is employed as a common method in lichen biomonitoring. Lichens are collected from unpolluted areas and are then exposed to polluted environments for a specified duration. It has been noted by Klimek et al. that the success of this technique depends on the background concentration of pollutants and the vitality of the transplanted lichens (Klimek et al., 2015). Similarly, it was demonstrated by Abas et al. (2022) that the lichen '*Usnea misaminensis*' can be utilized as a reliable biological indicator for measuring urban air pollution, confirming its effectiveness when compared to traditional monitoring instruments (Abas et al., 2022).

Advancements in lichen research have recently been focused on high-resolution assessments of air quality. Lichen carbon, nitrogen, and sulfur contents, along with stable-isotope-ratio signatures, have been utilized by Niepsch et al. (2023) to evaluate air quality in urban centers. This approach is recognized for providing a nuanced understanding of pollutant deposition and dispersion in complex urban environments, where traditional monitoring methods may fall short.

The diversity of lichen species in a given area has also been identified as a qualitative measure of air quality. It was found by Belguidoum et al. (2022) that changes in lichen diversity were closely linked to air pollution levels, particularly in urban areas with significant anthropogenic impacts (Belguidoum et al., 2022). The correlation between lichen diversity and pollution levels underscores the importance of lichen diversity as a bioindicator, as the cumulative effects of multiple pollutants, including particulate matter and nitrogen oxides, are reflected.

In addition to diversity, lichen functional traits are also regarded as informative. It was emphasized by Pinho et al. that lichen functional diversity is sensitive to atmospheric ammonia levels, indicating that specific lichen species can be utilized to monitor particular pollutants (Pinho et al., 2011). This functional approach is recognized as complementing traditional diversity assessments and enhancing the robustness of lichen-based biomonitoring.

The urban environment of Jelgava, Latvia, is regarded as a unique case study for the monitoring of air pollution using bioindicators such as lichens. This approach is facilitated by the sensitivity of lichens to various atmospheric pollutants, particularly heavy metals and sulfur dioxide, which makes them effective indicators of air quality in urban settings (Pilecka-Ulcugaceva et al., 2021).

One notable methodology utilized in Jelgava involves the transplantation of lichens. Lichen samples are collected from less polluted areas and are exposed to urban environments for a predetermined duration. The physiological responses of the lichens, along with the accumulation of pollutants, are analyzed to assess air quality. For instance, it was demonstrated by Lackovičová et al. (2013) that the lichen '*Evernia prunastri*' exhibited significant changes in physiological parameters in response to urban pollution levels, indicating a decline in heavy metal concentrations following a reduction in emissions in Bratislava. These findings can be extrapolated to similar urban contexts like Jelgava (Lackovičová et al., 2013).

In addition to transplantation studies, the assessment of lichen diversity and vitality is employed to provide valuable insights into air quality. It was highlighted by Matwiejuk in Białystok (2011) that the average concentrations of accumulated elements in lichens were lower than in other Polish cities, suggesting a relatively better air quality in that urban area. This methodology can be applied to Jelgava, where the monitoring of lichen diversity may reveal the impacts of local pollution sources, such as traffic and industrial activities.

Furthermore, the use of lichen bags, as described by Petrova (2015), is implemented to monitor air quality in areas with high traffic and industrial activity. In this technique, lichens are placed in mesh bags at various urban locations, and the accumulation of pollutants over time is assessed (Petrova, 2015). This method is recognized as particularly effective in Jelgava, where specific sites can be targeted for detailed pollution studies.

The physiological responses of lichens to air pollutants have also been extensively documented. For example, it was explored by Yemets et al. (2014) that airborne pollutants affected lichen growth and viability along a rural highway in Norway, demonstrating the correlation between pollutant concentrations and lichen health. Such studies provide a framework for understanding how lichens in Jelgava might respond to local air quality conditions.

Moreover, the integration of lichen monitoring with other environmental assessments is considered beneficial for enhancing the understanding of urban air quality. The research by Guttová et al. (2011) in Bratislava illustrated how lichen responses reflected broader trends in air pollution, particularly in urban areas where emissions have significantly decreased since the 1990s (Guttová et al., 2011). This approach is recognized as adaptable for Jelgava, allowing for a comprehensive assessment of air quality over time.

The aim of this study is to evaluate the Air Purity Index (I.A.P.) in Jelgava City and to identify changes in air quality over time, utilizing bioindicators such as

lichens to assess the impacts of urban pollution and environmental dynamics.

Materials and Methods

Research area

The assessment of air quality in Jelgava using lichen bioindication has been conducted in a standardized 10-year cycle since 1996, with full surveys carried out in 1996, 2006, and 2016. This study focuses on the comparative analysis of air quality across these three years. Identical sampling protocols, plot layouts, and indicator species assessments were used during each monitoring cycle to ensure comparability and long-term trend evaluation.

Jelgava, located in the central part of Latvia, is recognized as the fourth-largest city in the country and is considered an important regional hub for education, culture, and industry. The city is situated approximately 40 kilometers southwest of the capital, Riga, along the Lielupe River, which has been historically significant for its development, economic activities, and environmental dynamics. An area of approximately 60 square kilometers is covered by the city, and a population of around 55,000 residents has been recorded in recent demographic data.

Jelgava lies at an elevation of approximately 3 to 5 meters above sea level, making it part of the lowland region of Latvia. This relatively flat terrain is characteristic of the Zemgale Plain, which influences hydrological processes and pollutant dispersion patterns within the city. The city's land use is predominantly characterized by residential, commercial, and industrial zones, interspersed with green spaces and parks. Additionally, agricultural land surrounds the city, with fields and pastures making up a significant portion of the regional landscape. These agricultural areas, while economically significant, are also potential sources of diffuse pollution, such as ammonia and particulate matter.

The climate of Jelgava is classified as humid continental (Köppen climate classification Dfb), with cold winters and mild summers. The average annual temperature is approximately +6 °C, with January being the coldest month (-3.5 °C average) and July the warmest month (+17.5 °C average). Annual precipitation averages around 600-700 mm, with the majority occurring during the summer months. Winters are typically marked by snowfall, which facilitates pollutant deposition, while the warmer months improve air circulation and promote pollutant dispersion.

The urban landscape of Jelgava has been shaped by historical and industrial development. Industrial activities, including food processing, metalworking, and manufacturing, have been historically concentrated in the city. While economic growth has been facilitated by these industries, environmental challenges, particularly regarding air and water quality, have also been posed. Urban traffic and industrial emissions are considered contributing factors to localized air pollution, which is compounded by the flat topography and limited vertical mixing of air masses in certain conditions.

Jelgava's environmental significance is further highlighted by its proximity to the Lielupe River, which acts as an ecological corridor for pollutant transport and serves as an important waterway for the region. The interaction of urban, industrial, and agricultural activities within this landscape underscores the need for integrated environmental management.

Jelgava is regarded as a unique case study for air quality evaluation, particularly through the use of innovative approaches such as bioindicators like lichens. Such studies are expected to contribute to the development of sustainable urban planning and environmental policies, ensuring long-term well-being for both residents and ecosystems.

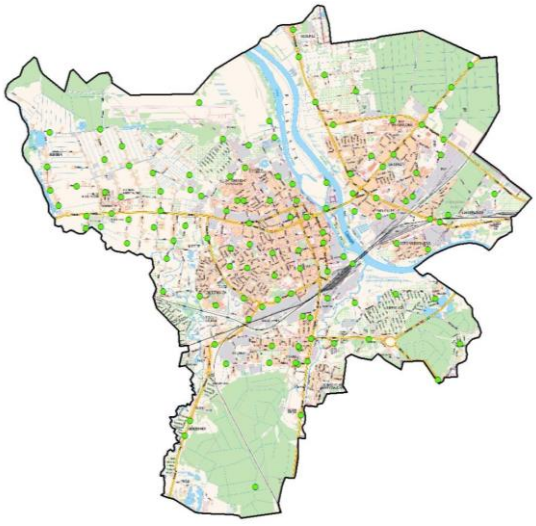
Data collection

To conduct lichen indication, the city was divided into 104 sample plots based on building density, the location of industrial enterprises, and transportation corridors. The central district was divided into 52 sample plots, each measuring 500 m x 500 m, while the remaining city area was divided into 52 sample plots measuring 1000 m x 1000 m. This arrangement of sample plots was established based on air quality studies conducted in 1996 and 2006. In 2016, an additional 21 sample plots were added due to urban development and the expansion of built-up areas ʻFigure 1'. In total, lichen indication was performed in 125 sample plots in 2016.

In each sample plot, 10 trees were selected for lichen counting. The trees were chosen to ensure similar age, height, and dimensions. On each tree trunk, all lichen species were recorded within the height range of 30 cm to 2 m. On the side of the tree trunk with the highest abundance of lichens, the percentage cover of lichens was evaluated for each species.

Figure 1

Sample plots in Jelgava city in 2016



Data analysis

The Air Purity Index (I.A.P.) is determined for each sample plot and consists of the sum of the products of the toxic tolerance factor Q and the occurrence degree for all lichen species. The index is calculated using Equation 1:

$$I.A.P. = \sum_{i=1}^{n} Q_i \cdot f_i \quad (1)$$

where:

I.A.P. - Air Purity Index,

n - the number of lichen species in the studied area,

Q - the toxic tolerance factor (constant for each lichen species), calculated using Equation 2:

$$Q = \frac{n_1}{n_2} \quad (2)$$

where:

n_1 - the total number of sample plots where the species of interest is found,

n_2 - the total number of sample plots containing all lichen species.

The occurrence degree is determined by combining the percentage cover of the lichen species and its frequency in each sample plot. The f-values are assigned as follows:

f=1: Rare species with minimal coverage,

f=2: Rare species or species with 1–5% coverage,

f=3: Occasional species or species with 5–10% coverage,

f=4: Frequent species or species with 10–20% coverage,

f=5: Very frequent species with coverage exceeding 20%.

In the study, 1,250 deciduous trees of various species were selected. Trees were chosen to ensure similar age, crown shape, and exposure, as well as comparable growth conditions. Most of the selected trees were located along streets and roadsides.

The Air Purity Index (I.A.P.) data were utilized to develop Air Purity Index (I.A.P.) maps using Geographic Information Systems (GIS) with the Inverse Distance Weighting (IDW) interpolation method. This approach allowed for the spatial visualization and analysis of air quality distribution across the studied area, providing a detailed representation of variations in air purity.

Results and Discussion

Air quality monitoring conducted in Jelgava in 2016 revealed notable trends in pollution distribution across the city ‘Figure 2’. Improvements were observed in various areas, including Satiksmes Street, Dobeles/Lielā Street, Lithuania Highway, and RAF residential zones. However, significant air quality deterioration was noted near the wastewater treatment plant, SIA Larelini, Palīdzības Street, and areas outside the center, such as Langervalde Park, Brīvības Boulevard, and Riga Highway.

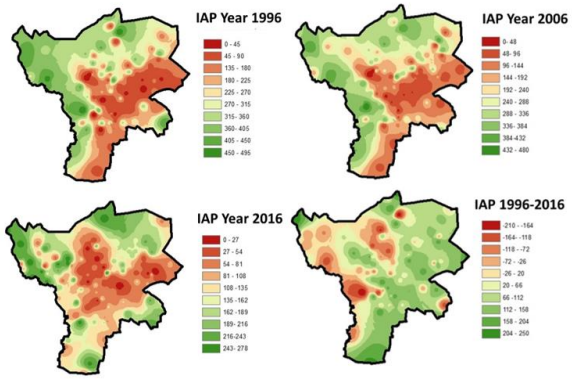
High air pollution zones were found to cover 1.66 km² (2.75%) of the city’s area in 2016, representing a reduction from 1996 (4.06%) but a slight increase compared to 2006 (2.49%). These zones were primarily concentrated in the city center and near Langervalde Park. Moderate pollution zones were reported to span 26.54 km² (44.0%), reflecting a decrease from 2006 (48.51%) but an increase in the city center, where they accounted for 71.15%. Outside the center, a decline in moderate pollution zones was noted, dropping to 36.54% since 2006.

Clean air zones were recorded to cover 32.12 km² (53.25%) of Jelgava in 2016, showing an increase compared to 1996 and 2006. While clean air areas outside the center expanded to 61.54%, a significant decline was observed in the city center, where clean zones accounted for only 23.08%.

These findings highlight shifting pollution patterns, with air quality improving outside urban centers and increasing challenges identified in densely populated central areas.

Figure 2

Air quality monitoring results in Jelgava city by applying the Air Purity Index (I.A.P.)



The air quality monitoring conducted in Jelgava in 2016 revealed significant trends in pollution distribution across the city, with both improvements and ongoing challenges being highlighted. It was observed that certain areas, particularly Satiksmes Street, Dobeles/Lielā Street, Lithuania Highway, and the RAF residential zones, experienced notable improvements in air quality. These findings indicate that targeted interventions and policies may have been effective in reducing pollution levels in these regions. However, the deterioration of air quality near the wastewater treatment plant, SIA Larelini, Palīdzības Street, and areas outside the city center, such as Langervalde Park and Riga Highway, has raised concerns about localized pollution sources, which require further investigation and management.

The spatial analysis of pollution zones in Jelgava revealed that high air pollution zones were found to cover 1.66 km² (2.75%) of the city’s area in 2016, representing a reduction from 4.06% in 1996 but a slight increase from 2.49% in 2006. This fluctuation suggests that while overall air quality has improved, certain areas have remained vulnerable to pollution, particularly in the city center and near Langervalde

Park. The persistence of high pollution zones in these areas has been attributed to increased traffic, industrial emissions, and possibly the effects of urbanization, which often result in higher concentrations of pollutants in densely populated regions (Kleperis et al., 2016).

Moderate pollution zones were reported to span 26.54 km² (44.0%) of Jelgava, reflecting a decrease from 48.51% in 2006. However, an increase in moderate pollution levels within the city center, where they accounted for 71.15%, has been noted, suggesting that unique challenges are being faced in urban core areas. The concentration of moderate pollution in the city center has been linked to traffic congestion, construction activities, and emissions from nearby industrial facilities, which are common contributors to urban air quality issues (Kleperis et al., 2011). Conversely, a decline in moderate pollution zones outside the center, dropping to 36.54% since 2006, was noted, indicating that efforts to improve air quality in suburban and rural areas may be yielding positive results.

Significant clean air zones were recorded, covering 32.12 km² (53.25%) of Jelgava in 2016. This represents an increase compared to previous years, suggesting that measures aimed at reducing pollution have been effective in expanding areas of clean air. Notably, clean air areas outside the center were observed to have expanded to 61.54%, indicating that residents in these regions are benefiting from improved air quality. However, a significant decline in clean air zones within the city center, where they accounted for only 23.08%, was observed, underscoring the urgent need for targeted interventions to address pollution in urban hotspots.

The shifting pollution patterns observed in Jelgava are indicative of broader trends in urban air quality management. Improvements in air quality outside urban centers suggest that emissions from transportation and industry have been successfully reduced through strategic policies. However, challenges faced in the city center highlight the need for comprehensive urban planning that considers the unique characteristics of densely populated areas. Stricter emissions regulations, enhanced public transportation options, and the promotion of green infrastructure are recommended as measures to mitigate pollution.

Moreover, the correlation between air quality and public health has been well-documented. Studies have shown that exposure to air pollutants is linked to various health issues, including respiratory diseases and cardiovascular conditions (Hart et al., 2012; Adami et al., 2021). The persistence of high pollution levels in certain areas of Jelgava is considered to pose significant health risks to residents, particularly vulnerable populations such as children and the elderly. Therefore, ongoing monitoring and assessment of air quality are deemed essential for informing public health initiatives and ensuring the well-being of the community.

Conclusions

1. The long-term spatial analysis of air quality in Jelgava City provides valuable insights into the dynamics of urban pollution and the effectiveness of biomonitoring techniques.
2. A significant reduction in high-pollution zones was observed, decreasing from 4.06% in 1996 to 2.75% in 2016. While this suggests a possible positive effect of general urban development and environmental management, the lack of data on specific interventions limits definitive conclusions. A slight increase from 2.49% in 2006 to 2.75% in 2016 underscores the persistence of localized pollution hotspots.
3. The expansion of clean air zones to 53.25% of the city's total area in 2016, particularly in suburban regions, reflects positive impacts of urban green infrastructure and reduced emissions. This improvement aligns with efforts to decentralize urban activities and enhance environmental quality outside the urban core.
4. Despite overall progress, the city center experienced a decline in clean air zones, covering only 23.08% of its area in 2016. This trend emphasizes the need for targeted pollution mitigation strategies in densely populated areas, focusing on traffic management, industrial emission controls, and urban planning innovations.
5. The use of lichens as bioindicators has proven to be an effective and cost-efficient method for assessing air quality. The Air Purity Index (I.A.P.) provided a detailed representation of pollution distribution, enabling the identification of trends and problem areas that require attention.
6. To address ongoing challenges, stricter emissions regulations, the promotion of green infrastructure, and enhanced public transportation systems are recommended. Continued investment in biomonitoring programs and GIS-based spatial analyses will support the tracking of air quality trends and the formulation of evidence-based policies.
7. Persistent high-pollution zones in certain areas pose significant risks to public health, particularly for vulnerable populations. Integrating air quality monitoring with public health initiatives is essential for mitigating the adverse effects of urban pollution.

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RECOMMENDER SYSTEMS IN TOURISM: A COMPREHENSIVE SCIENTIFIC REVIEW

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Abstract
The rapid development within the tourism sector, coupled with the widespread accessibility of digital information, has necessitated the development and use of advanced tools to aid in navigating and managing the vast amounts of data within the industry. One of the main tools that have emerged as a solution to this issue is recommender systems, which can offer customized suggestions, enhancing the user experience by matching personal preferences with services, accommodations, activities, and destinations. This paper examines the integration of recommender systems into the tourism industry to support data analysis and enhance user experience through personalized recommendations. To achieve that, the paper presents a study that utilizes the mixed method approach to research with both quantitative and qualitative research methods to analyze existing literature on the application of recommender systems within tourism, highlighting their potential to transform user experience. In this, various algorithms related to recommender systems are reviewed. In addition, the paper also analyzes the challenges associated with tourism, like the need for real-time updates, seasonal variations, and the dynamic nature of tourist preferences, among others. The paper presents conclusions that include recommendations on the most suitable algorithms and approaches to augment the accuracy, robustness, and user-friendliness of recommender systems in tourism as well as a discussion of future directions.
Keywords: recommender systems, tourism, information filtering, collaborative filtering.

Introduction

Recommender systems (or recommendation systems) represent a subclass of machine learning (ML), specifically within the domain of information filtering which utilizes data to predict user preferences, narrow choices, and identify desired options from a large set of alternatives. They work by employing complex algorithms to deliver personalized recommendations based on user's preferences, past behavior, and historical data (Bulchand-Gidumal, 2022). They are especially helpful in scenarios where users have to decide on something from a potentially overwhelming list of things (Fararni et al., 2021). Today, recommender systems are used in multiple domains, with key examples including playlist generators for music and video services, service/product recommenders for online service providers and e-commerce shops, open web content recommenders, and content recommenders for social media networks. The systems can operate using single inputs, such as music, or multiple across and within platforms like search queries, books, and news, among others. Recommender systems can also be used for particular topics like online dating, restaurants, and financial services to provide tailored suggestions to users (Chaudhari & Thakkar, 2019).

In recent years, other sectors such as tourism have also started employing the capabilities of these systems (Fararni et al., 2021). In fact, recommender systems have grown to become a cornerstone in modern travel planning. This has resulted in a complete revolution of how users explore destinations, accommodations, and activities within different travel companies (Fararni et al., 2021). Within this sector, recommender systems have streamlined decision-making processes by providing tailored suggestions and options (Felfernig et al., 2018). For instance, the application of recommender systems in areas of tourism, such as customer service, has significantly simplified the planning phase for travelers. These systems analyze user interactions together with their preferences and historical patterns and use this data to offer personalized travel itineraries and suggestions with the aim of enhancing user experiences (Bulchand-Gidumal, 2022). However, these systems are not without limitations. For instance, concerns persist regarding the accuracy of recommendations as well as potential biases in interpreting user preferences. Likewise, there are also other concerns regarding the critical aspect of safeguarding user data and privacy (Chang et al., 2019).

As such, it is essential to understand the key concepts and aspects related to recommender systems before embarking on any attempt to develop or implement such a system. This research aims to explore the existing literature on recommender systems within the tourism domain to provide a comprehensive understanding of such concepts through an in-depth analysis of existing publications and a review of current state of art recommender systems. The focus lies in comprehending their underlying mechanisms, strengths, and limitations to identify potential areas of improvement. Therefore, the research ultimately seeks to unveil opportunities for enhancement and innovation by evaluating the successes and challenges faced by current systems.

Literature review

Systems use information registered on their database or from user profiles to determine travellers' preferences (Bulchand-Gidumal, 2022). Such an approach makes predictions based on the travel patterns and the visitors' history (Felfernig et al., 2018; Kontogianni & Alepis, 2020). However, Deldjoo et al. (2020) state that the dynamic nature of travel preferences would require more robust systems that would be able to predict based on real-time information obtained from the user. Having real-time predictions ensures that the system can advise travellers based on the current information as a method

of complementing the information registered in the past. This enhances the prediction accuracy and ultimately improves the ability to correctly provide customers with better travel choices (Chang et al., 2019). Also, there is a need to capture and analyse different forms of information such as graphics and videos. Graphics and video content can contain more detailed information compared to text content. Systems that can process this information are likely to have more data for reference when making predictions (Kontogianni & Alepis, 2020), thus higher accuracy may be achieved.

One of the main challenges with the recommender system is the availability of sufficient data (Niu et al., 2022). Prediction models rely heavily on availability of data to make more accurate and precise decisions. Availability of huge amounts of data ensures that there is enough information to make a prediction (Berkani, 2018). It is therefore important to have a recommender system that will capture and analyse information in a more efficient way to improve the accuracy of predictions (Logesh et al., 2018). Correcting different formats of information and including this data in predictions will increase the performance of the recommender system predictions (Massimo & Ricci, 2022). A review of the literature, reveals that recommender systems have become integral to modern travel planning, providing users with personalized recommendations based on their preferences, behaviours, and historical data (Beheshti et al., 2020). These systems have significantly impacted the tourism sector by streamlining decision-making processes and simplifying the planning phase for travellers (Niu et al., 2022). The application of complex algorithms allows these systems to analyse user interactions, providing tailored suggestions for accommodations, activities, and destinations, ultimately enhancing user experiences (Gillingham, 2019).

However, despite their widespread use and positive impacts, recommender systems in the tourism domain are not without challenges (Doborjeh et al., 2021). Accuracy of recommendations and potential biases in interpreting user preferences remain concerning, along with the critical issue of safeguarding user data and privacy (Chang et al., 2019). This research explores the existing literature on recommender systems in tourism, delving into their mechanisms, strengths, and limitations to identify areas for improvement and innovation.

The majority of existing travel recommendation systems rely on data from their databases and user profiles to predict travellers' preferences based on historical patterns and travel history (Bulchand-Gidumal, 2022). However, the dynamic nature of travel preferences necessitates more robust systems capable of real-time predictions, supplementing past information with current data for enhanced accuracy (Pantano et al., 2019). Real-time predictions ensure that users receive advice based on the most recent information, contributing to more accurate and up-to-date recommendations (Hamid et al., 2021).

In addition to real-time considerations, the need to capture and analyse diverse forms of information, such as graphics and videos, poses another challenge and opportunity for improvement in recommender systems (Pantano et al., 2019; Massimo & Ricci, 2022). While processing power requirements may be higher for analysing graphics and video content (Kontogianni & Alepis, 2020; Li et al., 2021), the potential for more detailed information could lead to higher prediction accuracy. As suggested by Roy & Dutta (2022), systems capable of effectively processing and integrating this type of information can enhance their reference data, ultimately improving prediction accuracy.

A critical challenge faced by recommender systems is the availability of sufficient data (Bulchand-Gidumal, 2022). Prediction models heavily rely on large datasets to make accurate decisions (Missaoui et al., 2019). The availability of extensive data ensures that recommender systems have enough information to generate precise predictions (Sánchez, 2019). It is imperative to develop recommender systems that efficiently capture and analyse information, correcting for different formats, and incorporating diverse data types to boost prediction accuracy (Renjith et al., 2020).

Following an in-depth review of the literature, several key trends and findings have emerged. Firstly, the importance of real-time information for accurate predictions has been highlighted as a key factor in enhancing recommender systems (Missaoui et al., 2019). Secondly, the capability to process and analyse diverse forms of information, such as graphics and videos, is seen as a potential avenue for improving recommendation accuracy (Doborjeh et al., 2021). Finally, addressing the challenge of sufficient data availability is identified as crucial for the performance of recommender systems.

Thus, the existing literature on recommender systems in the tourism domain emphasizes their significant impact on travel planning while acknowledging challenges related to accuracy, biases, and data privacy. This research contributes to the field by exploring opportunities for improvement and innovation, particularly focusing on real-time predictions, diverse information types, and efficient data capture and analysis. The identified trends and findings lay the groundwork for the development of robust and user-friendly recommender systems in the tourism industry.

The efficiency of recommender systems relies on the availability of information from the customer and the ability of the existing system to process the data and derive insights from it (Walek & Fojtik, 2020). Also, the accuracy of the recommender system when making predictions requires accurate and up-to-date information (Kontogianni & Alepis, 2020). While many of the existing systems used records stored in their databases over time, using real-time information can be more effective (Silveira et al., 2017). Focusing on the trends and research that has been carried out on recommender systems, the study presented in this paper shows the attempts being made to enhance their performance through collected information.

In addition to the challenges aforementioned, another significant aspect influencing the effectiveness of

recommender systems is user engagement and feedback mechanisms (Li et al., 2021). Engaging users in the recommendation process enhances the overall user experience and provides valuable data to be used in the improvement of recommendation algorithms (Renjith et al., 2020), which can be done by implementing interactive features such as rating systems, reviews, and personalized feedback loops (Wang, 2023). This potentially fosters a sense of involvement and ownership among users, leading to higher satisfaction levels and increased trust in the recommendations provided (Silveira et al., 2017).

Integration of social media data and collaborative filtering techniques additionally presents an opportunity for enhancing recommendation accuracy (Pradhan & Pal, 2020). By analysing users' social connections, shared interests, and past behaviours within social networks, systems can efficiently generate more personalized recommendations (Missaoui et al., 2019). Insights gained from such social media data ensure that users are given contextually relevant recommendations that are relevant to their planning and decision-making process (Pantano et al., 2019). Leveraging the data insights from social networks enriches the recommendation process and helps to mitigate issues of data sparsity and cold starts (Gao et al., 2022).

Additionally, adoption of hybrid recommendation approaches that combine content-based, collaborative, and knowledge-based filtering methods is theorized to overcome the limitations of individual techniques (Suryawanshi & Narnaware, 2020). By leveraging the strengths of different recommendation paradigms, hybrid systems promise more comprehensive and accurate recommendations that cater to the diverse user preferences in the tourism and travel field (Zhang et al., 2019).

The objective of this paper is to propose effective methods for collecting quality data required by prediction models by analyzing the current trends and efforts made through research to enhance the performance of the current recommender systems. Also, the study includes a survey that collects and analyzes different features of the existing systems that enable them to collect relevant information for efficient recommendations. Ultimately, the report will bring together facts about current research and existing systems in the travel industry. It will also include recommendations of the best approaches that can be applied and tested for enhancing the accuracy and precision of a recommender system.

Materials and Methods

A mixed-method approach was adopted in this study to enable a more comprehensive understanding of diverse perspectives on the topic and to support a thorough analysis and discussion of the results. The method integrates a systematic review and a qualitative survey to comprehensively investigate the landscape of recommender systems in the tourism sector.

Systematic Review

The significance of this method to the study is that it helps to extensively and intensively examine existing literature on recommender systems within the tourism domain. As such, the study heavily follows the guidelines provided by Gridach (2020) and draws insights from the application of this method by Zou et al. (2019). Relevant databases such as ACM Digital Library, IEEE Xplore, Scopus, and Google Scholar were searched following the established protocols for systematic reviews. A well-developed search strategy is necessary for effective use of this method. The strategy includes a well-framed search query containing keywords such as 'recommender systems', 'tourism', 'travel recommendations', and related terms to identify peer-reviewed articles, conference papers, and relevant publications.

On the other hand, the inclusion/exclusion criteria were defined to ensure the selection of studies that meet specific quality standards and relevance to the research objectives. Data extraction includes identifying key themes, mechanisms, strengths, limitations, and emerging trends related to recommender systems in the tourism industry.

Findings and Discussion

The required resources for the study were obtained by following the guidelines outlined in PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Kontogianni & Alepis, 2020). At the start, a total of 144 publications were identified as being pertinent to the study based on a selection of keywords detailed in Table 1 below. These articles were further reviewed by applying various filtering criteria, including the presence of an abstract, the relevance of the title and discussion to the study topic, clarity of results, the inclusion of a conclusion and references, publication information, and compliance with ethical standards. These measures were taken to ensure the articles' relevance and quality for the study. Figure 1 below depicts the process followed in selecting the article to be used in the study:

Table 1 below shows the inclusion and exclusion criteria included in PRISMA, showing the guidelines used to assess the articles for exclusion or inclusion.

Table 2 below summarizes the main contributions of the scientific publications identified for the study. The publications are grouped in 6 categories based on their discussion in relation to the impact and accuracy of recommender systems.

Analysis

Recommender systems are valuable tools for the tourism sector due to their capabilities of enhancing the user experience by suggesting destinations, activities, accommodations, and travel packages tailored to individual preferences.

This repository of historical data acts as the raw materials for refining recommendations and optimizing system performance over time.

Figure 1
A PRISMA diagram depicting the so selection process of articles for the study

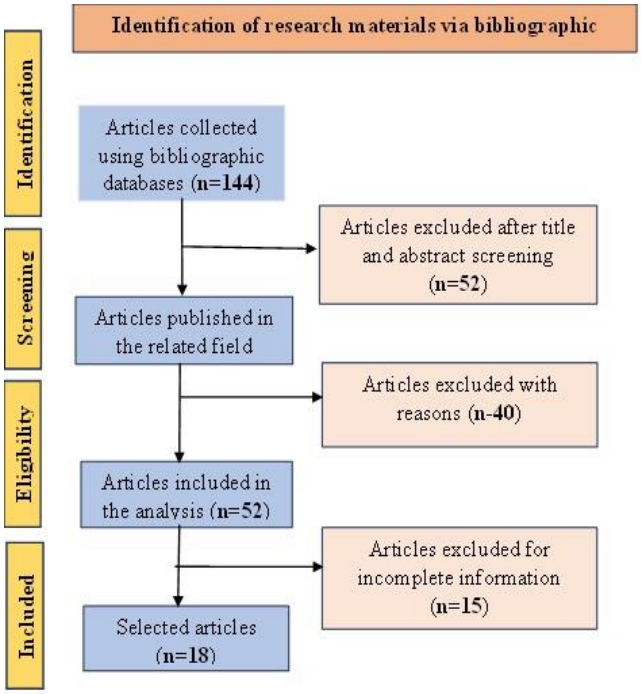


Table 1
Exclusion and inclusion for selection of articles for the research

Criteria	***Inclusion Criteria***	***Exclusion criteria***
Kinds of study	Peer-reviewed original publications	Editorials, reports, communication letters, white papers, and theses
Language	Publications written in English	Non-English and duplicate publications
Year of publication	Scientific articles and papers published between 2020 and 2024 (for the analysis of results)	Not relevant to the time range specified
Source	Papers and articles published only in conferences and academic journals	Publications that are missing key relevant information and review articles
Intervention	Recommender systems in tourism, information filtering	Basic and traditional methods
Region	Not limited to specific regions	–
Settings	Recommender systems	Not germane to recommender systems

The model Figure 2 depicts a recommendation system for tours and travel business, comprising four major components: the client, the application, a database server, and a recommendation computing system. It includes the following processes:
1. Acquisition of user data: The system initiates by gathering useful data from the user such as their preferences, past activities, location, and demographics.
2. Initial recommendation: The system then leverages the acquired user data to offer recommendations even before engaging the recommendation system. This initial step swiftly provides the users with custom suggestions, enhancing their overall experience from the outset.
3. Processing and storage of data: The application renders these recommendations to the users, and while they browse and use it, more data is obtained and stored in a robust database alongside the initial user data. This ensures accessibility for future reference and analysis.

Table 2
Systematic research findings

Category	***Authors***	***Main Contribution***
Pivotal Role in Travel Planning	Huang et al. (2022)	Acknowledged the transformative impact of recommender systems, streamlining decision-making processes and enhancing the planning phase for travellers.
	Kontogianni & Alepis (2020)	Highlighted the significant impact of recommender systems in the tourism sector, simplifying decision-making processes through tailored suggestions.
Accuracy and Biases	Al Fararniet al. (2021)	Raised concerns regarding the accuracy of recommendations and potential biases in interpreting user preferences within recommender systems.
Reliance on Historical Data	Zhang Mu et al. (2010)	Identified concerns related to safeguarding user data and privacy, addressing critical issues in the ethical implementation of recommender systems.
Reliance on Historical Data	Yoon & Choi (2023)	Explored existing travel recommendation systems' reliance on historical data and user profiles, emphasizing the dynamic nature of travel preferences.
Importance of Real-Time Information	Suryawanshi & Narnaware (2020)	Recognized the crucial role of real-time information in enhancing recommender systems, ensuring accurate predictions based on current data and historical patterns.
Diverse Information Types	Berkani (2021)	Explored the challenge and opportunity of diverse information types, such as graphics and videos, in improving prediction accuracy within recommender systems.
Enhancing Prediction Accuracy	Wang (2023)	Emphasized the potential for systems capable of processing graphics and video content to achieve higher prediction accuracy and reference data.
Data Availability Challenge	Massimo & Ricci (2022)	Highlighted the critical challenge of data availability, emphasizing the importance of extensive and efficient data capture and analysis for accurate predictions.

4. Preprocessing and data frame preparation: Prior to analysis, historical user data undergoes preprocessing to cleanse, transform, and data is organize it into a structured format conducive to identifying intricate patterns and associations within the data.

5. Algorithm selection and integration (R): The recommendation system selects and integrates suitable recommendation algorithms, such as **Apriori or FP Growth.** These sophisticated algorithms play a pivotal role in identifying.

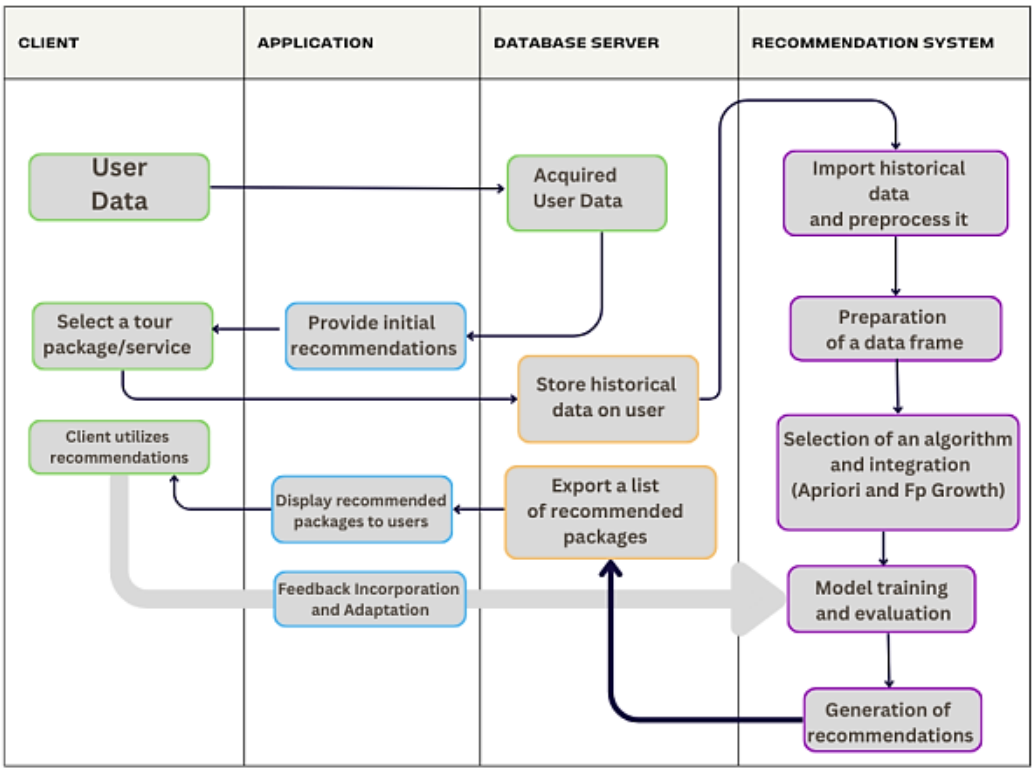
- Apriori Algorithm: This algorithm operates by identifying the frequency of item sets in transactional databases. Using prior data of the frequency of item sets, the algorithm discovers associations between different items. In the context of tour and travel, recommendations, Apriori can aid in the identification of common combinations of destinations, activities, and preferences, thereby facilitating the generation of personalized recommendations based on users past interactions.
- FP Growth Algorithm: FP Growth algorithm, on the other hand, utilizes a frequent pattern tree structure to mine frequent item sets directly without explicitly generating candidate sets. It can efficiently handle large datasets and is particularly effective for dense databases. In this context, FP Growth can identify frequent patterns of user preferences and activities, thus assisting in the generation of personalized recommendations tailored to individual preferences.

6. Model training and evaluation: The selected algorithms undergo a series of training using pre-processed data, followed by a thorough evaluation to guarantee efficacy in generating accurate recommendations. This iterative process ensures that the recommendation models are continuously refined and optimized.

7. Generation and export of recommendations: The recommendation system then generates personalized recommendations using the trained models. These are tailored to individual user preferences and past interactions. The recommendations are then exported for further utilization, ensuring seamless integration into the user experience.

8. Feedback and improvement: For the system to suffice, it must actively solicit feedback from users regarding the recommendations provided. The feedback is then analysed in an iterative process to refine the recommendation algorithms and adjust parameters, ultimately enhancing the quality and relevance of recommendations over time.

Figure 2
Recommender system flowchart



Source: taken from Hang Lei et al., 2018 and adopted by author.

Results and Discussion

The working hypothesis of the study posits that recommender systems play a vital role in the tourism sector. The results of the analysis consistently support the hypothesis by confirming the significance of recommender systems in the tourism sector. Manifold literature reviewed in this study confirms that these systems considerably boost user experience, which leads to higher engagement and conversion rates. For instance, research by Massimo & Ricci (2022), Berkani (2021) and Yoon & Choi (2023) revealed that tailored recommendations resulted in more booking conversions by up to 15 percent, accentuating the significance of recommender systems in this sector. Some of the key observed benefits of recommender systems in tourism include:

1. Pivotal Role in Travel Planning

Recommender systems have been conclusively determined as performing a crucial function in travel planning and changing the decision-making process through personalized recommendations based on user preferences and historical data (Missaoui et al., 2019). This result highlights the change that these systems have on user experience among tourism companies.

2. Accuracy Concerns and Potential Biases

The persistence of reservations for recommendation accuracy and prejudices in interpreting user preferences have been identified as significant challenges faced by recommender systems associated with the tourism sector (Roy & Dutta, 2022). Addressing these concerns is of utmost importance, as it ensures the dependability and credibility of recommendations, thereby enhancing user satisfaction.

3. Historical Data and User Profiles

One obvious result is that existing travel recommendation systems are inescapably dependent on historical data and user profiles to predict the preferences of travellers based on travel history and patterns (Gillingham, 2019). This underscores the dynamic shift of travel preferences and stresses for further development of more flexible systems that can afford predictions in real-time.

4. Importance of Real-Time Information

Real-time data has been unambiguously deemed to be

essential for the improvement of recommender systems, providing timely information and historical data (Suryawanshi & Narnaware, 2020). This result emphasizes the need to develop adaptive recommender systems that respond in real time based on users' evolving preferences, which improves suggestions for relevance and timeliness.

5. *Diverse Information Types: a Challenge and an Opportunity*

Notably, diverse forms of information including images and videos in travel advice have been identified as a very practical finding that has to be addressed (Berkani, 2021; Wang, 2023). While taking note of the increased processing power needs, this assumes a possibility for providing more detailed information that can represent an opportunity to upgrade recommender systems.

6. *Critical Challenge of Data Availability*

The fundamental challenge of data scarcity has been identified, as many predictive models rely heavily on large datasets to generate accurate results (Massimo & Ricci, 2022). This highlights the urgent necessity to resolve data availability problems by creating appropriate development of effective strategies for data capture and analysis in order to provide successful functionality recommender systems.

Besides these specific results, the qualitative insights resulting from data gathered through a mixed-method approach add useful information about users' experiences and preferences that make an ideal complement to trends found in the systematic review. These aggregated findings serve as a solid basis for future research and development initiatives, helping design improved advisors that are more flexible, and reflective of the evolving nature of travel planning.

Conclusions

1. This study offers a detailed examination of recommender systems in the tourism sector, presenting key observations that illustrate the current state and indicate potential future developments. The study provides concrete evidence of the significance of recommender systems through a qualitative analysis that provides a strong basis for recommender systems' ground-breaking ability in the tourism sector. First of all, it cannot be overstated that these systems play a decisive role in travel planning; they completely revolutionize the principles and procedures for decision-making by offering adaptive suggestions based on user preferences and historical data. While consistent reservations as well as accuracy and possible biases underscore the need for continuous work on refining these systems, it is vital that they are able to present reliable suggestions, improving user satisfaction and trust.

2. While this approach is effective, it highlights the need for more adaptive systems to manage real-time predictions. Given the dynamic nature of travel preferences, the industry shall strive to provide recommendations that reflect evolving user behaviour, with an emphasis on integrating real-time information into system functionalities. In addition, the incorporation of diverse information types, such as charts and video highlights that enhance the processing capacities of recommender systems, may lead to improved prediction accuracy and the provision of more detailed recommendations.

3. A major priority concerning the future of recommender systems is to address the issues related to data accessibility i.e. Data privacy and regulations (GDPR, CCEA), Siloed data across platform, Limited access data to third party and Data format & quality issue. In the future, recommender systems in tourism will likely face an impasse between revolution and further advancement. In this regard, future research should focus on enhancing accuracy, eliminating biases and data imperfections, and developing more adaptable user-friendly, and highly reliable recommender systems.

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CYBERSECURITY POLICY ANALYSIS AND RESEARCH COOPERATION IN THE BALTIC STATES

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Abstract
In the digital era, cybersecurity has emerged as a cornerstone of national security and economic resilience, especially for the geopolitically sensitive Baltic States - Latvia, Lithuania, and Estonia. This study examines the evolution of cybersecurity policy and research collaboration in the region, highlighting significant disparities in research output, institutional capacity, and policy development. Using a mixed-methods approach that combines bibliometric analysis from Scopus (2012–2024) and qualitative review of national and EU-level cybersecurity strategies, the research evaluates the alignment between policy frameworks and research efforts. The findings reveal Estonia as the regional leader in cybersecurity research, accounting for 54% of publications, driven by early investments and the presence of NATO's Cooperative Cyber Defence Centre of Excellence. Conversely, Latvia and Lithuania show slower progress, hindered by delayed strategic planning and overreliance on EU funding. In addition, statistical analysis in ANOVA was applied to assess the relationship between funding and the increase in publications. Furthermore, while research collaboration across the region exists, it remains fragmented and underutilised. The paper proposes cooperative models between key institutions and emphasises the need for a unified regional cybersecurity research strategy. Multidisciplinary integration and increased national investment are critical to advancing cyber resilience. Strengthening intra-regional collaboration and diversifying funding mechanisms is imperative to enhancing the Baltic States' cybersecurity posture and contributing to the EU's collective digital defence.
Keywords: cybersecurity policy, cyber threat intelligence, cyber resilience, research collaboration.

Introduction

Cybersecurity has become the foundation of national security and economic stability in the digital age. In recent years, the Baltic States – Latvia, Lithuania and Estonia – have faced increasing cyber threats targeting critical infrastructure, government institutions and the private sector.

Some of the most intense cyberattacks targeting Latvia occurred on November 14 and November 22, 2022. During these incidents, the hacktivist group Killnet used Telegram to disseminate calls for coordinated distributed denial-of-service (DDoS) attacks against various institutions across the Baltic region. The targets included entities within the national security and defence sectors (CERT-LV, 2023). In addition to geopolitical challenges, the regulatory environment of the European Union (EU) is becoming increasingly rigid. The NIS2 Directive, which entered into force in 2023, requires countries to strengthen cybersecurity requirements by introducing stricter frameworks for companies and public authorities.

At the same time, cooperation between the Baltic States in research and cybersecurity has developed significantly, especially in the context of integration and regional initiatives of the European Union. The EU Strategy for the Baltic Sea Region, established in 2009, has been an important tool for fostering cooperation in various policy areas, including cybersecurity and research (Szejgiec-Kolenda & Duma, 2020). This strategy has significantly strengthened the cross-border cooperation of the Baltic States, which is necessary to address cybersecurity challenges more effectively.

The importance of cybersecurity policy is also shaped by increasing social, economic, and technological pressures from governments. Countries are increasingly trying to develop their cybersecurity capacity to remain competitive internationally and protect critical infrastructure (Deibert & Crete-Nishihata, 2011). This trend proves that cybersecurity policy is no longer just a technical framework – it is a key factor in the strategic development of countries.

These threats, regulatory requirements and regional cooperation initiatives show that cybersecurity policy is no longer just a technical issue but a critical political and economic priority.

The Baltic States have actively developed their cybersecurity strategies. However, their policy coordination and cooperation in research are still fragmented. The main problems hindering an effective regional cybersecurity policy are insufficient regional cooperation – although all three Baltic States are EU and NATO member states, their cybersecurity research and policy development is mainly carried out separately rather than coordinated and the allocation of funding and resources – research and innovation in cybersecurity mainly depend on support from EU funds, which may not be stable enough in the long term.

This study aims to analyse the dynamics and structure of the results of cybersecurity research in the Baltic States in the framework of cybersecurity policy development. The analysis of the international research partnership in Latvia, Lithuania, and Estonia can provide insight into the research potential of the Baltic States in the field of cybersecurity and the potential for building mutual assistance mechanisms.

The geopolitical situation, digitalisation, changes in the international security environment, military aggression and cyberattacks, threats to national security in recent years have facilitated both research and the establishment of new laws, regulations and

policies to develop priority directions and an action plan for the prevention of threats to national security. In the European Union, the Baltic States, which include Latvia, Lithuania and Estonia, play a special role in cybersecurity. These countries, which are at the crossroads of geopolitical tensions, have become focal points for cybersecurity discussions due to their strategic location, technological progress, and historical experience with cyber threats. The collaboration among the Baltic States in research and cybersecurity has evolved significantly, particularly in the context of European Union (EU) integration and regional initiatives. The EU Strategy for the Baltic Sea Region, established in 2009, has played a pivotal role in fostering cooperation among these nations. This strategy has addressed various policy domains, enhancing transborder collaboration among the Baltic States. Consequently, understanding Latvia, Lithuania, and Estonia's cybersecurity policies is extremely important to understand the wider European cybersecurity environment and identify areas for collaborative research initiatives and improvement of decision-making systems.

There is insufficient strategic and sustainable coordination and cooperation between industries, cybersecurity research communities and governments. The Union suffers from insufficient investment and limited access to know-how, skills and equipment in the field of cybersecurity, and only a few of the Union's cybersecurity research and innovation results are translated into tradable solutions or scaled up across the economy. Cybersecurity has become a critical area of security challenges in today's interconnected world, and the increasing frequency and complexity of cyber threats underline its importance. As countries seek to protect their digital infrastructure and data assets, policymakers are tasked with formulating robust cybersecurity policies to mitigate risks and ensure cyberattack resilience. One of the regions at the forefront of these efforts is the European Union (EU), where Member States have recognised the need for collective action to address cybersecurity challenges effectively. The new Directive (EU) 2022/2555 of the European Parliament and of the Council of 14 December 2022, also known as the NIS2 Directive (Directive (EU) 2022/2555), has entered into force, providing for the implementation of measures to achieve the same high level of cybersecurity in all EU Member States (European Union, 2022). In all three Baltic States, significant steps are being taken to implement the NIS2 Directive, focusing on legislative changes, compliance of companies and international cooperation.

Article 7 requires Member States to adopt, as part of their national cybersecurity strategies, policies to promote and develop R&D initiatives and to support academic and research institutions in the development of cybersecurity tools. The list of critical sectors also includes research organisations. In Latvia, cabinet regulation No. 158, adopted on 28 March 2023, 'On the Cybersecurity Strategy of Latvia for 2023-2026' (Latvian Cabinet of Ministers, 2023), also stipulates that the courses of action are public awareness, education and research and action direction for 'International cooperation and justice in cyberspace'. To understand the following policy steps and opportunities for cooperation, it is necessary to identify the current state of research and collaboration in the field of co-security.

The cybersecurity policy of the Baltic States reflects a multifaceted approach, which includes the legal framework, institutional mechanisms and international partnerships aimed at improving cyber resilience and protecting national interests. Given their relatively small size and common historical heritage, these countries often work closely within the EU framework to address common cybersecurity challenges while adapting strategies to their specific context.

The main research objects of our research are the cybersecurity policy and research cooperation of Latvia, Lithuania and Estonia, the legal framework, the chronology of cybersecurity laws adopted by each country and their analysis, including rules related to data protection, incident response and critical infrastructure protection. Understanding the regulatory framework is essential to assess the scope of cybersecurity governance and identify areas where harmonisation or improvement is needed.

In cybersecurity, the Baltic States have recognised the importance of collective action to enhance their cybersecurity posture. Research indicates that while there is a tendency for collaboration outside the Nordic-Baltic region, the need for a unified approach within the region is increasingly acknowledged (Sandnes, 2021).

By delving into these research objects, insights can be gained for research cooperation in the Baltic States; this study seeks to promote knowledge sharing, capacity building and innovation in cybersecurity management, thus improving the collective resilience of the European Union and its Member States against cyber threats.

The novelty of the research is that it is an interdisciplinary approach that analyses and integrates security research trends and technological development with potential research cooperation networks of the Baltic States and appropriate policies in the security field. This can help identify and develop new technologies and approaches to address security challenges.

The central aspect of the novelty of the study is the mapping of cybersecurity cooperation models of the Baltic States, which has not yet been thoroughly analysed in the research literature. Also, the integration of technological development and research trends with security policy creates a holistic view of regional cybersecurity and the development of practical recommendations for cybersecurity research networks in the Baltics, which could contribute to developing and implementing new security solutions in the policy.

Materials and Methods

This study used a tiered methodology that combined bibliometric analysis and qualitative policy document analysis. The integration of these methods made it possible to identify the main challenges and development trends and develop recommendations for more effective regional cooperation in cybersecurity. While several studies explore European cybersecurity trends, few focus on the Baltic states as a distinct geopolitical and scientific unit. The integration of regional strategy documents, national research outputs, and funding structures across Latvia, Lithuania, and Estonia has not been comprehensively addressed in existing literature. The combination of methods provided a full-fledged analysis, combining empirical data on research development and the evaluation of regulatory policy. The design of the study was based on bibliometric analysis to identify research activity in the field of cybersecurity in the Baltics, qualitative content analysis of documents, analysis of policy documents and strategies to identify Baltic cybersecurity research cooperation networks.

To study the dynamics of cybersecurity research, the Scopus database (Elsevier, n.d.) was used, where the analysis of publications was carried out, searching for information by the keywords formula, 'cybersecurity', or 'cyber security', or 'information security', 'Baltic States', or 'Latvia', or 'Lithuania', or 'Estonia'. As a parameter, the period from 2012 to 2024 was used. The data selection was carried out using the Boolean search method, which allows you to accurately formulate search terms and expand or narrow the results, depending on the keywords chosen.

Analysed documents: Latvian Cybersecurity Strategy 2023-2026 (Latvian Cabinet of Ministers, 2023), Lithuanian National Cyber Security Strategy 2022 (Ministry of National Defence of Lithuania, 2022), Estonia's National Cybersecurity and Cyberdefense Posture (Center for Security Studies, 2020), EU NIS2 Directive Implementation Guidelines (Directive (EU) 2022/2555) (European Union, 2022). All cybersecurity policy documents analysed in this study were available in English as official translations or published versions provided by national ministries or cybersecurity agencies. A manual thematic analysis was also carried out to identify key cybersecurity policy priorities.

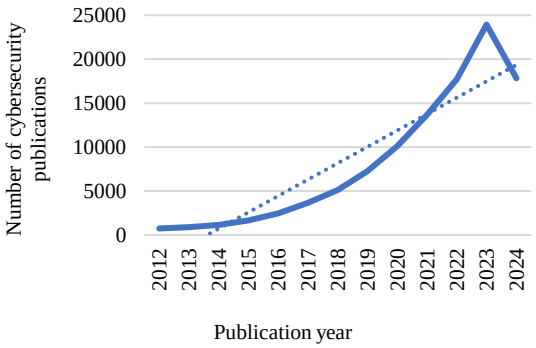
The statistical ANOVA analysis used the dependent variable - the number of cybersecurity research publications. This represents the total number of cybersecurity-related research papers published between 2012 and 2024 in Estonia, Latvia, and Lithuania. The data were obtained from the Scopus database (Elsevier, n.d.) by filtering for publications affiliated with institutions in these three countries. The Independent variable (categorical) is the country (Estonia, Latvia, Lithuania). The three Baltic States serve as categorical factors to assess whether there is a statistically significant difference in the number of publications among them. The primary objective of ANOVA and correlation analyses was to determine whether differences in research output among the Baltic States were statistically significant and whether those differences could be explained by variations in funding levels.

Results and Discussion

Concerning cybersecurity research, which can be found in the Scopus database (Elsevier, n.d.) under the keyword 'cybersecurity' in the period 2012-2024, the total number of publications found is 106256 documents; the graph of the trend of growth in publications is shown in Figure 1, which confirms that cybersecurity is a particularly relevant topic of security research around the world. However, it is new, dated to the first documents in 2000, and has a notable increase with each passing year, starting in 2016. The apparent drop in 2024 is likely due to incomplete indexing in the Scopus database at the time of data extraction (March 2025). Publications from late 2024 may not have been fully processed or included yet.

Figure 1

Growth in cybersecurity research publications (2012-2024)



Source: Scopus.

Cybersecurity research in the Baltic States has developed rapidly, especially after 2016, when European Union (EU) cybersecurity frameworks and funding programmes were introduced. Bibliometric data from Scopus (Elsevier, n.d.) show that between 2012 and 2024, Baltic scientists published 756 scientific articles in cybersecurity. Latvian scientists have published 128 (17%) documents, Lithuanian scientists 220 (29%) documents, and Estonian scientists 408 (54%) documents, becoming the leaders of the Baltic States in the field of cybersecurity research publications. This could be due to the historic trigger point on 27 April 2007, when Estonia experienced a series of politically motivated cyberattacks that lasted for 22 days. (Estonia's National Cybersecurity and Cyberdefense Posture, 2020) Moreover, the presence of NATO's Cooperative Cyber Defence Centre of Excellence (CCDCOE) in Tallinn and the government's early investment in cybersecurity research following the 2007 cyberattacks. The dominance of Estonia in publication

output is not merely quantitative but reflects deeper institutional readiness and strategic alignment. Estonia's early policy adoption and embedded cyber defense infrastructure (e.g., CCDCOE) correlate strongly with publication volume and collaboration intensity.

This fact also contributed to the creation of Estonia's first cybersecurity strategy in 2008, which is regularly being improved. In 2008, Estonia's cybersecurity strategy aimed to intensify research and development in cybersecurity and promote international cooperation in research. The example of Estonia shows that research in this area existed before the problem; the problem gave rise to policy, and research followed it with a 15 per cent increase in research articles after 2007. Latvia developed its first Cybersecurity Strategy 6 years later, in 2014, but Lithuania's first cybersecurity strategy was developed and approved in 2011. It must be concluded that in the case of Lithuania and Latvia, scientific research in cybersecurity was much more proactive regarding time than policymaking.

By analysing the data using statistical methods, the ANOVA test ($p = 0.0137$, $F = 4.84$) confirms statistically significant differences in the number of publications between Estonia, Lithuania, and Latvia. Tukey's post-hoc analysis of the HSD shows that Estonia is statistically significantly ahead of Latvia and Lithuania, which indicates a stable and long-term growth in scientific activity. This difference is due to the presence of the NATO CCDCOE Centre in Tallinn (CCDCOE, n.d.), the early implementation of the cybersecurity strategy (2008) and the high rating of the Global Cybersecurity Index (GCI) (88.5).

Lithuania and Latvia, on the other hand, are lagging significantly behind, as the first cybersecurity strategies were adopted later (Latvia – 2014, Lithuania – 2011), and the national funding of these countries for cybersecurity research is still limited. The Tukey test did not identify significant differences between Lithuania and Latvia, which shows that the dynamics of cybersecurity research in both countries are similar. The results of ANOVA and post-hoc analysis confirm significant differences in cybersecurity research activity in the Baltic States, and Estonia is the regional leader in terms of the number of publications and the level of research infrastructure and international cooperation.

Analysing the number of scientific publications in cybersecurity among the universities of the Baltic States, it can be concluded that Estonian institutions dominate this area. Out of a total of 1234 scientific documents, Tallinn University of Technology (TalTech) and Tartu University account for the largest share of publications, while in Lithuania, the most significant contributions are provided by Kaunas University of Technology and Vilnius Gediminas Technical University, and in Latvia by Riga Technical University.

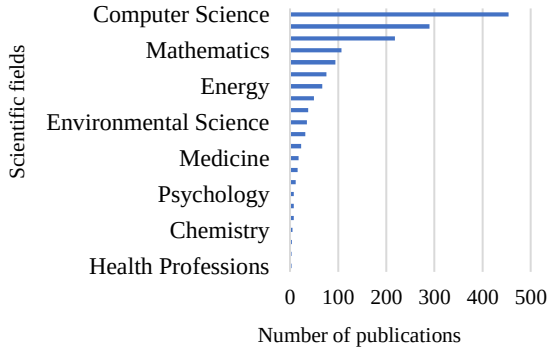
Of all the publications analysed, 45% are peer-reviewed journals, followed by conference proceedings with 42.6%, while book chapters and scientific reviews account for 7.8%. The proportion of conference papers indicates active involvement in international cybersecurity and technological development. The high proportion of conference materials indicates strong international cooperation, as the cybersecurity industry is developing rapidly, and the latest research is presented at international conferences before being published in journals.

Estonia's cybersecurity research leadership is closely linked to the widespread cyberattacks in 2007, catalysing the development of a national cybersecurity strategy and international cooperation. Following these events, the NATO Centre of Excellence for Cooperative Cybersecurity (CCDCOE) was established in Tallinn, which has played a key role in the development of research and international projects (CCDCOE, 2020), the Estonian Defence Forces Cyber Training Centre since 2012 and the Estonian Centre for Digital Development since 2017, promote cooperation with global experts and also funding for research. Although Latvia developed the Cybersecurity Strategy in 2014, its impact on scientific research became noticeable only after 2018, when the attraction of EU funds for research increased. Meanwhile, the establishment of the Lithuanian National Cyber Security Centre in 2023 is just beginning to have an impact and additional data are needed to assess its long-term research effectiveness. The Lithuanian Cybersecurity Strategy was established in 2011, and the first cybersecurity law was adopted in 2018.

Computer science and engineering dominate when analysing the scientific fields in the Baltic States, where cybersecurity-related publications have been produced. However, social sciences, mathematics, decision-making science, business and management, and energy also play a significant role, as illustrated in Figure 2.

Figure 2

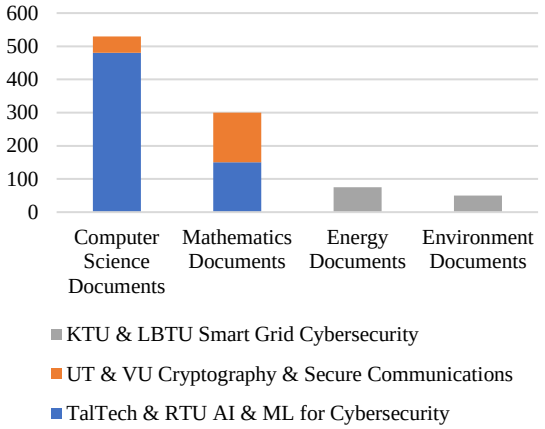
Research Publications by Field in Cybersecurity in Scopus (2012-2024)



These findings suggest that effective cybersecurity requires a multidisciplinary approach, integrating technical, social, psychological, and legal dimensions. Cooperation between universities in the Baltic States can significantly improve the quality and scope of cybersecurity research. By joining forces and

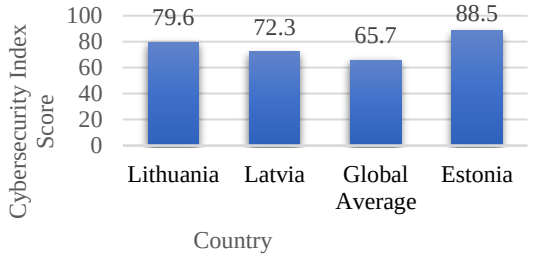
specialisations, universities can achieve better results and significantly contribute to ensuring cybersecurity. By analysing the research directions of universities in the Baltic States in the field of cybersecurity, potential opportunities for cooperation can be identified to use resources more efficiently and expand the scope of research. Potential cooperation models Figure 3 have been created based on the analysis of previous data.

Figure 3
University collaboration (2012-2024) in cybersecurity research (Baltic States)



Particularly successful collaboration partnership models could be established between TalTech (Estonia) and RTU (Latvia): Collaborative projects on AI and machine learning for cybersecurity, focusing on threat detection and incident response.
UT (Estonia) and VU (Lithuania): Joint research on cryptography and mathematical models for secure communications and data storage. KTU (Lithuania) and LBTU (Latvia): Collaborative research on smart grid cybersecurity, aiming to develop security solutions for energy distribution.
This study provides valuable insights into the development and challenges of cybersecurity research in the Baltic States. The results can serve as a basis for further collaborative research and policymaking to ensure a safer and more resilient cyberspace.
No matter the desire and necessity for research cooperation and policymaking in cybersecurity in the Baltic States, practical collaboration in cybersecurity research is closely related to the available funding.
By aligning research priorities with policy objectives, the Baltic States can use their strengths in the field of cybersecurity to build a more resilient society and economy. The Global Cybersecurity Index (GCI) (International Telecommunication Union, 2024) serves as a windstorm for the impact of research funding and policy-making in the Baltic States. The GCI objectively measures national commitments to cybersecurity, covering key pillars (legal, technical, organisational, capacity building and cooperation measures). For politicians, this index serves as a report highlighting strengths and weaknesses, guiding strategic planning, resource allocation, and the need for investment. Higher GCI scores may make it easier to justify further or increased investment in cybersecurity research and infrastructure. Strong performance signals the effectiveness of current strategies, while countries with lower GCI scores may need to step up efforts and investment. Estonia, with 88.5 and a leading top 10 GCI score - Figure 4, can be associated with strategic early investments in digital infrastructure and cybersecurity. The emphasis on cybersecurity since the 2007 cyberattacks has contributed to strong research results and effective policies.
The Lithuanian indicator 79.6 reflects a balanced approach to different pillars of cybersecurity. Its efforts to establish a national cybersecurity hub and implement a coherent regulatory framework have made a positive contribution. Latvia's 72.3 indicator indicates progress and growth opportunities. Targeted investments in capability development and cybersecurity programs can help improve its GCI rating. Closer cooperation between research institutions and government agencies could improve the impact of cybersecurity policies.
Considering the dominance of computer science and mathematics in cybersecurity research, the Baltic States should prioritise funding for projects that translate these theoretical achievements into practical applications. Figure 3 confirms that computer science is the main branch of science (over 450 documents), but mathematics also occupies an important place. Research on the security of smart electricity grids is significant for Estonia, Lithuania and Latvia. The energy sector is the third most important field of research in cybersecurity (50-100 documents). Social sciences and psychological studies that can help understand human behaviour and motivation in cyberattacks are also important in cybersecurity. Many other branches of science, such as chemistry, health professions, and medicine, also play a significant role (0-50 documents).

Figure 4
Cybersecurity Index Scores in 2024



Source: Adapted by author from International Telecommunication Union (2024).

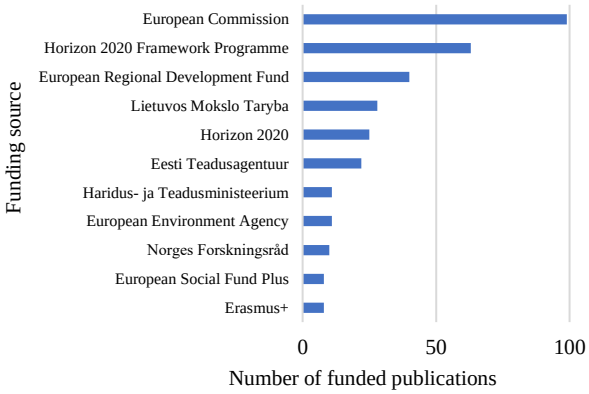
The Cybersecurity Index of the Baltic States (International Telecommunication Union, 2024),

Figure 4, is above the global cybersecurity index, which shows more outstanding commitment and efficiency in cybersecurity compared to the global average and shows that the Baltic States have made significant investments in cybersecurity. The most important sources of finance for cybersecurity research are funding from the European Union and the European Commission for research projects, mainly Horizon 2020 and the European Regional Development Fund. This is evidenced by the number of research documents compiled at Scopus (Elsevier, n.d.) by type of funder - Figure 5, which has undoubtedly been influenced by integrating the Baltic States into these research-funded programmes.

National funding of 28% for research and the Research Council of Norway are also important. The European Union's (EU) Digital Europe Programme fosters digital transformation and the diffusion of digital technologies across the European Union. The programme supports cybersecurity projects that are important for ensuring the security of the state and enterprises.

Figure 5

Main Sources of Funding for Cybersecurity Research in the Baltic States (2012–2024)



Source: Scopus.

Currently, the majority of cybersecurity research in the Baltics is based on EU funding (Horizon 2020 (European Union, 2013), Digital Europe, ERDF) 56%, so it would be valuable to assess the possibilities of diversifying financing, so that the Baltic States are less dependent on EU funds and set country-oriented goals for the research process and invest in strategic research directions that are important for the country. Similar to findings in Craigen et al. (2014), the Baltic region's heavy reliance on EU research funding reflects broader patterns of cybersecurity dependency observed in smaller EU economies.

Conclusions

Based on the bibliometric analysis, policy document research and statistical analysis carried out in the study, it can be concluded that Cybersecurity research in the Baltic States is a growing trend, but its development is still improvable.

1. Estonia is the leader in cybersecurity research in the Baltics, accounting for 54% of all publications (408 out of 756) and demonstrating the highest global Cybersecurity Index (GCI) rating (88.5). This is directly related to the long-term strategy, international cooperation and the development of institutional infrastructure. Lithuania (29% of publications) and Latvia (17%) lag, mainly because they introduced national cybersecurity strategies and institutional research centres much later. ANOVA statistical analysis ($p < 0.05$) confirms significant differences in cybersecurity research activity between the Baltic States.

2. International cooperation and EU funding are key factors in the development of cybersecurity research.

Estonia has actively attracted NATO and EU funding, contributing to its leadership position. NATO's Cooperative Cybersecurity Centre of Excellence (CCDCOE) in Tallinn has significantly contributed to research and international cooperation. The Estonian Centre for Digital Development and the Cyber Training Centre for the Defence Forces also play an important role in research and the development of new technologies.

Latvia and Lithuania rely mostly on EU funds (Horizon Europe, Digital Europe, ERDF) and have yet to develop national funding mechanisms to become more independent from external means.

3. The model of research cooperation between the Baltic States is not yet sufficiently developed.

Scientific cooperation between the Baltic States is not yet optimal, as the research institutions of each country operate in isolation and not as a single regional network.

Potential cooperation models for strengthening the Baltic region are emerging between TalTech (Estonia) and RTU (Latvia) – application of artificial intelligence in cybersecurity, University of Tartu (Estonia) and Vilnius University (Lithuania) – joint research in cryptography and secure communication protocols, Kaunas University of Technology (Lithuania) and Latvia University of Life Sciences and Technologies (LBTU) – cybersecurity of energy and smart electricity grids.

The recommendation is for the Baltic States to develop a common cybersecurity research strategy, including the common use of resources and infrastructure.

4. The sectoral structure of cybersecurity research reveals the importance of multidisciplinarity. Cybersecurity research is not just a matter of computer science or engineering but requires a multidisciplinary approach - Computer science (45%) and engineering (30%) dominate research. In comparison, Social Sciences (10%), psychology (5%) and energy security (10%) are also important factors.

For the Baltic States to prepare more effectively for cyber threats, it is necessary to develop interdisciplinary cooperation involving lawyers, psychologists, and energy experts.

5. The Baltic States must increase their national cybersecurity research contribution.

EU funding accounts for the largest share, or 56% of the research budget in the Baltic States. However, countries must develop funding mechanisms in the long term to ensure independent and stable research and development.

It is vital to increase national investment mechanisms in cybersecurity research through state aid programmes.

Closer collaboration between academic institutions, government agencies, and the private sector is essential to advancing applied research and innovation in cybersecurity. Establishing dedicated funding mechanisms, such as the Baltic Cybersecurity Research Fund, can incentivise joint research initiatives, facilitate knowledge transfer, and accelerate the development of advanced cybersecurity solutions tailored to regional challenges. The integration of the Baltic and European cybersecurity ecosystems should be promoted to strengthen the region's defences against cyberattacks.

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THE USE OF SMART HOME SYSTEMS TO IMPROVE USERS' SLEEP QUALITY

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Abstract
This study explores the design and theoretical evaluation of a smart home system aimed at improving sleep quality through real-time integration of data from wearable devices and environmental sensors. Recognizing sleep as a critical factor for health, productivity, and emotional well-being, the research proposes a personalized, adaptive approach to optimize indoor environmental conditions during sleep. The system continuously monitors temperature, humidity, lighting, noise, and air quality, adjusting them to meet individual needs. A comprehensive simulation model incorporates machine learning and rule-based systems to process multimodal data from smartwatches (tracking sleep stages, heart rate, and movement) and smart home sensors (measuring ambient conditions). Based on this data, the system makes dynamic environmental adjustments to support optimal sleep conditions. Simulation results showed that sleep quality improved significantly under specific environmental conditions—approximately 21°C temperature, 45% humidity, 380 ppm CO_2, and noise levels below 30 dB. These findings confirm that smart home systems can enhance restfulness and comfort, contributing to long-term health benefits. Beyond technical feasibility, the study discusses challenges such as data interoperability, privacy, and scalability in real-world use. Recommendations for future work include expanding health-related parameters, conducting broader user studies, and developing deeper personalization informed by biometric and behavioral trends. The proposed system provides a solid foundation for intelligent home environments that support preventive healthcare and tailored wellness solutions, contributing to the growing field of personalized, data-driven health technologies.
Keywords: smart home, sleep quality, environmental monitoring, wearable devices, personalized healthcare.

Introduction

In recent years, the integration of smart home technologies and Internet of Things (IoT) solutions into everyday life has opened new possibilities for enhancing personal health and well-being. Devices such as smart thermostats, lighting systems, and environmental sensors have become widely available, enabling the continuous monitoring of indoor conditions and user behavior (Tkalčič, 2023). When paired with data-driven analysis methods, these technologies offer the potential to create personalized health interventions within the home environment.

Sleep quality is widely recognized as one of the most essential factors influencing physical and mental health, cognitive performance, and emotional stability. Yet, modern lifestyles and suboptimal environmental conditions often lead to sleep disturbances. Common issues such as excessive light exposure, improper temperature, poor air quality, and ambient noise can negatively affect sleep patterns and reduce overall restfulness (Cook, 2017; Bamidis, 2021). Addressing these factors through intelligent environmental control has become an important area of research.

This study investigates how smart home systems can be designed to support better sleep by automatically adjusting key environmental parameters in response to individual user needs. The focus is placed on integrating data from wearable devices—such as smartwatches monitoring sleep phases, heart rate, and movement—with sensor data from the home environment. A simulation-based approach is used to evaluate how temperature, humidity, noise levels, lighting, and air quality influence sleep quality, and to develop a system capable of real-time adaptation.

The motivation for this research stems from both the relevance of sleep in public health and the increasing availability of smart home infrastructure. The goal is to explore a personalized and autonomous system that not only monitors but also responds to the user's physical state during sleep. Through the use of machine learning algorithms and rule-based control mechanisms, the system aims to enhance sleep quality by maintaining optimal environmental conditions tailored to each individual.

Materials and Methods

Data Sources

The simulation relied on synthetic data representing a variety of smart home devices and systems. These included smart thermostats for temperature control, automated lighting systems, indoor air quality sensors, and ambient noise detectors. Although real-time user data were not collected, the simulated datasets were constructed based on typical usage patterns and documented ranges observed in prior studies. This approach ensured a controlled yet realistic foundation for testing environmental adjustments under varying conditions.

Simulation Environment

A virtual smart home model was developed to replicate different household scenarios, enabling the analysis of how changes in environmental parameters would influence sleep-related outcomes. The simulation accounted for both temporal variations (e.g., nighttime temperature shifts) and spatial factors (e.g., sensor placement and room configuration), providing a dynamic setting for evaluating the proposed system.

Measurements and Evaluation

Two key aspects were measured throughout the simulation process:

• Impact of environmental quality on sleep-related health indicators: The model tracked changes in environmental conditions such as temperature, humidity, air quality, and noise levels and their effect

on simulated indicators of sleep quality and physiological stress.

• Effectiveness of personalized recommendations: The system's ability to provide individualized adjustments based on user-specific needs was evaluated by comparing sleep outcomes across different simulated scenarios, with and without environmental adaptations.

Results and Discussion

Key Findings

The simulation results indicate that the management of environmental parameters—particularly lighting, temperature, and air quality—based on data collected from smart devices has a substantial impact on user well-being. Adjustments made in response to sensor input contributed to noticeable improvements in modeled sleep quality and overall comfort levels under various virtual conditions.

Significance of the Findings

The study demonstrates that smart devices, when integrated into an autonomous system, can deliver effective health-supportive interventions without requiring active user involvement. By continuously monitoring and adapting environmental conditions, the system provides a non-intrusive method for enhancing sleep quality, which may contribute to broader physical and mental well-being.

This approach also supports the growing trend toward the digitalization and personalization of healthcare. Rather than relying on generic or static settings, the system dynamically tailors environmental adjustments to match the unique physiological responses and preferences of each user, based on real-time data.

Comparison with Existing Research

While previous studies have often focused on analyzing individual devices in isolation, this research takes a more holistic and integrated approach (Bettini, 2022; Islam, 2020). By combining data from multiple sources—such as smartwatches monitoring sleep phases and heart rate, and environmental sensors tracking temperature, humidity, and air quality—it becomes possible to model and optimize indoor conditions with greater precision.

This integrated method allows for the generation of personalized environmental recommendations, offering a significant advancement over traditional systems that lack adaptive or context-aware features.

Simulation Model Design

1. Simulation Objective

The primary aim of the simulation was to model the impact of various environmental parameters—specifically temperature, humidity, lighting, and noise—on sleep quality, and to evaluate the ability of a smart home system to adjust these parameters automatically in response to changing conditions.

2. Data Sources and Input Parameters

Smartwatch data: Simulated sleep quality data were generated based on established scientific literature and typical sleep models, including phases such as REM and deep sleep.

Environmental data: Artificial datasets were created to reflect variations in temperature, humidity, air quality, noise, and lighting throughout the night, simulating realistic in-home conditions.

3. System Components

Environmental parameter simulation: Modeled based on input from virtual sensors, reflecting real-time shifts in indoor conditions.

Adaptive control algorithm: Automatically adjusted environmental variables to support optimal sleep quality.

Sleep quality simulation: Implemented using mathematical models and logical frameworks to assess how environmental changes influence sleep outcomes.

4. Algorithm Selection and Modeling

Machine learning algorithms: Applied to simulate adaptive responses based on historical data, enabling the system to learn optimal adjustments over time.

Rule-based systems: Included conditional logic, such as increasing humidity to 60% if levels dropped below 50%, allowing for direct parameter control based on predefined thresholds.

5. Scenario Description

The simulation was structured to represent different environmental conditions and evaluate their impact on sleep quality. Four core parameters were modeled: temperature, humidity, CO_2 concentration, and noise level. The sleep quality outcomes were derived from assumed relationships between these variables and physiological rest, grounded in findings from existing sleep research.

Simulation Scenarios:

1. Temperature Variations

Temperature was simulated within a range of 19 °C to 23 °C, based on the assumption that the optimal sleep temperature lies between 20 °C and 22 °C (Samadi et al., 2023). The simulation examined how slight deviations from this optimal range affect sleep quality.

2. Humidity Variations

Humidity levels were varied between 40% and 60%. Existing research suggests that low humidity can cause physical discomfort, while excessive humidity may contribute to poor indoor air quality.

3. CO_2 Concentration Variations

Carbon dioxide (CO_2) levels were simulated in the range of 380 to 420 ppm (parts per million). Elevated CO_2 concentration is assumed to negatively influence sleep depth by reducing the availability of oxygen in the sleeping environment.

4. Noise Level Variations

Noise levels were simulated within a range of 30 dB (decibels) to 42 dB. Lower levels of ambient noise are generally associated with improved sleep quality, while increasing noise can lead to sleep disturbances.

Simulation strategy:

Each scenario was assigned specific parameter ranges and evaluated by analyzing its effect on sleep quality, expressed on a scale from 0 to 100.

Multiple data points were generated for each scenario, combining different values of environmental parameters to simulate realistic conditions and identify optimal settings.

Result Analysis:

The simulation scenarios revealed that optimal sleep quality (92%) could be achieved under the following environmental conditions:

- Temperature: 21 °C
- Humidity level: 45%
- CO_2 concentration: 380 ppm
- Noise level: 30 dB

As shown in Figure 1, sleep quality increased significantly when the room temperature approached 21 °C.

These results made it possible to identify the key factors and their optimal values necessary for configuring the smart home system to support better sleep quality.

Simulation and Visualization of Results:

Python was used to generate the simulation data and visualize the outcomes through graphs—for example, showing the relationship between sleep quality and temperature or noise level.

The simulated results were compared across different scenarios to assess variations in system performance and sleep quality outcomes.

1. Data Acquisition

Data were collected from two primary sources:

Smartwatches: The study utilized smartwatches equipped with various sensors capable of monitoring sleep phases, heart rate, activity levels, and overall sleep quality. These data were used to assess specific aspects of sleep, including deep sleep, light sleep, and REM phases.

Smart home sensors: These included smart thermometers, humidity sensors, air quality monitors, lighting control systems, and noise level detectors. The data collected from these sensors were used to analyze environmental parameters potentially affecting sleep quality, such as room temperature, humidity, carbon dioxide concentration, lighting intensity, and noise levels.

2. Data Processing and Analysis

The collected data were processed to create datasets suitable for analyzing sleep quality and identifying correlations between sleep patterns and environmental parameters. The processing workflow included the following steps:

Data cleaning: The datasets were cleaned to remove missing values and external noise that could distort the analysis. This step ensured the accuracy and reliability of the data used in subsequent modeling.

Correlation analysis: Statistical methods were applied to examine the relationships between various environmental factors—such as temperature, humidity, lighting, and others—and sleep quality. The analysis aimed to identify which variables had the strongest influence on specific sleep phases, such as REM and deep sleep.

Regression analysis: Regression models were developed to predict sleep quality based on environmental conditions. These models formed the foundation for algorithms capable of estimating sleep outcomes in response to changes in indoor parameters.

3. System Development and Simulation

To optimize environmental parameters, a smart home system was developed that could automatically adjust indoor conditions using the collected data. The system consisted of the following components:

Smart thermostats: Smart thermostats were used to regulate room temperature according to the user's preferences and sleep phases. Based on the study's findings, temperatures that are too high or too low can negatively affect sleep. Therefore, the thermostats were configured to maintain an optimal range, typically between 18 °C and 20 °C.

Smart lighting and illumination systems: Smart lamps were employed to adjust both the intensity and color of the lighting in alignment with the user's circadian rhythm. According to the data, light brightness and spectrum influence both sleep onset and depth. Consequently, lighting was dimmed in the evening to promote smoother transitions into sleep.

Air quality monitoring and regulation: Smart humidifiers and air purifiers were integrated to automatically maintain appropriate air quality and humidity levels, based on readings of carbon dioxide concentration and relative humidity.

Noise level control: Noise sensors were used to monitor sound levels within the room. If noise exceeded the optimal threshold, the system could activate noise-reducing devices, such as white noise generators, to restore a quiet sleeping environment.

4. Simulation and Results Analysis

To evaluate the effectiveness of the smart home system and its ability to improve sleep quality, a simulation was developed that modeled various scenarios involving dynamic environmental parameters and user sleep data. This simulation made it possible to analyze how changes in different environmental factors influence sleep quality and whether the smart home system could effectively adapt indoor conditions to create an optimal sleep environment.

4.1. Scenario Development

The simulation was based on several environmental parameters obtained from both smartwatches (e.g., sleep cycles, heart rate, movement) and home sensors (e.g., temperature, humidity, lighting, air quality). Each of these parameters was modeled individually and in combination to assess their collective impact on sleep quality.

Initially, a set of baseline conditions considered optimal for sleep quality was established:

Temperature: 18–20 °C (research indicates this range promotes a deeper sleep);

Humidity: 40–60% (helps maintain skin moisture balance and prevents discomfort caused by dryness or excessive humidity);

Lighting: Low, especially with reduced exposure to blue light, which influences melatonin secretion;

Air quality: Low CO_2 concentration and adequate oxygen levels in the room.

During the simulation, these parameters were systematically altered to evaluate how different environmental changes affect sleep quality.

4.2. Simulation Processes and Methodology

The simulation was carried out in several stages:

1. Data aggregation – Data were collected from smartwatches, capturing user sleep patterns, and from smart home sensors, monitoring environmental conditions. These data were used to define baseline parameters and identify potential sleep issues, such as disturbances or fragmented sleep.
2. Modification of environmental parameters – During the simulation, adjustments were made to environmental conditions, including temperature, humidity, lighting, and air quality. Changes in sleep quality were recorded based on metrics such as REM sleep duration, heart rate, and body temperature.
3. Smart home system response mechanism – The smart home system was automated to detect changes in input data and adjust environmental conditions accordingly (e.g., modifying temperature or lighting). These adjustments were made in real time using integrated sensors and control algorithms based on the user's sleep needs.
4. Data analysis – After each scenario, the results were analyzed and compared with the initial baseline data. Statistical and data processing tools were used to examine how changes in environmental parameters affected sleep quality and to evaluate the system's effectiveness in adapting the environment.

4.3. Scenario Data Description

The simulation was designed to model various environmental conditions and their impact on user sleep quality. Four key parameters were taken into account: temperature, humidity, CO_2 concentration, and noise level. Sleep quality data were generated based on assumptions regarding the influence of these environmental factors, as established in previous scientific studies.

Scenarios

1. Temperature variations: Temperature was simulated within a range of 19 °C to 23 °C, based on the assumption that the optimal sleep temperature lies between 20 °C and 22 °C. The simulation explored how slight deviations from this range affect sleep quality.
2. Humidity variations: Humidity levels were varied between 40% and 60%. Research indicates that low humidity may cause discomfort, while excessive humidity can lead to poor air quality.
3. CO_2 level variations: CO_2 concentration was simulated in a range from 380 ppm to 420 ppm. It is assumed that elevated CO_2 levels can reduce sleep depth by decreasing oxygen availability in the room.
4. Noise level variations: Noise levels were simulated between 30 dB and 42 dB, considering that lower noise levels tend to improve sleep quality, while higher levels may cause disturbances.

Simulation Strategy

1. Each scenario was assigned specific parameter ranges and evaluated by analyzing its impact on sleep quality, which was expressed on a scale from 0 to 100.
2. REM sleep duration was also modeled to assess how environmental conditions influence deep sleep.
3. Multiple data points were generated for each scenario, combining different parameter values to simulate realistic conditions and help identify optimal settings.

Result Analysis

The scenario results showed that optimal sleep quality (92%) could be achieved under the following environmental conditions:

- Temperature: 21 °C
- Humidity level: 45%
- CO_2 concentration: 380 ppm
- Noise level: 30 dB

These scenarios made it possible to identify the key factors and their optimal values required for effective adjustment of the smart home system.

4.4. Results

An analysis of the simulation data identified the following optimal environmental parameter values associated with the highest sleep quality score (92%):

- Temperature: 21 °C
- Humidity: 45%
- CO_2 concentration: 380 ppm
- Noise level: 30 dB

The table (Table 1) below presents the complete set of simulation data:

Table 1

Simulation data

Sleep Quality (%)	***Temperature (°C)***	***Humidity (%)***	***CO_2 Level (ppm)***	***Noise Level (dB)***
85	20	50	400	35
78	22	55	420	40
92	21	45	380	30
88	23	50	410	38
80	19	60	390	42

These optimal parameters indicate the conditions under which the smart home system should be configured to achieve the highest sleep quality.

Figure 1
Relationship between sleep quality and temperature (°C)

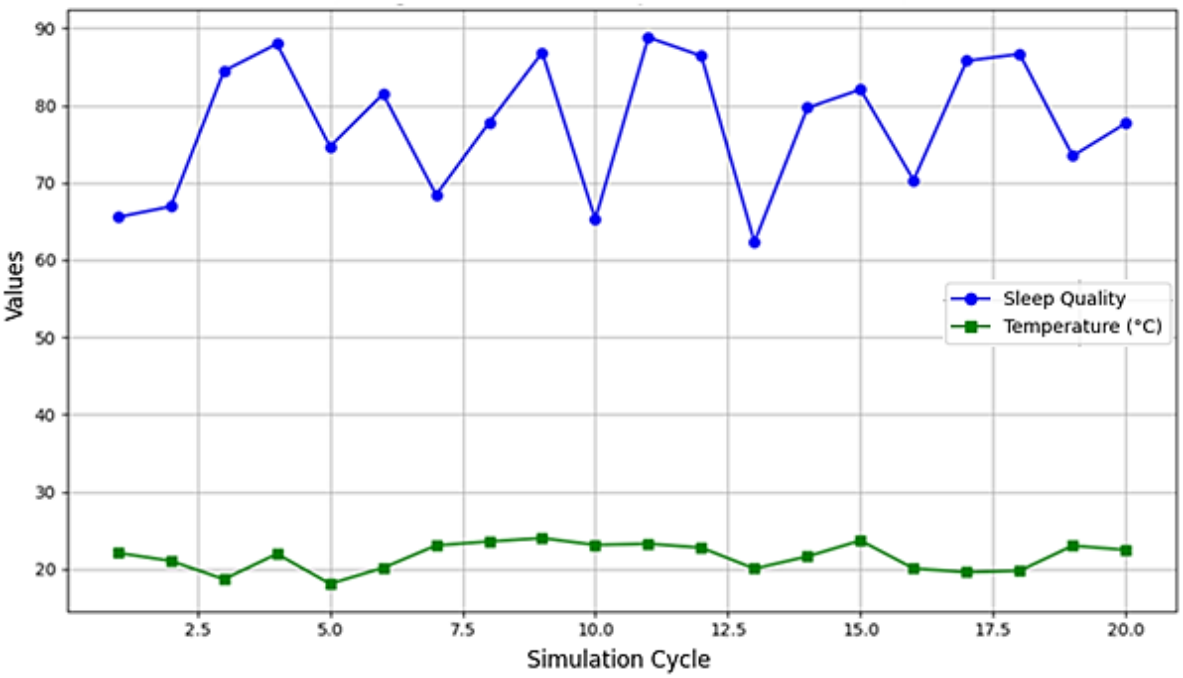


Figure 2
Relationship between sleep quality and humidity (%)

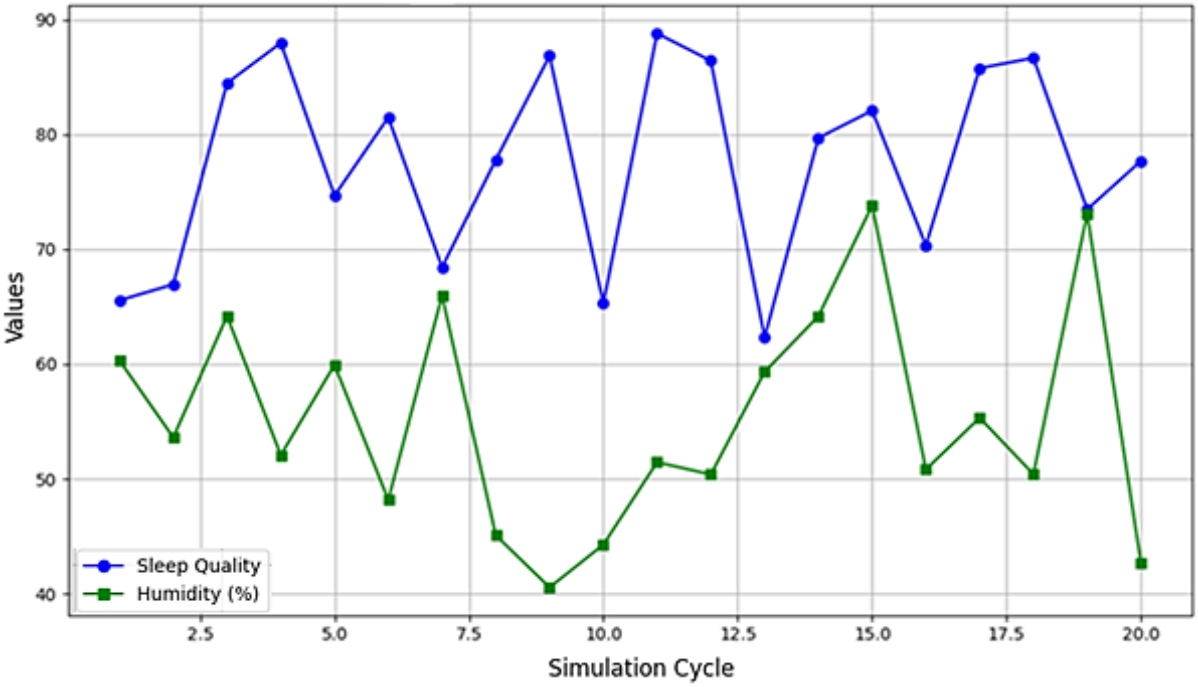


Figure 3

Relationship between sleep quality and CO_2 level (ppm)

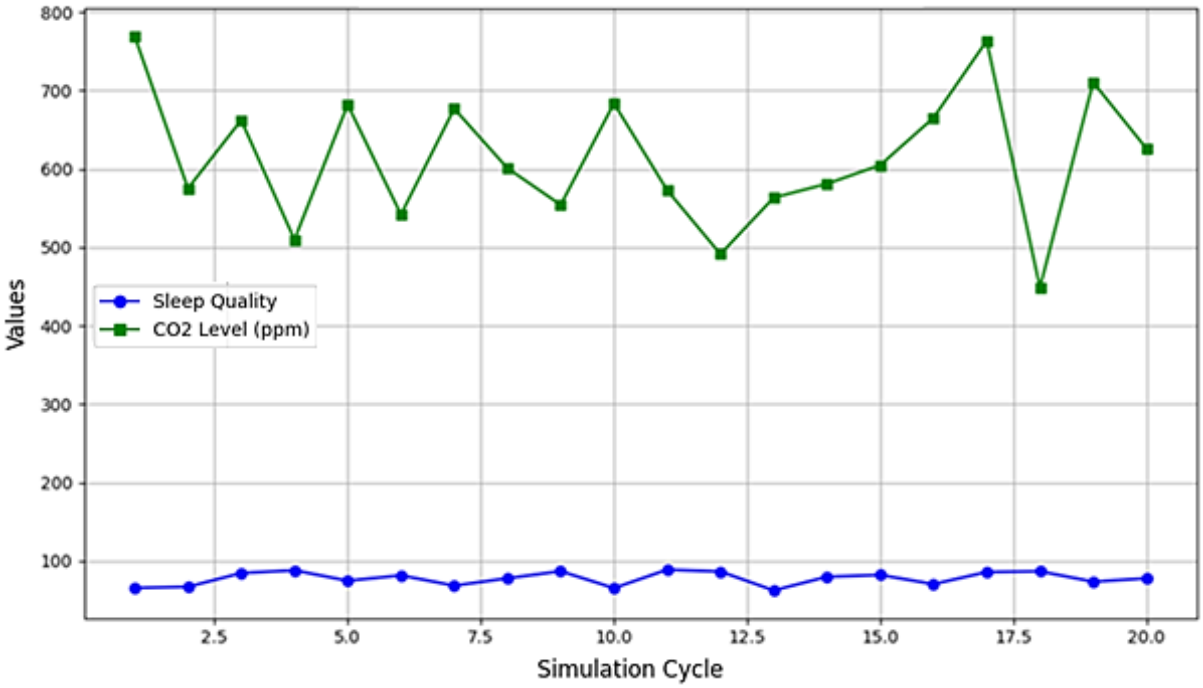
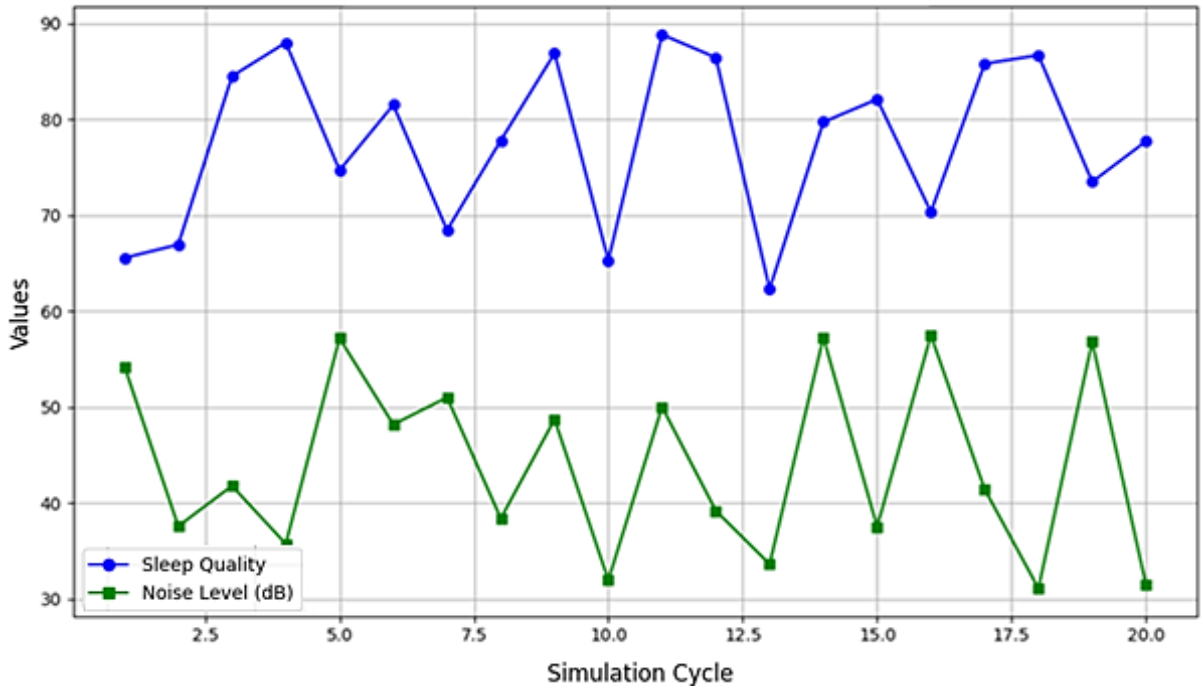


Figure 4

Relationship between sleep quality and noise level (dB)



The simulation results pointed to several important conclusions regarding the impact of environmental parameters on sleep quality:

Temperature: Sleep quality was the highest when the room temperature was maintained between 18 °C and 20 °C. Increasing the temperature above this range (more than 22 °C) led to sleep disturbances, which were reflected in smartwatch data—such as increased sleep fragmentation and shorter REM phases.

Humidity: The optimal humidity range for improving sleep quality was between 40% and 60%. Both excessive dryness and high humidity caused

discomfort and negatively affected sleep (for example, increased restlessness reflected in elevated heart rate). This pattern is illustrated in Figure 2, which shows a noticeable decline in sleep quality outside the 40–60% humidity range.

Lighting: Low light levels, particularly with reduced blue light spectrum, significantly improved sleep quality, especially during the early hours of sleep (Kweon, 2022). The simulation showed that overly bright lighting delayed sleep onset and reduced the duration of the REM phase.

Air quality: Elevated CO_2 levels or low oxygen concentration in the room caused sleep disruptions, as indicated by sleep quality metrics—for example, an increase in the number of awakenings. Figure 3 demonstrates the inverse relationship between CO_2 levels and sleep quality.

Overall, the simulation results confirmed that a smart home system capable of adjusting these parameters can significantly enhance sleep quality by maintaining optimal conditions tailored to individual users.

4.5. Conclusions and Future Research Directions

The simulation results indicate that a smart home system capable of adjusting environmental parameters according to individual sleep needs can significantly improve sleep quality. Future studies are encouraged to expand the range of investigated variables by including additional environmental factors, such as airborne pollutant levels or the influence of sleep-disrupting elements.

Moreover, it is recommended that future research increase the sample size in order to gain a broader understanding of how various environmental conditions affect sleep quality across different user profiles.

Conclusions

Smart homes equipped with integrated intelligent devices can serve as an effective tool for improving user health by providing personalized recommendations based on IoT and AI technologies. The results of this study support the viability of such systems while also highlighting the need to address challenges related to data security and system interoperability.

This research conducted an in-depth analysis of how smart devices and smart home technologies can be used to enhance sleep quality by adjusting environmental parameters to meet individual user needs. The findings and simulation outcomes confirm that environmental factors—such as temperature, humidity, lighting, noise level, and air quality—have a significant impact on sleep quality. Accordingly, smart home systems that respond to these parameters can substantially improve the user's sleep experience.

The main conclusions drawn from this study are as follows:

1. Impact of environmental parameters on sleep: Analysis of data from smartwatches and smart home sensors revealed that temperature, humidity, lighting, and noise levels directly affect sleep quality. For example, an optimal temperature range of 18–20 °C supports deeper sleep, while high noise levels disrupt sleep cycles and reduce restfulness. As shown in Figure 4, the lowest noise level (30 dB) corresponds with the highest modeled sleep score.
2. Personalized recommendations: The results indicate that a smart home system capable of tailoring environmental conditions to individual needs significantly enhances sleep quality. Data collected from smartwatches enable the creation of personalized recommendations for ideal temperature, lighting, and other adjustments that help users achieve deeper and more restful sleep.
3. Automation and real-time adaptation: A smart home system that uses real-time data from sensors and smartwatches can autonomously adjust environmental conditions without interfering with the user's daily routine. This level of automation offers considerable convenience, eliminating the need for manual adjustments each night.
4. Long-term improvement of sleep quality: Over time, a smart home system that continuously adapts the environment can help improve the user's overall health and well-being. Better sleep quality contributes to higher daytime productivity, improved emotional balance, and reduced stress—factors that support a healthier lifestyle.
5. Technology integration and future potential: The study highlights the potential for developing a broader smart home ecosystem that integrates additional health-monitoring devices such as heart rate monitors, blood pressure sensors, and other medical-grade tools. Such integration would enable even more precise and effective environmental adjustments tailored to individual health needs.
6. Recommendations for future research and development: To further improve these systems, future studies should expand the range of environmental parameters being evaluated, including the presence of sleep-disrupting elements (e.g., allergens, CO_2 levels). It is also recommended to explore the integration of other smart devices into the smart home environment and to conduct broader user studies to refine algorithms that adapt conditions based on individual sleep patterns and health profiles.

In summary, this study contributes to the development of smart home technologies and explores their potential to enhance human health and well-being. By integrating smart devices and artificial intelligence, it is possible to create effective and personalized systems that provide a supportive living environment aligned with the user's health needs and that improve sleep quality.

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ANALYSIS OF LAND USE CHANGES IN THE 19TH–21ST CENTURY: THE CASE OF JUODAIČIAI, LITHUANIA

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Abstract
The primary problem of land use changes from the 19th to the 21st century lies in human-driven landscape transformations that impact ecosystems, biodiversity, and sustainable management. The study examines changes in land use in Juodaičiai eldership (Jurbarkas district) during the 19th–21st centuries. GIS technologies and digitized 19th-21st century maps were used to identify changes in land use. The study utilized military-topographic maps of the Russian Empire (1860–1915), interwar Lithuanian topographic maps (1933–1940), Soviet topographic maps (1988), the Lithuanian georeferenced spatial data set, LIDAR data (2009–2010), and orthophoto maps, analyzed using ArcGIS Pro software. The study used 3D terrain models and GIS technologies to analyze land-use changes. It found that from the 19th to 20th century, agricultural land expanded by 39.8%, mainly at the cost of forests, which decreased by 42.4%. During the Soviet era, forest areas increased by 12.7%, while urbanized areas shrank. In the early 21st century, forest and agricultural land remained stable, but intensive logging, affecting 23.6% of current forest areas, continues. This study reveals that while the land use in Juodaičiai eldership has undergone significant shifts over two centuries, the persistent tension between human activity and environmental sustainability remains the defining challenge for future landscape management.
Keywords: land use, land-use change, digital maps.

Introduction

Land use describes how humans utilize the land's surface. It involves the land's resources, the goods and benefits they provide, and the actions and practices employed to manage it (Wang & Yang, 2020).

Land systems represent the terrestrial component of the Earth system, encompassing human land use, socioeconomic activities, technological investments, and both the benefits and unintended consequences of these actions. Transformations within land systems, including human-induced changes to ecosystems and landscapes, are significant drivers of global environmental change (Verburg et al., 2013).

Over the past 60 years, humans have altered nearly one-third of the Earth's land surface. These changes present significant challenges to global food security, climate change, and biodiversity. Rapid shifts in land cover have primarily been driven by intensive human activities, including agriculture and urban development (Wang et al., 2023).

The Earth's land surface is predominantly utilized for agriculture, forestry, and urban activities, including infrastructure and residential areas. Environmental and socio-economic changes drive land-use transformations, which can adversely affect human well-being. Understanding the complex relationships between land-use factors and ecosystem services is essential for mitigating these impacts (Schirpke et al., 2023).

Changes in land systems present significant challenges to sustainability and require a comprehensive understanding of the drivers behind land-use and land-cover change. Land system science makes a substantial contribution by offering innovative methodologies and empirical insights into the patterns, processes, and underlying causes of these changes (Meyfroidt et al., 2018).

In recent decades, climate change, soil degradation, and Land Use/Land Cover Changes have heightened the risk of land degradation, making it one of the most critical ecological challenges on a global scale (Bajocco et al., 2012).

Land use changes impact the variety, quantity, and distribution of ecosystem services. Drivers such as population growth, migration, and socio-economic developments also shape societal demand for these services. The alignment between service supply and demand is crucial for human well-being, as the loss of critical services can have significant social and economic consequences (Sturck et al., 2015).

Land cover and land use changes can cause a variety of ecological effects, particularly on soil health and water quality, are influenced by even minor changes in farming practices in rural areas. Fine-scale analyses are essential for fully understanding these processes. Developing models to predict land cover changes is crucial for identifying areas at risk and informing sustainable policies. Future landscape studies can provide valuable insights to forecast responses to subtle changes, enabling more targeted and effective actions (Houet et al., 2010).

Rapid urbanization has transformed landscape patterns and ecological functions, leading to a reduction in ecosystem services and giving rise to various ecological and environmental challenges. Investigating the spatiotemporal interactions between urbanization and ecosystem services (ES) can offer valuable insights to support regional sustainability and inform policy development (Luo et al., 2022).

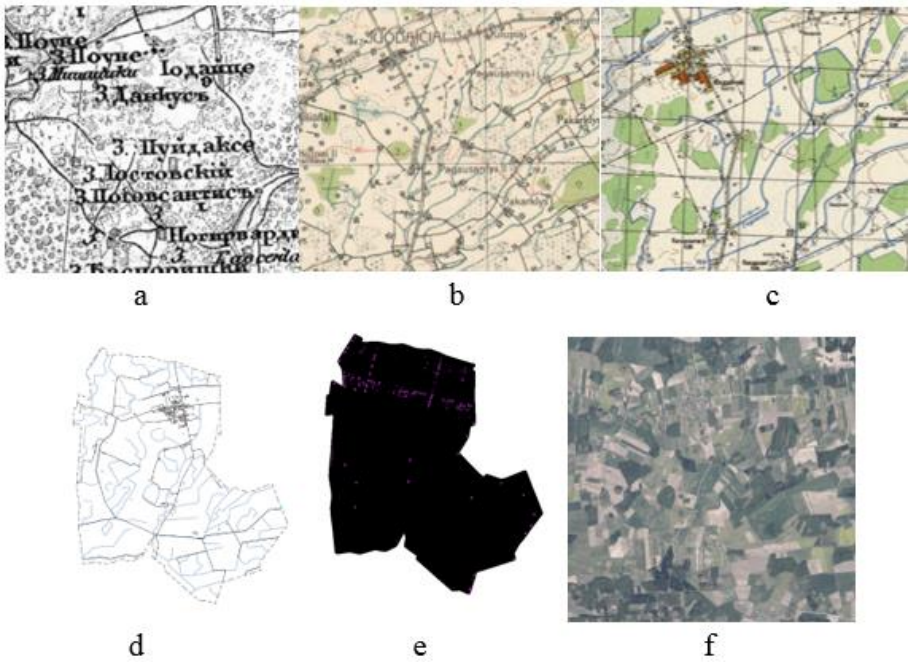
The effect of land use/cover change on the spatial distribution and fluctuation of ecosystem service values is still not well understood, which complicates the development of land use management policies aimed at

promoting harmonious development (Ying et al., 2023).
Land and ecosystem changes, along with their implications for global environmental change and sustainability, present a significant research challenge. Land change models are complex due to the interplay between human and environmental dynamics, necessitating spatial precision. The spatial arrangement of land uses and covers both influences and is influenced by these processes (Turner et al., 2007).
The land use change analysis offers crucial insights for monitoring landscapes, managing land resources, and prioritizing conservation efforts over large areas (Nedd & Anandhi, 2022).
Humans significantly influence landscapes through activities like urban expansion, deforestation, and the restoration of wilderness areas around abandoned mines. While mathematical models can aid in understanding and predicting land use changes, many models either fail to address cause-and-effect relationships or become overly detailed in describing specific processes (Budrikis, 2024).
The land use change models assist in interpreting the causes and effects of land dynamics, providing valuable support for policymakers in decision-making. The literature presents a variety of models from diverse disciplines, each with distinct strengths and limitations, making the selection of an appropriate model a challenging task (Noszcyk, 2019).
The land use and system changes are key to addressing global issues like food security, climate change, and biodiversity. Human activities, such as urbanization and agriculture, have significantly altered ecosystems. Analyzing these changes and using predictive models is crucial for assessing their impact on land use, ecosystem services, and human well-being. Effective land management relies on scientific knowledge to help policymakers prioritize conservation and tackle ecological challenges.
The subject of this article is the agricultural land area of the Juodaičiai eldership, located in the Jurbarkas district, Lithuania.
The objective is to assess the changes in land use areas from the 19th to the 21st century using digital and historical topographic maps, along with GIS technologies.
Tasks:
1. Compare historical and contemporary maps and analyze the changes in forest, agricultural land, and urbanized areas.
2. Assess land use changes over different periods (19th-21st centuries).
3. Calculate the rate of change in agricultural and forest land areas and evaluate potential future land use change scenarios.
4. Use GIS software and LIDAR data to create 3D landscape models and visualize the changes.

Materials and Methods

The distribution of soil fertility scores according to intervals was carried out based on a map obtained from the Lithuanian Geoinformation System (Žemės išteklių…, 2025), and various geographical and historical data were also analyzed.
Selection of the study area: considering the soil fertility score and the impact of urbanization development, the Juodaičiai eldership, which is characterized by high soil fertility and is favorable for agricultural activity was chosen. The Juodaičiai eldership is located in the northeastern part of the Jurbarkas district municipality, which is the smallest eldership in this district. The selected area is based on historical and geographical considerations.
Topographic maps and data sources: various topographic maps were used during the study to help analyze land changes over different periods. To investigate land use changes from the 19th to the 21st century, the study was conducted using historical topographic maps. These maps recorded the situation at the respective periods, and by digitizing them and combining them with modern data, the research was carried out.
The following data sources were used:
1. Military topographic maps of the European part of the Russian Empire, created by the Military Topography Department (1860–1915). Scale: 1:126,000. The map sheet is rectangular, measuring 58x42 cm, covering a 73x53 km area ‘Figure 1a’, in black and white.
2. Interwar topographic maps of Lithuania, scale 1:100,000 (1933–1940). These maps depict the territory of the country at that time; the size of the map sheet is 47x45 cm ‘Figure 1b’, in color.
3. Soviet topographic maps at a scale of 1:50,000 (1988) ‘Figure 1c’, in color.
4. Georeferenced spatial data set of the Republic of Lithuania’s territory (Oficialiosios statistikos…, 2025b) ‘Figure 1d’.
5. LIDAR data (2009–2010), obtained from the Lithuanian Spatial Information Portal (Geoportal, 2024) ‘Figure 1e’.
6. Orthophoto map ‘Figure 1f’.
ArcGIS Pro software was used for the research. GIS technologies provide the ability to extract data from raster images, in this case, from digitized maps. During the research, a situation arose where some of the maps were not georeferenced. Specifically, these were maps from the 19th and early 20th century. In such cases, after conducting a visual analysis of topographic objects, location-based features that had not changed their position over time were selected. Their coordinates were determined in the LKS94 coordinate system, and map georeferencing was performed.
Continuing with the research, databases were created and object vectorization was carried out.
The forest cadastre database was loaded into the ArcGIS Pro file, and data corrections were made. Some data in the loaded database were outdated, so a visual comparison of the cadastre database with the orthophoto was necessary to identify newly performed clearings.

Figure 1
Data sources: a) Fragments of 19th-century maps, b) Fragments of early 20th-century maps, c) Fragments of late 20th-century maps, d) Georeferenced spatial data sets, e) LIDAR data, f) Orthophoto map



A 3D terrain model was created from the LIDAR point cloud using the IDW interpolation method. 3D landscape models were created to visualize changes in the territories and compare data from different time periods. 3D landscape models, in contrast to two-dimensional representations, enable the visualization of an area's current or historical state in a more realistic and familiar form. They offer a clearer understanding of the interrelationships among hydrography, road networks, forested areas, and built-up territories.
The georeferencing data set was uploaded.
The comparison of the obtained data was performed, and the rate of change of non-forest land use was calculated for different periods using the following formula:

$$v_f = \frac{S_{t2} - S_{t1}}{t_1 - t_2} \quad (1)$$

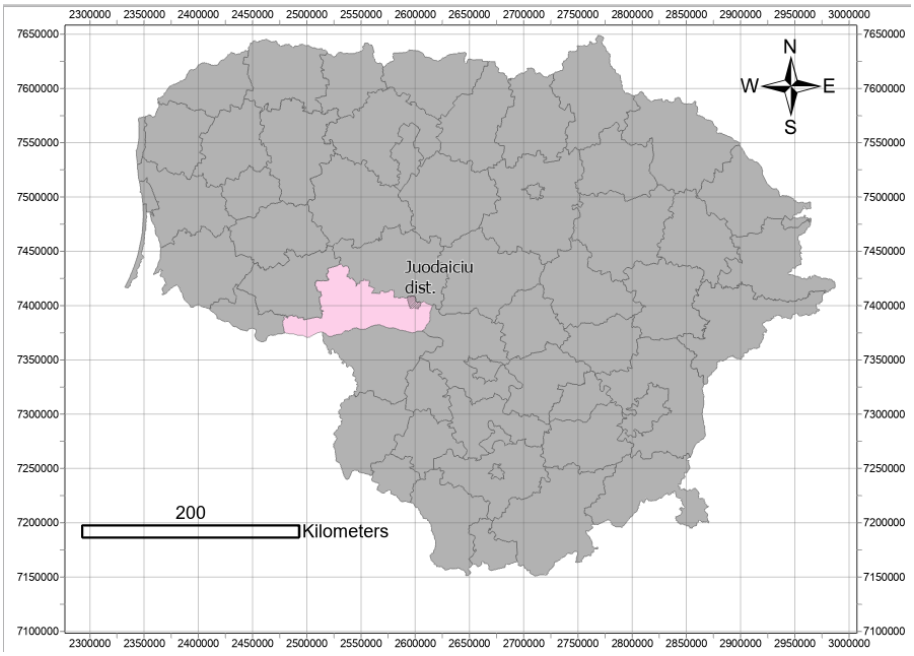
where:
- v_f is the rate of change in non-forest land use;
- t_1, t_2 are the years of the two time periods;
- S_{t1} and S_{t2} are the non-forest land areas (m²) for the years t_1 and t_2, respectively.

A land use analysis was conducted to assess changes in forest, agricultural, and urbanized areas over time. The study examined shifts in land allocation for forestry, agriculture, and urban development, offering insights into the dynamics of land use transformation.

Results and Discussion
This study provides a unique century-long analysis of land use changes in Juodaičiai Eldership, Jurbarkas District. Using historical maps, soil productivity data, and LIDAR-derived elevation models, it reveals how natural resource potential (e.g., soil fertility) interacts with anthropogenic pressures like agriculture and urbanization.

Description of the object
To determine land use changes, the Juodaičiai eldership, located in Jurbarkas district, was chosen ‘Figure 2’. The municipality is situated in the northeastern part of Jurbarkas district and is the smallest of all the municipalities in the district. The first mention of Juodaičiai eldership, after which the municipality is named, appears in written sources from 1568. At that time, there was very little land used for agriculture, only a few valaks (1 valakas ≈ 21 hectares), and the surrounding area was covered with forests.
The area of Juodaičiai eldership is 31.34 km². The municipality consists of seven elderships: Juodaičiai, Misiūnai, Pagausantys I, Pagausantys II, Pakarklys, Pavietava, and Užringis.
The population density in eldership is 10.3 people/km² (Oficialios statistikos…, 2025a). The population change in the Juodaičiai eldership is shown in ‘Figure 3’. It is evident that the population was at its lowest during the 19th century. In the 20th century, the population significantly increased, but started to decline in the first half of the 20th century.

Figure 2
Administrative division of the Republic of Lithuania; Juodaičiai eldership in Jurbarkas district



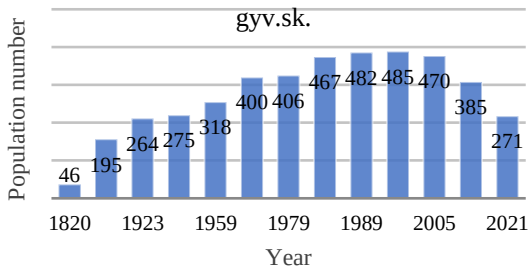
As the population increases and agricultural equipment and technology advance, the opportunity and need to cultivate more arable land and expand settlement areas have arisen. In most cases, this process is carried out at the expense of forested areas.

Soil Fertility Score Determination

The average soil fertility score of the Republic of Lithuania is 39.79 (Žemės išteklių…, 2025). The soil fertility scores in the Republic of Lithuania are divided into the following intervals: 0.01-22.00; 22.01-27.00; 27.01-32.00; 32.01-37.00; 37.01-42.00; 42.01-47.00; 47.01-52.00; 52.01-57.00; 57.01-62.00; 62.01-67.00; 67.01-100.00.

The most fertile lands are in central Lithuania. Since ancient times, soil fertility and a high fertility score have been one of the key factors creating favorable conditions for the expansion of agricultural areas. The Juodaičiai eldership, located in the Jurbarkas district of Lithuania, was chosen for the study due to this factor.

Figure 3
Population change in the Juodaičiai eldership



When selecting this district, the soil fertility scores of all municipalities were determined, and the percentage of municipalities falling into the above intervals was calculated (Table 1). Based on the results of the study, the Juodaičiai eldership was selected.

Table 1
The distribution of soil fertility scores in the municipalities of Jurbarkas district

Soil fertility fcore interval	***Percentage of municipalities in Jurbarkas district based on fertility score***
27.01-32.00	8.3
32.01-37.00	16.7
47.01-52.00	41.7
52. 01-57.00	33.3

According to the 2025 data, the average soil fertility score of Jurbarkas district is 50.49, and in the Juodaičiai eldership, it is 52.58. These data show that the soils of Juodaičiai eldership have a high fertility level, which is among the highest in Lithuania. This high fertility score is particularly important for agricultural activities, as it ensures favorable conditions for growing various crops and developing agriculture. Such favorable soil fertility is a key factor because the fertile soil characteristic of this area not only enables high crop productivity but also creates favorable conditions for the long-term and sustainable development of agricultural activities.

Creating a Surface Model of Juodaičiai eldership

The geomorphological parameters of a territory play a crucial role in determining its suitability for various land uses, including agricultural and other

anthropogenic activities. These parameters encompass features such as elevation, slope, landforms, and relief, which can directly impact the effectiveness of land management and the feasibility of cultivation.

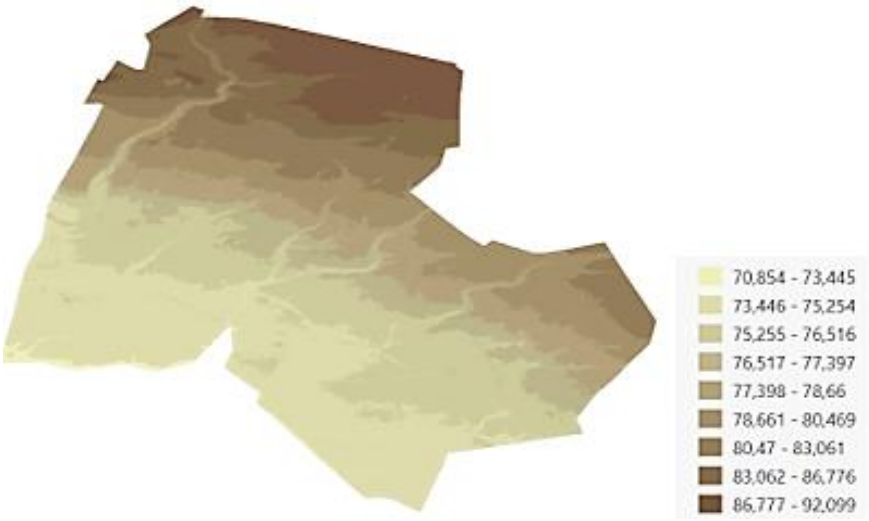
For the Juodaičiai eldership, a surface model was created using advanced GIS software, LIDAR point cloud data, and the IDW (Inverse Distance Weighting) surface modeling algorithm. These tools enable the generation of precise digital elevation models (DEMs), providing a detailed representation of the terrain's physical attributes. The resulting surface model ‘Figure 4’ reveals important insights into the spatial distribution of elevation across the area.

The model indicates that the elevation changes by 22 meters as one moves from the southern to the northern part of the eldership. The southern part is characterized by lower elevations, while the northern part is situated at higher elevations. This gradual increase in elevation from south to north implies a relatively smooth terrain, with only minor fluctuations in the landscape. However, more pronounced variations in elevation are observed along the river valleys, where erosion and sediment deposition create more noticeable changes in the landscape.

This steady variation in elevation, coupled with the favorable soil conditions indicated by a high soil productivity index, makes Juodaičiai eldership an ideal location for agricultural activities. The absence of severe topographic changes, particularly in the central and northern parts of the territory, allows for efficient farming practices, including crop rotation, irrigation, and mechanized farming.

Figure 4

Digital elevation model of the Juodaičiai eldership



Land use changes of Juodaičiai eldership

The use of cartographic sources provides the opportunity to obtain data about the condition of the territory during the mapped period, which has since been irreversibly changed. This is particularly relevant when conducting research on changes, taking as a reference the situation from a century or two ago.

In this case, the topographic maps of the late 19th and 20th centuries offer a unique opportunity to examine the agricultural land use, forest areas, and analyze their changes over time. By scanning the data presented in these maps, layers were obtained that store information about forested areas, urbanized areas, and agricultural land. The table below (Table 2) lists the area occupied by various elements of the territory during the studied periods, in percentages and hectares. Considering the technological advancements and population growth during the 19th and 20th centuries ‘Figure 3’, there was an increased demand for cultivated land and urbanized areas.

Table 2

Areas of territorial elements relative to the total area of Juodaičiai eldership, in hectares and percentages

Territory Elements	***19th Century II half***		***20th Century I half***		***20th Century II half***		***21st Century I half***	
	%	***ha***	***%***	***ha***	***%***	***ha***	***%***	***ha***
Forest	46.2	1464.6	5.1	162.8	17.8	563.7	16.8	533.5
Clearings	1.3	42.2	0	0	0	0	0	0
Urbanized area	2.0	62.7	4.6	145.5	2	63.0	0.3	9.5
Agricultural land	50.5	1600.8	90.3	2862	80.2	2543.6	82.9	2627.4

The research results presented in the second table show significant changes that occurred during the study period, especially at the turn of the 19th to 20th century. One of the main changes was the increase in agricultural land, which rose from 50.5% in the 19th century to as much as 90.3% during the interwar period. These changes were largely related to the reduction of forested areas.

Significant deforestation occurred as early as the mid-19th century, which had long-term effects on the area's ecosystem and land use. At that time, the area of cut forests accounted for 2.8% (42 ha) of the total forested area, which was a substantial loss. During this period, forests were not protected by the strict legal framework that exists today, so they could easily be converted into agricultural land. This opened up opportunities for the expansion of agricultural activity as more land was needed to meet the growing population's demands and ensure food supply.

As a result of these changes, the increase in agricultural land became the main factor leading to the significant reduction of forested areas, especially at the beginning of the 20th century. Furthermore, this also created the conditions for urbanization, as the demand for urbanized areas grew alongside the increase in population and diversification of economic activities. The expansion of urbanization and agriculture during the 19th and 20th centuries often went hand in hand, which could have led to further transformation of the landscape and changes in ecological systems.

These processes were most pronounced during the interwar period, when the share of agricultural land reached record levels, and forests continued to decrease. It can be concluded that this period saw the most intense changes in landscape and land use structure, the effects of which were felt in later periods, including the 20th and early 21st centuries. The sizes of land use changes are presented in Table 3.

The results presented in Table 3 and 'Figure 5' show that agricultural land areas increased the most during the period from the 19th century (second half) to the first half of the 20th century, by as much as 39.8%. The rate of change in these land areas was calculated using the 1 Formula provided in the Methodology. It was determined that the growth rate of agricultural land areas during the 19th century (second half) to the 20th century (first half) was the highest compared to all other periods, reaching 18.55 ha/m. During the same period, the greatest increase in urbanized areas was also observed, at 2.6%.

Table 3

Land use changes in Juodaičiai eldership from the 19th to the 21st century

Territory Elements	***20th Century I half - 19th Century II half***		***20th Century II half - 20th Century I half***		***21st Century I half - 20th Century I half***		***21st Century I half - 19th Century II half***	
	%	***ha***	***%***	***ha***	***%***	***ha***	***%***	***ha***
Forest	-42.4	-1344.6	+12.7	+400.9	-1	-30.2	-29.4	-973.4
Urbanized area	+2.6	+82.8	-2.6	-82.5	-1.7	-53.6	-1.7	-53.3
Agricultural land	+39.8	+1261.3	-10.1	-318.4	+2.7	+83.8	+32.4	+1026.6

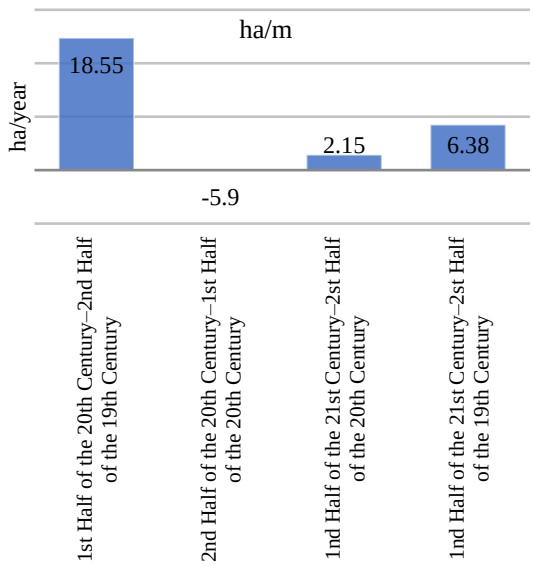
These changes are likely related to the agricultural technology advancements at the end of the 19th century, the rapid population growth 'Figure 3', and significant deforestation during World War I. Additionally, the land reforms following Lithuania's regained independence and the formation of homesteads contributed to this transformation.

After World War II, during the occupation period, there were land seizures, collectivization, and repression. As a result, the population decreased, and the agricultural land area shrank, while forest regeneration processes took place. This led to a 12.7% increase in forest area (compared to the total area of the municipality), and the forested area grew 3.5 times compared to the early 20th century.

From the second half of the 20th century to the first half of the 21st century, forest and agricultural land areas remained relatively stable. Agricultural land slightly increased, and forest areas decreased. The growth rate of agricultural land was 2.15 ha per year. Urbanized areas shrank, which can be linked to population decline, partly due to migration.

Figure 5

Rate of change of agricultural land areas, ha/year



Since the restoration of independence and particularly after joining the EU, environmental regulations have made it more difficult to convert forest land into other land uses. This change is much more complicated than during the 19th and 20th centuries.

However, forest logging still occurs today. The analysis of forest cadastre data shows the current area of deforested land (Table 4).

Table 4

Exploitation of Existing Forests

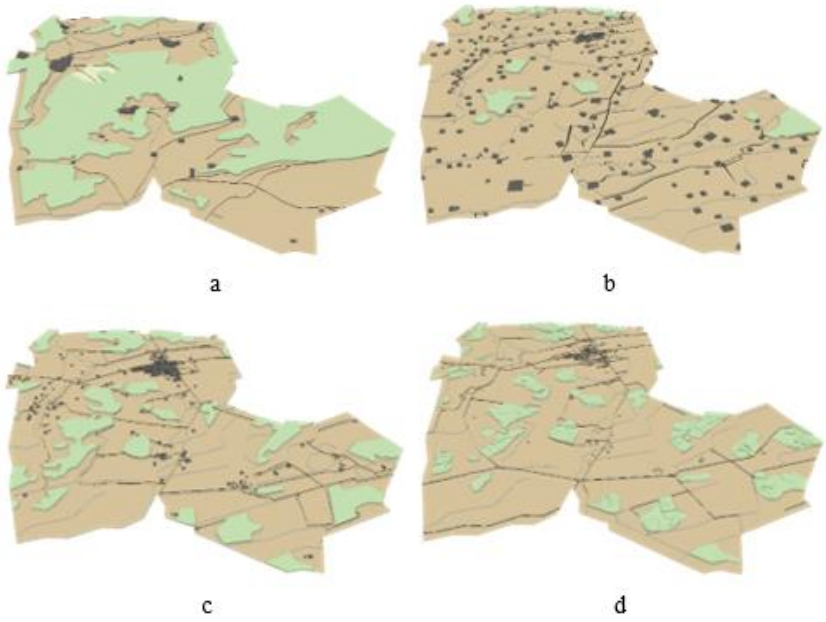
Forest	***Percentage of total forest area***	***Forest area (ha)***
Cutover forest area	23.6	124.7
Uncut forest area	76.4	404.3

Therefore, the forest is still being intensively logged. In the Juodaičiai eldership, about a quarter of the forested area has been cut. If we calculate the rate of forest area decrease from the second half of the 19th century to the first half of the 20th century, it was 19.1 ha per year. Currently, the rate of logging is 93.2 ha per year, which exceeds the logging rates observed during the studied period. It can be assumed that if the forest areas were not protected by legal frameworks, after the logging, they might have been converted into agricultural land, as the area is known for having one of the highest soil productivity rates in the Republic of Lithuania and is highly suitable for agricultural use. Since this eldership is far from major cities, agriculture is likely the only source of income for local residents.

The 3D landscape models of the Juodaičiai eldership, created using ArcGIS software and presented in 'Figure 6', provide the opportunity to visually compare the relationship between built-up areas, forest areas, and agricultural land across the studied periods.

Figure 6

3D models of the landscape change in the Juodaičiai eldership: a) second half of the 19th century, b) first half of the 20th century, c) second half of the 20th century, d) first half of the 21st century



The analysis determined that in the second half of the 19th century, with a smaller population, landscape development was limited. Built-up areas were minimal, and forested areas covered a significant portion of the territory. At this time, the area of land used for agricultural purposes was relatively small. Forests dominated, and urbanization was underdeveloped. This could be linked to the fact that the region was less urbanized and most of the land was designated for natural use.

In the first half of the 20th century, there was a significant growth in urbanization and agricultural development. During this period, the area of residential and agricultural land increased. Due to rapid technological advancements, agricultural activity and the population grew, which stimulated expansion. Forests remained an important landscape element, but began to shrink due to the increasing demand for agricultural land.

In the second half of the 20th century, the landscape essentially reached stability. This landscape remained relatively unchanged until the early 21st century.

In the first half of the 21st century, the balance between forested areas and agricultural land remained similar. Forest protection and legal regulations prevented a faster decrease in forest areas, but agricultural land continued to dominate the landscape. Urbanization, though slightly increased, still had minimal impact on this district. Therefore, during this period, landscape changes were more related to

stabilizing land use and implementing forest protection initiatives.

These 3D models clearly demonstrate how the landscape has changed over the century and the key factors that led to land use changes. Primarily, this is linked to agricultural development and urbanization, but the role of forests and legal regulations in shaping the landscape cannot be overlooked.

To assess potential future land use scenarios for the Juodaičiai eldership, several factors must be considered, including current trends, historical changes, and regulatory frameworks. Based on this analysis, the following scenarios are possible:

1. Continued agricultural expansion, driven by high soil fertility and limited urbanization. In this case, agricultural land is likely to increase, forests may decrease slowly, and urbanization will remain limited.
2. Forest recovery and stabilization, aimed at strengthening forest protection and sustainability initiatives, could allow forests to regenerate, leading to an expansion of forests, a slight decrease in agricultural land, and low urbanization.
3. Urbanization and infrastructure development could accelerate due to improvements in infrastructure and regional development programs, allowing urbanized areas to expand. Agricultural land may decrease, and forest loss will be minimal.
4. Sustainable land use and integrated development, where a balanced approach is maintained, preserving both agriculture and forests through sustainable practices, would stabilize agricultural land, increase forests, and keep urbanization limited.

The most likely future scenario for the Juodaičiai eldership is continued agricultural dominance with moderate forest protection efforts. However, strong regulatory frameworks and sustainable practices could lead to balanced, integrated development. Urbanization will remain limited, but local growth will depend on infrastructure investments, and climate change will influence land-use decisions.

The landscape and land use structure of Juodaičiai Eldership have undergone significant changes from the 19th to the 21st century, primarily due to agricultural expansion driven by fertile soils and population growth. The most intensive transformations occurred in the early 20th century, when agricultural land rapidly expanded at the expense of forests. In recent decades, land use has stabilized, with agriculture remaining dominant, forest areas relatively preserved due to legal protections, and urbanization remaining limited. Current trends and regulatory frameworks suggest a continued dominance of agriculture, accompanied by moderate forest conservation and minimal urban development.

Conclusions

1. Juodaičiai eldership has undergone significant land use changes over time. In the 16th century, it was sparsely populated with abundant forests and little agricultural land. By the 19th and 20th centuries, population growth and agricultural advancements led to widespread deforestation, peaking in the early 20th century when agricultural land rose to 90.3%, up from 50.5% in the 19th century.
2. Juodaičiai eldership stands out with its high soil fertility score of 52.58, one of the highest in Lithuania, which has been pivotal for agricultural growth. This fertile land supports diverse crops and ensures the long-term viability of agricultural activities. Furthermore, the GIS and LIDAR-based surface model revealed a terrain with minimal elevation changes, making it highly suitable for mechanized farming.
3. Geomorphological analysis of the region confirms that Juodaičiai eldership's terrain is favorable for agriculture. The relatively flat to gently rolling landscape, with only minor variations in elevation (a 22-meter difference from south to north), makes it an ideal location for modern agricultural practices, supporting both crop rotation and mechanized farming systems.
4. Land use underwent significant changes from the late 19th to the early 20th century, marked by a 42.4% reduction in forested areas (1,344.6 ha) and a 39.8% increase in agricultural land (1,261.3 ha). Following World War II, deforestation slowed due to land reforms and legal protections although agriculture continued to dominate. By the early 21st century, agricultural land stabilized at 82.9%, with forests experiencing moderate recovery.
5. The region saw limited urbanization, with urban areas remaining small in comparison to agricultural land. The greatest urban growth occurred during the early 20th century, but due to population decline in recent decades, urbanization has remained minimal. Despite this, infrastructure improvements may lead to some growth in urbanized areas in the future.
6. Forest management continues to be a critical issue in Juodaičiai eldership, where intense logging activities persist. However, forest protection laws enacted after independence have contributed to a reduction in the rate of deforestation. In the absence of these regulations, much of the forested area could have been converted into agricultural land, given the region's fertile soils. As of now, 23.6% of the forested area has been logged, with 76.4% remaining intact.
7. The most likely future scenario for Juodaičiai eldership is continued agricultural dominance, supported by moderate forest protection efforts. With strong legal frameworks and sustainable practices, the region will likely experience a balanced development, where agriculture remains dominant, urbanization is limited, and forest conservation continues to play a significant role.
8. Practical recommendations for future land use in Juodaičiai include strengthening forest protection regulations and promoting sustainable agricultural practices. In particular, efforts should be prioritized to slow the conversion of forested land to agricultural use, especially given the high fertility of the soil, which could otherwise lead to further agricultural expansion at the expense of forests.

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SUSTAINABLE URBAN PLANNING MODELS TO INTEGRATE RURAL ECONOMIES IN UKRAINE DURING MARTIAL LAW

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Abstract
Sustainable urban planning to integrate rural economies in Ukraine during martial law presents unique challenges due to disrupted infrastructure, population displacement, and resource constraints. In such circumstances, there is a need to form economic resilience in urban-rural systems through optimisation of resource allocation models for agricultural production and distribution, reintegration of urban-rural populations and redistribution of labour, use of decentralised governance between urban and rural areas, digital integrated governance. The aim of the study is to explore and apply sustainable urban planning for ensure resilience, adaptability and maintaining rural economic activity to support both urban and rural populations during martial law. The study is based on the analysis of agricultural production, supply chain security and urban market access; the investigation into the impact of martial law on rural productivity and urban market demand; and the examination of the employment of displaced urban and rural populations in economic activities, including agriculture and resource processing. The paper identifies the role of decentralised administrations in maintaining essential functions between urban and rural areas, assesses the system of rural resource management in Ukraine during martial law, and examines the level of integration of digital systems to maintain governance continuity in rural areas. The research results suggest the creation of a national urban-rural resilience framework focusing on integration rural economies with urban centers in Ukraine during martial law. In terms of long-term development goals, directions for further integration of the urban-rural economy are proposed through the creation of innovation hubs that integrate agriculture, technology, and renewable energy sources.
Keywords: urban areas, rural areas, populations, decentralised governance, innovation hubs.

Introduction

Ukraine's agricultural sector plays a vital role in national and global food markets. The integration of rural economies into sustainable urban planning has never been more critical for Ukraine, particularly under the constraints of martial law. Russia's military aggression in Ukraine created unprecedented challenges for both urban and rural areas, disrupting economic activities, displacing populations, and straining infrastructure. In this context, sustainable urban planning models that integrate rural economies are not only essential for recovery but also for building resilience and ensuring long-term development. Martial law has further emphasized the need for innovative approaches that bridge the gap between urban and rural regions, fostering economic interdependence, resource optimization, and social cohesion.

Sustainable urban planning models aim to create synergies between cities and rural areas, ensuring that both benefit from shared resources, infrastructure, and economic opportunities. These models are particularly relevant in Ukraine, where rural areas play a critical role in agriculture, energy production, and natural resource management, while urban centers serve as hubs for innovation, governance, and services. By integrating rural economies into urban planning frameworks, Ukraine can address key challenges such as food security, energy independence, and equitable development, even in the face of wartime disruptions.

This approach involves leveraging digital technologies, decentralized governance, and green infrastructure to create a cohesive system that supports both urban and rural populations. For instance, digital platforms can facilitate supply chain management for agricultural products, while decentralized energy systems can provide reliable power to remote areas. Additionally, sustainable urban planning can promote the development of rural-urban clusters, where cities and surrounding villages collaborate on economic projects, infrastructure development, and social services.

During martial law, the integration of rural economies into urban planning becomes even more critical. Rural areas often serve as safe havens for displaced populations, requiring enhanced infrastructure and services to accommodate increased demand. At the same time, urban centers must adapt to support rural economies by providing access to markets, technology, and financial resources. By adopting sustainable urban planning models, Ukraine can ensure that both urban and rural regions contribute to and benefit from the nation's recovery and growth.

The scientific literature contains studies on sustainable urban planning models to integrate rural economies. The integration aspects of urban and rural areas are considered in the context of social development, using the methodological tools of dynamic series to study the impact on integration from the point of view of the flow of rural population and the city's steam-power structure, temporal and spatial differences, and government intervention development (Xu et al., 2019). It is proposed to apply an innovative approach to stimulate rural development and spatial structure by providing urban services for its residents and residents of neighbouring villages to overcome rural problems at the social, economic and environmental levels (Allawi & Al-Jazaeri, 2023). The 'life quality theory' is used to study the interaction between the space of rural settlements and the quality of life of their

inhabitants; optimisation of the spatial organisation of rural settlements should be achieved through support for rural livelihoods and concentration of agricultural and industrial spaces, distribution of various types of resources and infrastructure development (Tang et al., 2018). In the context of sustainable development of territories, the authors propose mechanisms for bridging the gap between urban and rural areas using a regression model and indicators of rural demography and urbanization (Wei et al., 2021). The authors propose a model of sustainable urban-rural cooperation for poverty alleviation in rural areas based on the analysis of benefits and costs, especially for the environment through the growth of industrial production (Ji et al., 2019). The authors investigate landscape models, their consequences and sustainability on the impact of urban-rural integration, taking into account socio-economic and environmental indicators and innovations (He et al., 2024).

A review of the scientific literature has shown that there is a substantial body of research in the field of urban-rural integration for spatial planning and ensure sustainable development. However, there are no studies of these aspects in wartime conditions, and further generalisation of existing approaches is needed, taking into account the limited functioning of agricultural entities in rural areas, ensuring spatial planning and inclusion of rural-urban associations.

Materials and Methods

The methodological basis of the study is a monographic review and identification of factors that influence the integration of urban and rural areas in Ukraine, as well as social, economic, environmental and spatial processes that occur there during the period of martial law. The sources of information are the statistical data of the State Statistics Service of Ukraine on the agricultural sector. The results of the implementation of decentralisation and community development reforms in Ukraine were used to study practical cases of successful use of decentralised governance and digital integrated governance between urban and rural areas by territorial communities of Ukraine. A sequence structure is used to build an algorithm for the formation of sustainable urban planning models to integrate rural economies in Ukraine during martial law.

Results and Discussion

The ongoing war in Ukraine since 2022 has had a significant impact on the production, processing and distribution of agricultural products, causing physical destruction, logistical difficulties and changes in agricultural policy.

According to the State Statistics Service of Ukraine, in 2022, agricultural production decreased by 25% compared to 2021. In particular, production at agricultural enterprises decreased by 28% and at private farms by 18.6%. In crop production, the decline was 28%, and in livestock production – 12%. In 2023, production recovered. Agrarians harvested 79.2 million tonnes of products, including 58.4 million tonnes of grains and pulses and 20.8 million tonnes of oilseeds. Sugar beet production increased by 29% compared to 2022 (SSCU, 2024).

Changes in volumes of agricultural production were caused by the occupation of part of Ukraine's territories and the loss of agricultural land; problems with the supply of fertilisers, fuel and seeds, which led to a decrease in yields; and a reduction in the workforce due to mobilisation and migration. The distribution of agricultural products in Ukraine was affected by logistical challenges – the blockade of seaports in 2022-2023 made export more difficult, and disruption of domestic transport routes and infrastructure.

It is also worth noting that the hostilities have led to large-scale internal displacement and external migration, which has significantly affected the ratio of urban to rural population in Ukraine. In 2024, the share of the rural population in the total structure was 21%, and in 2022 – 30% (SSCU, 2024).

We have studied the main models of agricultural production and distribution used by actors during martial law in Ukraine (Table 1). The studied and identified models are based on the mechanisms of adaptation of agricultural producers to wartime conditions, introduction of innovations in production and distribution, state and international support.

As a result of the hostilities and the losses incurred by agricultural producers, the problem of ensuring the security of agricultural supply chains and access to urban markets has arisen.

To this end, a number of activities were organised by stakeholders, including the development of alternative logistics routes (increasing the use of road and rail), strengthening local agri-food systems (development of productive small and medium-sized farming, processing and development of regional agro-industrial clusters). This, in turn, has strengthened the capacity of local agri-food systems, made them less vulnerable and ensured that agricultural raw materials (for processing companies) and products (for urban and rural populations) are supplied.

The hostilities in Ukraine have caused significant changes in the demographic situation and the labour market, affecting the reintegration of urban and rural populations and the redistribution of labour.

As a result of the hostilities, many territorial communities in Ukraine are under occupation or in the area of active hostilities, which has led to the displacement of people both within and outside the country. In this regard, Ukraine has created a digital platform (Clarity Hromada) to track the current status of territorial communities, which helps to coordinate efforts to reintegrate the population.

Table 1
Models of agricultural production and distribution used by entities during martial law in Ukraine

Models	***Characteristics***
Diversification of production and processing	Development of agricultural raw materials processing at the local level (urban and rural areas) in relatively safe areas.
Implementation of innovations and technological solutions in production	Active use of innovative technologies, such as precision farming, drones for crop monitoring and optimisation of fertiliser and pesticide use.
Support for small farmers	Introduce a state programme of financial assistance to farmers to ensure sustainable agricultural production in the frontline regions of Ukraine and facilitate access to markets.
Alternative transport routes and sales logistics	Developing transport infrastructure, including railways and roads, to ensure uninterrupted supply of agricultural products to domestic and foreign markets.
Cooperation with international partners in the production and marketing of agricultural products	Implementation of support programmes for the agricultural sector, including financial assistance, tax breaks and grants for infrastructure development, humanitarian and technical assistance to stabilise agricultural production and ensure food security.

Source: authors' research.

In addition, the government is implementing a policy in the de-occupied territories aimed at restoring state authority and reintegration, including the restoration of social and economic infrastructure, and ensuring security and justice in urban and rural areas. In the regions of Ukraine most affected by the military aggression, the number of jobs has decreased and competition for available vacancies has increased. This resulted in an imbalance between labour supply and demand, as many enterprises were forced to reduce production, especially in rural areas. The burden on the rural population, in particular on the cultivation of raw materials and food production, increased.

There is a shortage of labour due to the mobilisation of men, women, children and the elderly often work in agriculture, and the level of mechanisation is declining due to the lack of fuel or spare parts, forcing a return to manual labour. Unemployment tends to increase in urban areas due to the closure of enterprises, while in rural areas there is a shortage of labour. Women often take on roles previously held by men, leading to changes in the social structure of the population in both urban and rural areas. Rural people often migrate to cities in search of work or security, which can lead to urban overcrowding.

The martial law in Ukraine has had a significant impact on agricultural productivity and urban market demand. The main reasons are a reduction in planted areas and changes in production technologies that lead to lower yields. The total harvest of grains and oilseeds decreased from 107 million tonnes in 2021 to a projected 77 million tonnes in 2024 (SSCU, 2024). In addition, export restrictions, declining agricultural production and supply chain disruptions have led to shortages of certain foods in urban areas. This, in turn, led to an increase in food prices, which affected the purchasing power of the urban population. At the same time, urban markets have faced the need to adapt to the new conditions by seeking alternative sources of supply and implementing new logistics solutions to ensure food security. In western Ukraine, this problem was partially solved by importing agricultural products, concentrating production and developing wholesale trade. This process was actively promoted by local governments and the international community, which provided financial support to farmers, developed internal logistics and implemented programmes to encourage local production.

The economic sustainability of urban and rural systems in Ukraine during martial law is achieved through the financial autonomy of territorial communities. This involves, in particular, reducing the dependence of local budgets on state subventions and grants by increasing the share of own revenues, seeking additional sources of funding (such us grants and donations), and adapting the budget process to ensure the continuous execution of local budgets and prompt response to the needs of urban and rural communities.

During martial law, territorial communities used forms of decentralised governance and digital integrated governance between urban and rural areas to ensure resilience and territorial development. Under decentralised governance, local authorities have a better understanding of the needs of their communities and can respond more quickly to challenges, optimise the use of budget funds by directing them to the most important projects, and stimulate rural development through the transfer of powers to the local level to promote infrastructure, education, healthcare and other areas in rural areas. Digital technologies play a key role in ensuring effective management of urban and rural areas. They allow for data integration, process optimisation and transparency in decision-making. Digital integrated governance between urban and rural areas ensures effective coordination of resource allocation in times of war, allows for real-time analysis

of the state of infrastructure, resources and needs of the territories, provides transparency in the use of budget funds and decision-making, and helps decision-makers make informed decisions. During martial law, urban and rural communities in Ukraine use existing and create new digital platforms to manage production resources, monitor infrastructure and communicate between communities, use the IoT to monitor the condition of roads, energy systems, water supply, etc., and use electronic services for citizens to provide access to public services, which is especially important for remote rural areas.

The above-mentioned aspects have led to increased integration of urban and rural areas in Ukraine during martial law. This has found practical expression in several key areas:

- the development of transport infrastructure: This includes – improving the road network between cities and villages to ensure the mobility of people and food.
- Creation of economic clusters: This involves – uniting urban and rural enterprises for joint production and sales of agricultural products.
- Development of social infrastructure: – This means ensuring equal access to education, healthcare and other services for urban and rural populations.
- Support for small and medium-sized businesses: – This entails creating conditions for the development of farms in rural areas, which helped reduce migration to cities.

We have summarized examples of successful use of decentralized governance and digital integrated governance between urban and rural areas by territorial communities of Ukraine, which significantly contributes to the effective creation of sustainable urban planning models to integrate rural economies in Ukraine during martial law (Table 2). Also it identified directions for urban-rural integration and the implementation of innovative projects by territorial communities of Ukraine (Table 3).

The tables shows that decentralized administrations play a key role in preserving the basic functions between urban and rural areas. They ensure effective resource management, infrastructure, social services, environmental and economic development, which contributes to the balanced development of both types of territories.

Table 2

Cases of successful use of decentralised governance and digital integrated governance between urban and rural areas by territorial communities of Ukraine

Direction of implementation	***Case description***
Decentralized governance	The Berehove territorial community (Zakarpattia region) united the city of Berehove and the surrounding villages. Due to decentralization, the community has received funds for infrastructure development: roads have been repaired, new schools and medical facilities have been established. It actively attracts international assistance to implement projects such as restoring the street network and developing tourism.
	The Pokrovsk territorial community (Dnipropetrovsk region) united the city of Pokrovsk and rural settlements. The community focused on developing social infrastructure: new kindergartens were built and administrative service centers were opened. Funds were raised from international donors to implement energy efficiency projects.
	Zolochiv territorial community (Lviv region): united the city of Zolochiv and surrounding villages. The community is actively developing tourism infrastructure, restoring historical monuments and creating new routes for tourists. Transparent budget management mechanisms have been introduced, allowing citizens to control expenditures.
Digital integrated governance	The Diia platform is a national platform that provides electronic services for citizens, including the rural population. Through Diia, you can get a driver's license, register a business, apply for social benefits, and more. This greatly simplifies access to public services for residents of remote villages.
	The Electronic Construction Cadastre system allows for online construction permits, which simplifies the process for local communities and businesses. It is especially useful for rural areas where obtaining permits used to be difficult.
	Digital platforms for farmers – platforms such as AgriChain, Kernel, AgriEye help farmers manage supply chains, analyze market prices, and obtain financing. This allows agriculture to operate more efficiently and integrate into the national and international economy.
	Electronic auctions for local budgets – many territorial communities use electronic systems to conduct tenders for the purchase of goods and services. This ensures transparency and reduces corruption risks.

Source: summarised by authors based on Decentralization, 2024.

Table 3
Cases of successful urban-rural integration and the implementation of innovative projects by territorial communities of Ukraine

Direction of implementation	***Case description***
Integration of urban and rural areas	Development of transport infrastructure – in many regions, new public transport routes have been created to connect cities and villages. For example, in Lviv region, a Smart Bus system has been introduced that allows rural residents to easily get to the city.
	Creation of economic clusters – in Kharkiv region, urban enterprises cooperate with rural farmers to produce and sell products. This helps to ensure a stable income for the farmers.
	Development of tourism clusters – in the Carpathian region, urban tourism operators are working with rural communities to create eco-trails and develop rural tourism.
Innovation projects	Smart Villages – a smart village project was implemented in the village of Stari Petlivtsi (Kyiv region), which includes solar power plants, energy-efficient lighting, and a water quality monitoring system.
	Digital education hubs – many rural schools have created digital classrooms where students can receive education through online platforms such as All-Ukrainian School Online.
	Electronic healthcare services – telemedicine consultations are being introduced in rural communities, allowing residents to receive qualified care without having to travel to the city.

Source: summarised by authors based on Decentralization, 2024.

Taking into account the above-mentioned aspects of the state of the resource potential and the volume of activities of agricultural enterprises, models of production and distribution of agricultural products, demographic changes in the labor market and migration processes, mechanisms of interaction and integration of urban and rural territorial communities, development of decentralized governance and digital integrated governance aimed at economic sustainability, social equality and environmental sustainability, we propose an algorithm for the formation of sustainable urban planning models to integrate rural economies in Ukraine during martial law (Table 4).

The algorithm for applying sustainable urban planning to ensure resilience, adaptability and support for rural economic activity during martial law includes a number of steps aimed at integrating urban and rural areas, optimizing resources and ensuring sustainable and inclusive territorial development.

Taking into account the current military situation in Ukraine, we propose specific directions for the further integration of urban and rural economies. Our approach is based on the algorithm for the forming sustainable urban planning models, designed to integrate the rural economy. This involves creating innovation hubs that combine agriculture, technology and renewable energy sources. Such hubs will ensure the sustainability of agri-food systems and food security, increase the overall integration, and foster the sustainable and inclusive development of these territories. In view of the creation of innovation hubs, it is proposed to actively introduce technical-technological solutions for agriculture, such as precision farming, IoT for monitoring soil and crop conditions, drones for field processing; create technology transfer centers where farmers can access the latest developments and learn how to use them. It is recommended to develop digital platforms for data exchange, market price analysis, supply chain management and financing, and provide access to electronic markets for product sales. An important structural unit of the innovation hub should be an energy department for the development of renewable energy sources, including the creation of solar, wind and biogas power plants in rural areas. This will ensure energy independence and reduce greenhouse gas emissions by focusing on sever key areas: the introduction of microgeneration for individual farms and rural communities: the development of energy saving projects for agricultural enterprises and residential buildings, and the use of energy efficient technologies in the production and processing of agricultural products.

Training centers and research laboratories should function effectively at the innovation hub. Training centers should organize training programs for farmers, entrepreneurs and youth on the use of innovative technologies in agriculture and energy, cooperate with universities and research institutions to conduct research, and develop new technologies for restoring damaged soil, infrastructure, etc. The activities of research laboratories should be aimed at testing new plant varieties, soil cultivation methods and energy solutions; developing environmentally friendly technologies for agriculture and energy; introducing waste sorting and recycling systems in rural areas; using organic waste for biogas and organic fertilizers; developing projects for soil restoration, forest and water protection; and implementing environmental standards for agriculture.

Table 4

Algorithm for the formation of sustainable urban planning models to integrate rural economies in Ukraine during martial law

Stage 1. Analysis of the current state			
assessment of infrastructure: a study of the state of transport networks, energy systems, water supply and other key infrastructure elements	assessment of economic potential: analysis of the agricultural, industrial and tourism potential of rural areas	social analysis: assessment of population needs, including education, health and social protection	environmental assessment: identifying environmental issues and resources for sustainable development
Stage 2. Developing an integration model			
setting goals: set specific goals for urban-rural integration, such as increased economic activity, improved infrastructure and social equity		create an action plan: developing a detailed plan that includes implementation steps, resources and responsible parties	
Stage 3. Implementation of digital technologies			
digital platforms: creating platforms for resource management, infrastructure monitoring and e-services	telemedicine and distance education: ensuring access to medical consultations and educational programmes for the rural population		electronic markets: development of platforms for the sale of agricultural products and other goods
Stage 4. Infrastructure development			
transport infrastructure: improving the road network, building bridges and organising public transport	energy infrastructure: introduction of renewable energy sources such as solar panels and biogas plants		water supply and sewerage: building water supply and wastewater treatment systems
Stage 5. Supporting economic development			
support for small and medium-sized businesses: provision of grants, consultations and preferential terms for entrepreneurs in rural areas		development of the agricultural sector: providing farmers with machinery, seeds and access to markets	tourism: development of rural tourism, creation of tourism clusters that unite urban and rural areas
Stage 6. Social development			
education: establishing hub schools in rural areas where children receive quality education and introducing distance learning	healthcare: opening outpatient clinics, primary healthcare centres and introducing telemedicine for rural residents		social protection: providing assistance to vulnerable groups, including pensioners, the disabled and large families
Stage 7. Environmental sustainability			
waste management: establishing waste sorting and recycling systems that reduce the burden on the environment	conservation of natural resources: protecting forests, rivers and soils through the implementation of environmental standards		energy efficiency: implementation of energy saving projects in communities, such as insulation of schools, hospitals and other public buildings
Stage 8. Crisis management			
evacuation and resettlement: organising the movement of people from war zones to safe regions	humanitarian aid: providing the population with food, medicine and other essentials		restoration of infrastructure: repair of destroyed facilities such as schools, hospitals and residential buildings
Stage 9. Monitoring and evaluation			
permanent monitoring: continuous collection of data on infrastructure, economic activity and social indicators		performance evaluation: analysing the results of plan implementation and making necessary adjustments	
Stage 10. Public engagement and international support			
public initiatives: involving local communities in project planning and implementation		international support: attracting financial and technical assistance from international organisations	

Source: authors' proposal.

The development of the infrastructure component of the innovation hub should help improve the road network between cities and villages to ensure fast transportation of agricultural products; develop logistics centers for storage and distribution of agricultural products; ensure stable Internet connection in rural areas for the use of digital technologies; and create data centers for resource analysis and management.

Conclusions

1. The integration of rural economies into sustainable urban planning models is not only a strategic necessity for Ukraine during martial law but also a pathway to long-term resilience, economic stability, and social cohesion. The challenges posed by the ongoing war have underscored the importance of creating interconnected systems that leverage the strengths of both urban and rural areas. Sustainable urban planning models offer a framework for achieving this integration, ensuring that rural economies are supported, urban centers are strengthened, and the nation as a whole moves toward recovery and growth.
2. Despite the destruction of agricultural land, equipment and facilities, and environmental hazards, the agricultural sector in Ukraine demonstrated extraordinary resilience during martial law. Agricultural enterprises in Ukraine adapted to modern challenges, accumulated their own efforts and resource potential, and introduced innovations. The stability of agriculture in Ukraine has received continuous support from the government, international partners, and the private sector.
3. The martial law disrupted the structure of agricultural production and the supply chain of agricultural products and their access to urban markets. Agricultural enterprises used diversification of logistics routes and mechanisms to strengthen local food systems through the integration of urban and rural producers. Identifies and characterizes the models of production and distribution of agricultural products used by entities during martial law in Ukraine. The structure of urban and rural population in the regions of Ukraine has been disrupted. Due to internal and external migration processes, the number of residents in cities and villages has changed. Demand for labor in villages has increased as the number of men leaving the workforce due to mobilization has decreased. Women, young people, and the elderly began to perform most agricultural work.
4. Decentralized governance and digital integrated governance are key tools for ensuring the balanced development of urban and rural areas. In the context of martial law, these approaches allow for the efficient use of resources, transparency of governance, and improvement of the quality of life of urban and rural populations, as well as sustainable and inclusive development of urban and rural areas. Successful cases of decentralized governance and digital integrated governance between urban and rural territorial communities of Ukraine are considered.
5. The development of sustainable urban planning models to integrate rural economies in Ukraine during martial law is a necessary step to ensure economic resilience, social equality, and environmental sustainability. These models allow to optimize the use of resources, provide access to services for citizens of urban and rural areas. The proposed algorithm for applying sustainable urban planning to ensure resilience, adaptability and support for rural economic activity during martial law includes a comprehensive approach that includes analysis of the current situation, model development, introduction of digital technologies, infrastructure development, support for economic and social development, environmental sustainability, crisis management, monitoring and evaluation, as well as public engagement and international support. This approach allows for sustainable and inclusive development of both urban and rural areas in Ukraine, promoting their integration and enhancing resilience during martial law.
6. The creation of innovation hubs that integrate agriculture, technology, science and research, renewable energy, and infrastructure are key areas for further integration of the urban and rural economies in Ukraine. Such hubs will contribute to economic development, increase resource efficiency, and ensure sustainable and inclusive development. Successful implementation of these areas requires support from the government, international partners and active participation of territorial communities.

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THE 'GO-ALONG' INTERVIEWS FOR ASSESSMENT OF USERS' ATTITUDES TOWARD URBAN FOREST MANAGEMENT

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Abstract
Different stakeholders in urban forests have different interests, which are best captured through 'go-along' interviews. The aim of the research was to identify residents' views on the use of urban forests to ensure the delivery of social functions and to improve urban forest management practices. The 'go-along' interview method is a variation of qualitative interviewing used alone or in combination with other methods to explore and then improve understanding of people's experiences, in which people move when carrying out their activities or practices. The study looked at 4 urban forest areas in Latvia: the nature parks Ogres Zilie kalni, Bernāti, Ragakāpa and Langervalde forest. A total of 26 'go-along' interviews were conducted, where the principle of the researcher being guided by the interviewer was observed within the method used. The routes taken during the interviews were recorded in the *ArcGIS* application *QuickCapture*, in addition to taking photographs of places of interest and recording on a dictaphone the interviewee's perspective on the use of the particular urban forest in daily life, views on management and other insights. The planning and management process needs to consider and balance user preferences, national and local regulations, owner/manager commitments, opportunities and expert knowledge. Areas of varying levels of landscaping and maintenance should be created, so that visitors can choose the appropriate landscaping and intensity of visitation. People who choose to visit the forest have very positive feelings, which contribute not only to physical health, but also to a positive psycho-emotional state and relaxation.
Keywords: urban forest management, cultural ecosystem services, go-along, walk-along, landscape preference.

Introduction

When studying urban forests in Latvia, the authors were already familiar with the different interests of different stakeholders involved in urban forest processes in the Ogre Zilie Kalni and Bernāti Nature Parks - regulatory, management and user stakeholders (Kraukle et al., 2024). Visitor/user interests, evaluations and perceptions of urban forest processes and amenities can be very diverse, as was already evident in the authors' surveys of Latvian urban forest experts in 2024. Participatory interviews were used to find out the views of users. The aim of the research was to analyse the habits and attitudes of the public on the use of urban forests to maintain cultural ecosystem services, assure the realization of social functions, develop and improve urban forest planning, management practices. The go-along method is a practical way for citizens and urban planners to exchange ideas on how to make urban forests more accessible for walking (Miaux et al., 2010), all types of recreation, sports and other socially relevant activities.

Research and practice should take an integrated human-natural systems approach; urban forest planning and design should take into account not only scientific research and local knowledge, but also the interests and priorities of local people (Beckley et al., 2006; Janse & Konijnendijk, 2007; Stokmane, 2022; Wolf & Kruger, 2010). Understanding the green identity of a particular place can help to design urban forests that better meet the needs of the local community (Carpiano, 2009). Local residents, long-term and regular visitors can provide insights into specific local knowledge, local aesthetic and cultural preferences, social systems and attitudes to inform researchers and planners about appropriate design solutions (Barron et al., 2021). In line with these needs, go-along interviewing is a type of qualitative interviewing technique that is highly useful (alone or in combination with other methods) for exploring and subsequently improving understanding of people's experiences, relational perspectives on place and space, and the wider local area in which people move as part of their activities or practices (Carpiano, 2009; Cummins et al., 2007).

Materials and Methods

The go-along interview method is a type of in-depth qualitative interview conducted by researchers who accompany individual informants in a familiar setting, such as their immediate neighbourhood or a larger local area. 'Go-along' can be conducted as a 'walk' (i.e. while walking with the participant), a 'drive' (i.e. while driving) or a 'mixed' form that combines the two previous types (Kusenbach, 2003). The way in which this commuting takes place can vary depending on the context and size of the neighbourhood, but essentially all commuting involves an interview with the participant while getting to know their neighbourhood or other local context. In this sense, the researcher 'walks through' people's lived experience of their neighbourhood. As a method, therefore, 'walking through' offers the researcher a unique opportunity not only to observe people's surroundings, but also to study their perception, processing and navigation of the environment (Carpiano, 2009).

The study covered 4 urban forest areas in Latvia: the nature parks 'Ogres Zilie kalni' (between Ogre and Ikšķile), 'Bernāti' (near Liepāja), 'Ragakāpa' (in Jūrmala) and Langervaldes forest (in Jelgava). A total of 26 go-along interviews were conducted between 3 March 2022 and 25 January 2025.The method used followed the principle of the researcher being guided by the interviewer (see Table 1).

Table 1
Study areas and number of surveys

Urban forest study areas	***Nature park Ogres Zilie kalni***	***Nature park Bernāti***	***Langervalde Forest***	***Nature park Raga kāpa***	***Total***
Number of go-along surveys	10	6	5	5	26
% Number of go-along surveys	39%	23%	19%	19%	100%

The routes followed during the interviews were recorded in *ArcGIS QuickCapture.* Additionally, photographs were taken at key locations and the conversations were recorded using a dictaphone. These conversations were later transcribed, and the themes that emerged were organized into tables for further analysis and the development of conclusions. In this study, the interviewer was asked to follow a routine route in the area to describe feelings, perspectives on the use and management of the urban forest in question. Photographs were taken in places that were highlighted in the interview.

In practice, different terms are used to describe walk/go-along interviews (Bartlett et al., 2023) in qualitative research. There are numerous 'go-alongs or go-along interview' (Bell & Bush, 2021; Duedahl & Stilling Blichfeldt, 2020; Garcia et al., 2012) 'walking interview' (Lynch & Mannion, 2016), even 'wheeling with a wheelchair' (Parent, 2016). The variety of terms used shows that the method is widely and diversely used to describe walking/interviewing and can be used by researchers in different fields. In our case, depending on the specific area and the interviewee's habits, 'going along', 'driving and going along' (6), 'walking with the family' (5), 'walk along with your dog' (6) were actually used. Several of the interviewees (3) cycle in the area on a daily basis, but in order to be able to conduct and record the interview, it was conducted on foot.

In areas where one does not know many personal acquaintances, it can be challenging to find people willing to participate in interviews. People must be willing to share their personal experience and devote a significant amount of time ranging from approximately 40 minutes to 2.5 hours in our case. Most of the people who responded to the invitation to participate in the interviews were socially active people whom we approached through a contact person they knew personally. When approached, they were asked to show and tell us about their habits and ways of using the particular area of the forest, things they liked and disliked about the area.

Results and Discussion

A wide range of information was obtained in the interviews. In this study, the main focus is on the use of urban forests for recreation in order to improve their social function in planning and implementing urban forest management.

Based on the results of the study, we can agree with Kusenbach (Kusenbach, 2003) who identifies five themes that the 'go-along' method is well suited to explore and illuminate: [1] perceptions (i.e., informants' knowledge and values that shape their experience of the everyday social and physical environment); [2] spatial practices (i.e, the spatial ways in which people engage with their environment); [3] the link between biography and place; [4] the social architecture of the natural environment (i.e., different types or forms of human relationships and how informants position themselves in this social environment); and [5] social domains (i.e., patterns of interaction and how place shapes the nature of interactions). The following text in [square brackets] links to the relevant topics. The analysis of the data emerged a certain structure and correspondence with the urban forest functions previously proposed by the authors (Kraukle, 2013; Kraukle et al., 2022), extracted on the basis of the most relevant urban cultural ecosystem services (see Table 2). Cultural or non-material ecological services (Millennium Ecosystem Assessment, 2005) are important for people, providing socialisation and creativity, which in urban areas takes the form of various forms of recreation in natural environments to improve physical and psycho-emotional health, enjoying attractive landscapes and being inspired.

The psycho-emotional aspect of visitors - personal experiences [1], emotions [2], attitudes [4], aesthetic feelings - from the appreciation of landscapes, plants, landscaping [4] to vivid memories of visiting the forest in childhood and youth [3] - emerged as an important aspect in all the interviews. An important aspect of the stories is the emphasis on sensations [1] - beautiful sights in the landscape and small mosses or spider webs, the smell of May flowers (*Convallaria majalis*), the scent of chervil (*Ledum palustre*), blueberries, lingonberries (*Vaccinium myrtillus, Vaccinium vitis-idaea)*, the taste of nuts (*Corylus avellana)*, the special texture of sand on the beach or the cover of dead needles on the path, the taste of melting snow, the wind on the beach and the breeze in the forest. The different interests [4, 5] of the respondents in using the area, from quiet relaxation to intensive sport and competition, are also significant. Historical traces in the forest area are also of interest to people - hill forts, military heritage from the World War I and II, the Soviet era, cultural traces of resorts, entertainment facilities, sports infrastructure, industrial infrastructure heritage. Many mentioned the impact of Covid 19, with a huge influx of visitors to the nature parks, for which 'the municipality and the local population were not prepared [5]. People also draw attention to climate change, which they see in urban forests in the form of stronger storms, rainfall contributing to soil and

coastal erosion, trees uprooted by storms and damaged by insects and disease. Of particular note were the individual interviews conducted with people who typically lead tours in the areas, which tended to be longer and packed with information about the history and natural values of the area [4, 5]. There were significant differences in the interviewees' understanding of natural processes, natural values, conservation methods and opportunities [1, 4, 5].

Table 2

Urban forest features in Go-along interviews [1, 2, 3, 4, 5]

Urban forest functions	***Survey responses***	***Study areas***					***Comments from respondents***
		Zilie kalni	***Bernāti***	***Langervalde***	***Raga kāpa***	***Total***	
		Surveys mentioning the issue %					
Social	landscaping elements	35	23	15	12	85	different views on the need for landscaping
	trails, tracks	35	23	11	19	88	differing views on the need for amenities, with a strong aversion to boardwalks, which are very slippery and difficult to cross in wet weather
	history	32	19	19	15	85	historical facts are mentioned by the majority of respondents
Environmental	plants	19	19	19	16	73	specific plants are often mentioned
	invasive plants	8	0	11	4	23	an awareness of invasive plants, which are not very common in Bernāti, but very common in the Langervalde
Environmental education		4	8	0	0	12	environmental education not mentioned directly by any of the respondents, but 3 of them lead excursions in which they talk about environmental issues
Environmental protection	habitats	16	12	15	15	58	contradictory, sharply contrasting assessments
	positive attitude	11	11	8	8	38	positive attitudes among respondents involved in the environment or forest sector
	negative	7	4	8	8	27	lack of understanding of nature protection issues, considering dry trees to be ʿa mess in the forestʾ, not in favour of weeding invasive undergrowth species
Aesthetic	landscape attractive-ness	19	12	15	12	58	attractive, changing landscapes, beautiful plants; mainly attractive landscapes are landscapes that are well-tended, transparent, in 2 cases wild landscapes are more beautiful
Economic	income generation	0	8	4	0	12	berry picking for sale, floristry materials for work, forest thinning
Psycho emotional	emotions	39	23	19	19	100	all participants express their emotions
	positive	39	23	19	19	100	like the forest, silence, peace, landscapes
	negative	9	15	7	7	38	unmaintained forest, undergrowth, toilet malfunctioning, cyclists damaging the forest

There is a clear need to further explain environmental processes to the public, as well as the importance of deliberate, planned management an issue examined from an expert perspective in the authors` study on the experience of urban forest management in Latvia.

Urban forests are most often visited by people who live nearby or can reach the area within 15-20 minutes (Jang et al., 2022; Mcgrath et al., 2024; Moreno et al., 2021), which is the case in our study [2]. Most visitors live close to the forest (38%) or travel up to 5 km (46%), with only 15% of respondents travelling around 30 km, i.e. less than 30 minutes. Several of the visitors note that they are willing to travel further to visit particularly scenic or interesting places. The surveys show that visitors from Riga and other nearby cities go to the Ogres Zilie kalni, from Liepāja, Grobiņa and Rucava to Bernāti, from Jelgava to Langervalde Forest and, if they have more time, to Ķemeri National Park.

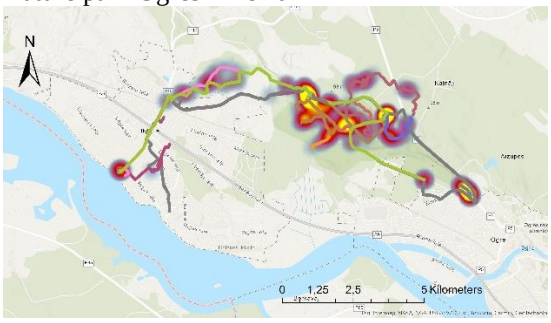
The respondents have been visiting urban forests for a long time [3]: interesting and emotional are the stories of people who have been visiting the area since childhood, or 'since birth' - in the case of our study - more than 40 years (35%), 30 years - 19%, 20 years - 8%, 10 years - 35%, only one respondent became acquainted with the forest 1 year ago.

Several respondents stated that they visit the area several times a week - every day or even several times a day during the summer bathing season [1, 2]. They use different routes every day, depending on the weather conditions, the amount of time allocated for activities, their health status and mood [1, 2, 5]. The routes followed during the interview are summarised on maps, highlighting the visitors` favourite routes [2] (different colour for each respondent) and the landscapes, places, plants or facilities mentioned by the interviewees and photographed by the interviewer are shown in 'cloud form' (thickening of dots, more intense colour) in the places of most activity [1, 2, 3, 4, 5], see Figure 1. The interviewees expressed their attitudes to the different places by simply stating the facts, noting the positive (attractive landscape, walkable paths, psycho-emotional rest, few people, silence, positive memories) or negative aspects (too many people, too many or too few amenities, lack of benches, trail surfaces, too many/too few litter bins, toilets that malfunction, garbage) [1, 2, 3, 4, 5].

Figure 1

Go along interview routes and photo locations [1,2]

Nature park Ogres Zilie kalni



Nature park Bernāti

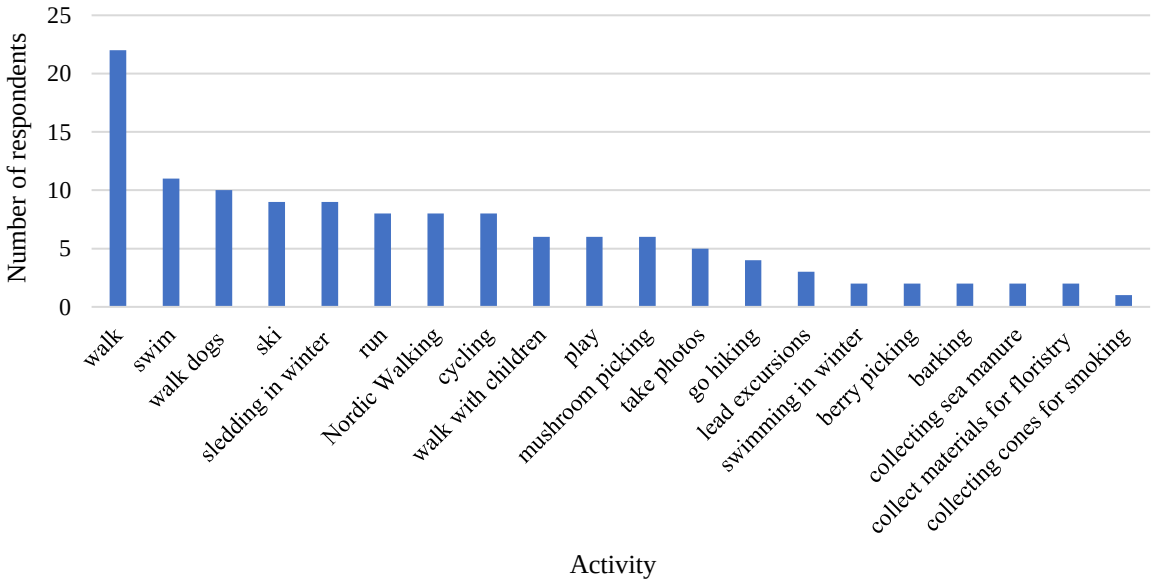
Nature park Ragakāpa

Langervalde Forest

The list of activities performed is interesting [4], see Figure 2, with walking, swimming and walking the dog being the most popular. The most frequently mentioned activities are the traditional, even archaic ones that have survived from very ancient times: nut-cracking (picking *Corylus avellana* fruits), collecting sea dung (washed up sea plants) to fertilise and improve the sandy garden soil, and collecting pine cones (*Pinus sylvestris)* to smoke fish caught in the sea.

In the urban forests, the green-blue structure with an articulated topography - a sufficiently transparent forest with hills bordering the water surfaces - is considered particularly attractive to visitors. In all three nature parks, the scenic, visually appealing extreme pine forests, fresh, dry air are particularly highlighted.

Figure 2
Respondents' activities in urban forests [1, 2, 4, 5]



The flat landscape of the Langervalde Forest, with frequent undergrowth, is considered boring or 'nothing special'. Free access to the beach is essential, building is forbidden, 'a nature park is a place where you can relax if you don't have your own fields'. Visitors understand the situation [4, 5] - it is good that it is managed and maintained according to a plan. Fellow citizens appreciate the improvements in public attitudes 'people have become tidier' and 'clean up after themselves'. During the interviews a rating was given to the facilities [1, 2, 4, 5]. Table 3 and 4 show how many people mentioned and rated a particular type of amenity positively (+) or negatively (-) in the interviews.

Table 3 shows respondents' ratings for site-specific and linear landscaping, Table 4 - landscaping features and small architectural forms. Briefly describing the amenities in the Ogre Zilie kalni, the majority of respondents appreciate the existing amenities, but also expect them to be further improved and developed. In Ragakāpa (5-) and Bernāti (3-), the local people do not really use the existing amenities, in fact, they avoid them, except when showing the area to visitors, tourists. The Ogre Zilie kalni are dominated by gravelly hills, Bernāti and Ragakāpa by sand dunes, which are well drained and suitable for natural paths, avoiding the swamps and wet vigas in these areas. The Nature Park areas have an extensive network of paths that have been walked over time, with individual information signs; in Ragakāpa there are individual boardwalks, some of which were dismantled in 2024 and replaced with gravel paths. The Langervalde Forest is very different, with mostly waterlogged ground, which is only easily accessible via specially created woodchip mulched paths and bridges over the many otherwise impassable gullies.

There are very different views on cycle and motorbike tracks. They are undoubtedly of interest to one group of users, but also a potential source of soil erosion, a source of noise in the case of motorcycles, and potentially dangerous to other visitors due to speed. If the people of Bernāti are happy that they have 'dealt with' motorcyclists by eliminating their activities in their territory, in the Ogres Zilie kalni there is a proposal from the people to find a place for them. The same goes for cyclists - in Bernāti and Ragakāpa there are no dedicated cycle paths, and their activities are restricted. Informal MTB trails have been established in the Ogres Zilie kalni for a long time and, according to the manager, they will be reviewed in 2024-2025, and a technical project will be developed to improve them, make them more interesting, safer and avoid impacts on the surrounding habitats. The gravel hills in the Ogres Zilie kalni are more resistant to soil erosion. In Bernāti and Ragakāpa, sand dunes are exposed to water and wind erosion due to loss of vegetation. In the Langervalde, the black soil is waterlogged and mobility is only possible on specially constructed paths with frequent mulching, which is not suitable for cycling.

Due to the high anthropogenic impact, the required campfire/grill sites have been created in 6 locations in the Ogre Zilie kalni and in 2 locations in Bernāti. In the Ogre Zilie kalni, Bernāti and Langervalde, wooden or stone sculptures and other artistic environmental elements have been created to attract visitors and serve as landmarks and signposts in the large forest areas.

Table 3

Amenity ratings in Go-along interviews, spot and linear landscaping [1, 2, 4, 5]

Facilities	***Casestudy areas (abbreviation)***				***Respondents' comments***
	Zilie kalni (ZK)	***Bernāti (BE)***	***Langervalde (LA)***	***Raga kāpa (RK)***	
	Rating in surveys (positive+; negative-)				
Spot/square landscaping					
Swimming places	7+	4+	no	2+	Used extensively everywhere, swimming is often the main purpose of a visit.
Observation tower	4+	2-	no	no	BE - no sea view, height restricted due to Nature Park regulations.
Lighthouse	no	3+	no	3+	Lighthouse serves as a landmark and destination.
Viewing places	3+	1+	no	1+	ZK - lookout at Dubakalns water body, BE - lookout at Mount Poussin, view of the surrounding forest, sea not really visible, RK - lookouts with view of the surrounding forest.
Gazebo	1+	1+	no	no	None of the respondents use.
Activity places	4-	5+	no	2+	ZK -Nature concert hall site, Rope paths - undergrowth trampled at activity sites, BE - big stand as a cinema screen, LOC recreation base, Dzintariņš café, RK - Open-air Museum; 36-line restaurant kiosk.
Car parking	2+5-	3+	no	1+	Areas without asphalt pavement have dust in the air in dry weather or mud and potholes in wet weather.
Linear landscaping					
Ski track	5+5-	1+	no	1+	NK - 10km of specially constructed ski slopes with lighting, BE and RK skiers enter the slopes themselves.
Trails	7+2-	4+4-	4+4-	5-	In all areas, local visitors do not use the marked, signposted trails, nor do they use the boardwalks, which are slippery in wet weather, difficult to cross with pushchairs and bicycles. Marked trails are used by visitors in a strange place.
Cycling trails	3+	1-	no	3+	There are spontaneous cycle paths in the NC which are heavily used. BE cyclists are restricted as soil erosion is encouraged. RK - used to have stricter rules, now they are less strict.
Horse trails	2+	no	no	no	ZK - horse riding damages the trail surface and makes it difficult for pedestrians and cyclists to use.
Access roads	1+3-	2+	0+	0+	NK driveway mostly gravel, dust in the air in dry weather, elsewhere there are tarmac driveways which are appreciated.

In the territory of the nature parks, there is a desire (forbidden by Latvian law) to spend the night in tents or on branch poles, which are visible in places in the territory. In Bernāti, there is a strong negative attitude towards caravans (2-), as there has been a large influx and this has caused inconvenience to the local population. The NC observes that there are only a few visitors with caravans who do not cause too much burden and inconvenience to other visitors.

Table 4

Amenity ratings in Go-along interviews, landscaping features and small architectural forms [1, 2, 4, 5]

Facilities	***Casestudy areas (abbreviation)***				***Respondents' comments***
	Zilie kalni (ZK)	***Bernāti (BE)***	***Langervalde (LA)***	***Raga kāpa (RK)***	
	Rating in surveys (positive+; negative-)				
Amenities					
Benches	6+	6+	2+	2-	Benches are not used by sports visitors in all areas, but all agree that benches are needed for visitors who cannot walk long distances, in areas with attractive views.
Waste bins	2+3-	1-	1+	0+	ZK: 36 bins in activity areas, near benches, BE: 36 bins in a small area, which is disproportionate. LA - deliberately not placed RK - placed by benches. Sharply different opinions in all areas: more are needed, but mostly no bins at all. The principle of 'what you bring you take away' should be followed.
Information boards, signs	3+	3+	3+	3+	Many mention the need for them, even those who use them more often say that signs help orientation, especially if the place is less well known.
Fire and barbecue areas	5+	0+	no	no	As the number of visitors increases, the equipment needs to be renovated and the layout rethought. None of the interviewees use them.
Wooden, stone sculptures	4+	6+	2+	no	Positive attitudes of respondents, they are popular attractions, included in walking routes, for weddings and other celebrations.
Toilets	5+	3-	no	0+	Positive about well maintained WCs, especially with water and heat. BE - particularly negative assessment of defectively constructed toilets that do not actually work.
Bridges	0+	1+	5+	0+	LA, BE - positively appreciate, especially note larger, specially built bridges, where without their construction it would be difficult to use the territory, ZK, RK small bridges on dry ditches, uneven terrain are not even noticed by visitors, not mentioned.
Changing cabins	1+	0+	no	0+	Important changing facilities on all beaches.
Stairs	3+	no	no	2+1-	rated better than boardwalks, but noting that they can be slippery, cannot be used by cyclists, pushchairs, people with disabilities.
Exercise, sports equipment	3+2-	no	no	no	ZK - good appreciation, need to renew older ones, expand facilities for larger groups of athletes, also for smaller children.
Biathlon shooting wall	1+	no	no	no	ZK - appreciates new, modern activities.
Counters	2+	0+	0+	no	ZK - positive, respondents interested in total number of visitors, BE, LA, RK - respondents do not mention.
Coffee machines	2-	1+	no	0+	ZK - strongly negative attitude, BE - positive, included in the 'ritual' of the visit, RK - is located, not mentioned in the survey
Lighting on trails	2+	no	no	no	ZK - there is lighting on some paths, but should be more

Although the interviewed visitors do not specifically mention this, rangers regularly observe acts of vandalism and deliberate damage to facilities. However, such damage is either promptly repaired or the affected facilities are dismantled entirely, making them less visible to visitors.

Ragakāpa is known for its informal 'policemen', local residents who 'keep order', and in the Ogre Zilie kalni and Bernāti, there is also a high level of public involvement, with visitors reporting irregularities to the local police or managers [4,5].

Visitors make suggestions [4,5] for improving the landscape: Asphalting access roads and car parks, upgrading play and exercise equipment, creating paths parallel to the ski slope, creating a disc golf course, reinforcing the path surface to make it wheelchair accessible, improving route signage (information on the length of the path, approximate time and difficulty of the route (whether it is wheelchair accessible), creating audio guides, creating site signs, wooden sculptures, signposted 'entry gates', the possibility of creating pay-per-visit sites to identify specific sites if their maintenance and service is improved, etc.). These suggestions from visitors help to understand the needs and priorities of the population.

Conclusions

The 'go along' interviews in urban and peri-urban forest areas, the case studies of Bernāti, Ragakāpa and Ogre Zilie kalni Nature Parks and the Langervalde Forest have led to a number of conclusions:

1. People who choose to visit the forest have very positive feelings, sentimental memories of childhood, youth, previous visits, which contribute not only to physical health through exercise and fresh air, calming, but also to a positive psycho-emotional state and relaxation. The results of the study show that the social, ecological, environmental education, environmental protection, aesthetic and economic functions of urban forests are important, but the psycho-emotional function of urban forests, as identified by cultural ecosystem services, is particularly important and should be taken into account in the planning and management of areas.
2. The planning and management process should take into account user expectations, national and local regulations, the commitments of owners or managers, available opportunities, and expert advice. The planning process should involve specialists and experts from various fields, as well as users from different sectors, each bringing their own knowledge, experience and needs, which may often be diametrically opposed. The planning process should, as far as possible, reconcile different interests.
3. In order to minimise conflicts and disagreements between stakeholders, it is essential to explain the environmental requirements or management peculiarities to users, which may initially provoke a strong reaction from users.
4. In most cases, the managers and experts have taken the visitors' suggestions into account in the planning process, but financial constraints make it impossible to implement everything. Suggestions from visitors can help to prioritise work.
5. Taking into account different opinions, one solution is to create different areas with more and less intensive landscaping and maintenance, so that visitors can choose the level of landscaping and visitor intensity that suits them.
6. Given the amount of information gathered in the 26 Go-Along interviews, further detailed research and conclusions should be considered.

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METHODOLOGICAL FRAMEWORK FOR THE LANDSCAPE ASSESSMENT IN SPECIALLY PROTECTED NATURE AREAS IN LATVIA

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Abstract
Specially protected nature areas (SPNA) are valuable ecological, social, and economic resources; however, they are also susceptible to various changes that can irreversibly impact their natural and scenic values. Often, tourism infrastructure is developed within these protected areas, creating walking routes through the most beautiful landscapes and establishing other facilities to provide services. It is essential to develop a methodological framework for landscape assessment to identify the landscape values that can be utilized for tourism development and establish conditions for managing and administrating these areas to provide protection of the landscape values. This article presents the methodological framework developed within the LIFE LatViaNature project for landscape assessment in SPNAs. It evaluates the landscape quality of SPNAs to ensure their preservation, enhancement, and dynamic future development planning. In Latvia, there are 658 specially protected natural areas of various types and sizes, not all possessing scenic qualities. In most of these areas, the focus of protection is primarily associated with the ecological and biological values of the territory. The developed methodology can serve as a document and guidelines for landscape assessment within the framework of a nature protection plan for definite SPNA and for the development of thematic landscape plans in municipalities and planning regions. It can be utilized by territorial planners and landscape architects to conduct landscape assessments in specific areas.
Keywords: landscape assessment method, landscape values, landscape qualities, protected nature areas.

Introduction

Specially protected natural areas (SPNA) serve as valuable ecological, social, and economic assets. However, they are also vulnerable to changes that may permanently alter their natural and scenic characteristics. In many cases, tourism infrastructure is introduced within these areas, including walking trails that showcase the most picturesque landscapes, observation towers, and other visitor facilities. Nature-based tourism and recreation in nature are growing trends significantly boosted by the COVID-19 outbreak in the spring of 2020 (Fredman & Margaryan, 2020), both internationally and in Latvia (Jūrmalis et al., 2022). Tourism and visitor management guidelines in protected areas are developed to protect nature from overload (Leung et al., 2018). To determine the landscape values that can be utilized for tourism development and prepare conditions for the management and administration of such areas, it is necessary to develop a methodological framework for landscape assessment in protected natural areas.

Adopting the European Landscape Convention (Council of Europe, 2000), which was also ratified by Latvia in 2007, human perception in landscape assessment became more relevant. Additionally, the landscape is recognized as a result of the interaction between humans and their environment, where natural processes and human needs are respected. Landscape assessment is also a significant stage in the implementation framework of the European Landscape Convention (Council of Europe, 2000), as it forms the basis for determining further measures in landscape protection, planning, and management. The European Landscape Convention does not prescribe a uniform approach for all European countries but rather highlights the specific characteristics of each country and the necessity for them to identify their objectives regarding landscape as a resource (Council of Europe, 2000).

Estonia has set preserving multifunctional and coherent landscapes as one of the Estonian Environmental Strategy 2030 objectives (Ministry of Environment, 2007). Other countries have developed landscape plans on different planning levels, like 'Landschaftsplan' in Germany or 'Atlas des Paysages' in France. In Switzerland, the landscape has historically been recognized as one of the foundations of its national identity (OFEV, 2020). In the Netherlands, general principles of landscape quality are integrated into national, regional, and municipal territorial strategies and planning. Landscape character assessment is conducted in England (Tudor, 2014) and Scotland (NatureScot, 2023).

In general, documents related to the assessment of landscapes in terms of territorial development include the following aspects:

- Landscape as a comprehensive system that includes ecological, socio-economic, and cultural aspects (Council of Europe, 2000; European Commission, 2019a).
- Landscape as a natural resource for ensuring ecological and human living quality (European Commission, 2019b; 2020).
- Landscape as a cultural environment, former of national identity and symbolism (UNESCO, 1972).

However, none of the documents specify how these tasks should be implemented.

The Law of the Republic of Latvia on Specially Protected Nature Areas (Latvijas Republikas likums, 1993; Ministru Kabineta noteikumi Nr. 686, 2007) states that one of the objectives of the establishment, protection, and management of protected nature areas is 'to protect and preserve the diversity of nature (rare and typical natural ecosystems, habitats of protected species, unique, beautiful landscapes characteristic of Latvia...)'. It aims to protect and preserve Latvia's characteristic landscape and those elements essential

for ensuring the ecological functions of protected species and habitats, as well as the cultural environment and landscape diversity. It also seeks to conserve environments suitable for public recreation, tourism, and nature-friendly management practices.

As part of the LIFE Integrated Project LatViaNature, a new e-platform for the Nature conservation plans (NCP) of SPNAs in Latvia is slated for implementation by 2028. This platform will feature a dedicated section for protected areas of high landscape quality and tourism development potential, where information regarding these areas' landscape quality and tourism can be submitted. The developing methodological framework for the landscape assessment of specially protected areas will specify the types and formats of data to be included in this section.

The article presents the methodological framework for landscape assessment of SPNAs developed within the LIFE project LatViaNature. The methodology aims to identify the landscape quality of these protected areas, ensuring the preservation, enhancement, and dynamic (adaptable to changes) planning of future developments while respecting conservation goals and guaranteeing public benefits derived from the landscape resources available within these protected areas.

Materials and Methods

Study object

Specially protected nature areas (SPNA) in Latvia are territories that are under state protection due to their specific qualities – biological diversity, habitats for rare species, geological and geomorphological formations, characteristic, traditional and scenic. In Latvia, there are 658 specially protected natural areas of various types and sizes (nature reserves, nature parks, reserves, etc., excluding protected trees (mature trees) and protected, big stones), not all of which possess scenic qualities (NCARL, 2024) (Figure 1). Almost half of these territories – 333 are Natura 2000 areas.

In most of SPNAs, the protection focus is associated with the territory's ecological and biological values. However, there are SPNAs that also include scenic and cultural heritage values, making them popular destinations for recreation and tourism and placing additional pressure on the existing protected areas.

Methods

Considering there is currently no unified methodology for landscape assessment in Latvia, including SPNAs, the methodological framework for the landscape assessment in SPNAs has been developed for its integration into Nature Conservation Plans (NCP) that will be elaborated for each nature protected area. The framework includes a two-step approach (Figure 2).

Landscape assessment in SPNAs is linked to the potential for tourism and recreational development. However, as mentioned earlier, the primary goal of many SPNAs is the preservation of biological and ecological values, with some areas even restricting visitor access entirely. Therefore, in the first step (Stage I), areas that do not require a landscape assessment and those that do require assessment are identified because their qualities serve not only as significant ecological assets but also as important cultural-historical, scenic, and socio-economic resources.

A key issue for Stage I is data availability in public databases without needing field surveys. Therefore, the criteria for the areas that do not require landscape assessment were:

1) the purpose of the establishment and protection of the Specially Nature Protected Area designated only for biological and ecological values;
2) the purpose of the establishment and protection of the area does not allow free access for visitors (for example, the strict protection and regulated protection zones of a nature reserve), OR the area cannot be used for tourism and recreation because it is not accessible;
3) at least 85% of the territory consists of a closed, homogeneous landscape structure of a single type (for example, homogeneous forest without open patches, roads and other elements);
4) there are no protected cultural or natural monuments in the area.

In the next step (Stage II), the selected areas under requirement for landscape evaluation are assessed based on predefined evaluation criteria.

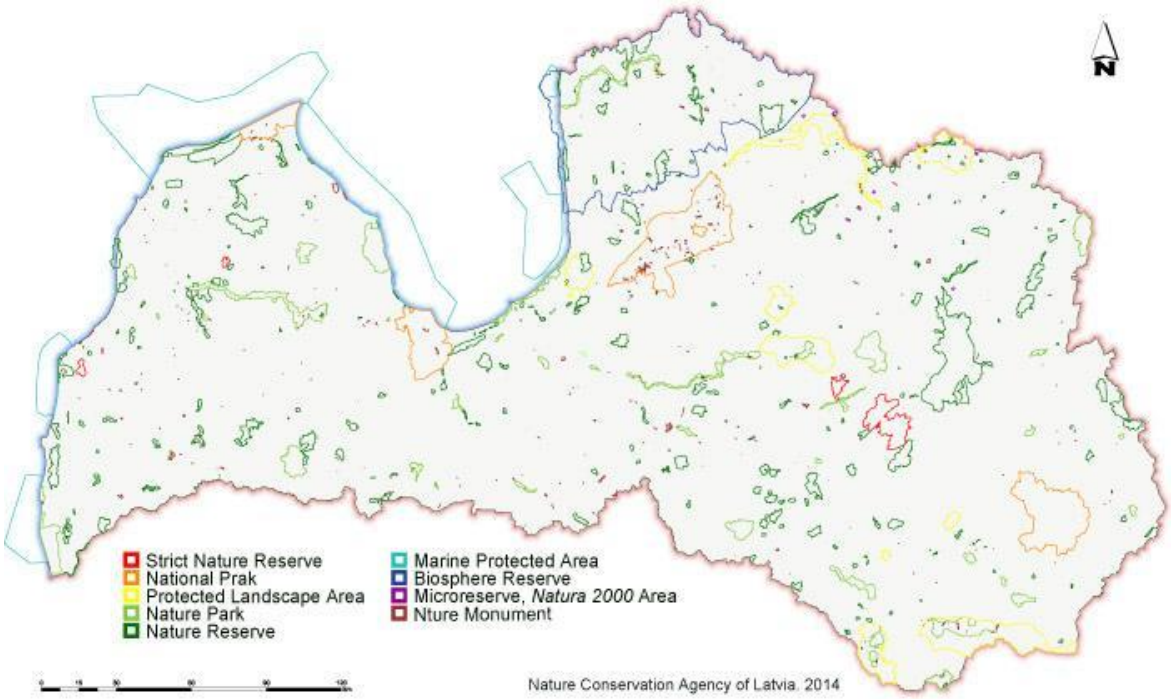
For the landscape assessment it has utilized and adapted several approaches already validated in Latvia and Europe (Simensen et al., 2018). Additionally, it incorporates the requirements outlined in existing regulatory acts, which stipulate that the nature protection plan must include a 'landscape assessment (in terms of aesthetic, ecological, and socio-economic aspects, as well as an analysis of the positive and negative impacts on the landscape as a whole within the protected area)' (Ministru Kabineta noteikumi Nr. 686, 2007).

Therefore, the methodological framework for the landscape assessment part for SPNAs under requirement for landscape evaluation includes 3 sections: 1) general characteristic of surrounded landscape; 2) landscape values (qualities) and 3) positive and negative effects on the landscape, recommendations for development and impact mitigation. The methodological framework for landscape assessment in SPNAs is schematically illustrated in Figure 3.

For the general characteristics of the landscape of a particular SPNA, the Landscape Character Assessment (LCA) approach is used (Tudor, 2014). The LCA, developed in the United Kingdom, has been employed in the section on landscape assessment, which examines the general characterization of the landscape (Fairclough et al., 2018). Many other countries have also utilized this methodology for landscape evaluation, with criteria adapted to their specific goals and landscape characteristics. The LCA serves as a tool that integrates natural and cultural landscapes along with human perception, describing the spatial framework for

the implementation of the European Landscape Convention (Council of Europe, 2000).
Within the Latvian National Research Program project ʻSustainable Management of Land Resources and Landscapes: Assessment of Challenges, Methodological Solutions, and Proposals' (LandLat4Pol, 2023), a characterization of Latvian landscapes was conducted in 2023.

Figure 1
Specially Protected Nature Areas in Latvia



Source: (NCARL, 2024).

Figure 2
The methodological framework for selection of SPNAs that do not require and those that require landscape assessment within the Nature Conservation Plans

STAGE I: Assessment of the need for applying landscape evaluation

Required

STAGE II: Landscape evaluation within the development of the Nature Conservation Plan

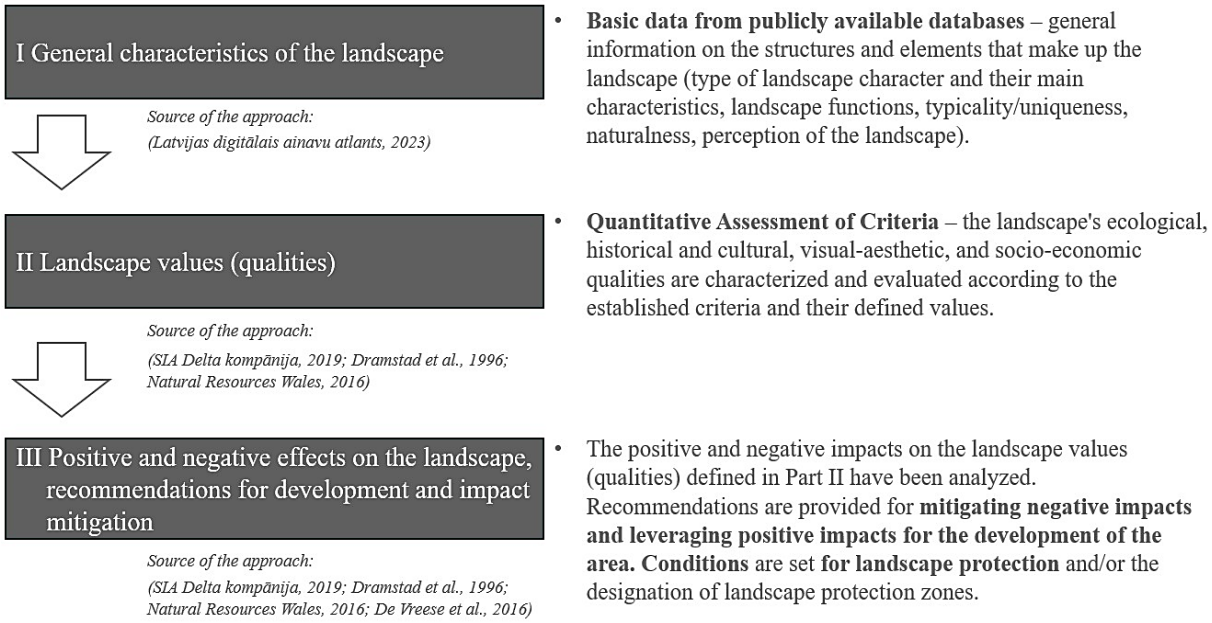
- General characteristics of the landscape.
- Landscape values (qualities).
- Positive and negative effects on the landscape, recommendations for development and impact mitigation.

Not required, as it meets the established criteria (can be evaluated without on-site inspection, based on publicly available data)

The purpose of the establishment and protection of the Specially Nature Protected Area (SNPA)	• Protection is designated only for biological and ecological values.
Accessibility and infrastructure	• The purpose of the establishment and protection of the area does not allow free access for visitors, OR the area cannot be used for tourism and recreation.
Landscape spatial structure	• At least 85% of the territory consists of a closed, homogeneous landscape structure of a single type.
Landscape elements	• There are no protected cultural or natural monuments in the area.

Source: Developed by Authors.

Figure 3
The methodological framework for the evaluation of SPNAs that required landscape assessment within the Nature Conservation Plans



Source: Developed by Authors.

This characterization is based on the LCA methodology, which has been modified to suit Latvian conditions. As part of this project, a digital atlas of Latvian landscapes (Latvijas digitālais ainavu atlants, 2023) was created, providing accessible data collected and obtained regarding Latvian landscapes and methodological materials concerning landscape assessment approaches in Latvia (Stokmane et al., 2023). Data from the Atlas have been utilized for general landscape characterization of the definite SPNA.

Criteria established within the Zemgale Regional Landscape and Green Infrastructure Plan for 2020-2027 (SIA Delta kompānija, 2019) have been adapted and utilized for assessing and evaluating ecological and socio-economic qualities of the landscape. The criteria were developed as part of the Interreg Latvia-Lithuania program project 'Enhancing Green Infrastructure in the Landscapes of Lowland Rivers/ENGRAVE'. The characteristics and numerical values of the established criteria have been utilized and adapted to determine and evaluate the ecological, historical, cultural, socio-economic, and visual aesthetic qualities of landscapes within the landscape assessment for the NCPs. Several criteria for assessing landscape qualities have been supplemented by adapting methodologies and criteria developed in other European countries based on the Landscape Character Assessment approach, such as the visual quality assessment criteria for landscapes in Wales (Wascher, 2005). For landscape ecological quality assessment, basic approaches of landscape ecological planning were utilized (Dramstad et al., 1996; Bennett, 2003). Visual assessment criteria were used for scenic quality assessment (Natural Resources Wales, 2016).

Results and Discussion

In this section selected criteria for SPNAs required landscape assessment are discussed and presented with practical examples from the pilot-study area – Nature Park 'Istra' located in eastern part of Latvia, in Ludza district municipality. According to the developed methodological framework, the landscape assessment to be conducted for the selected SPNAs consists of a general characterization, analysis of landscape qualities, and recommendations for landscape management and maintenance.

I General characteristics of the landscape

Existing landscape survey data from Latvia (Latvijas digitālais ainavu atlants, 2023) is utilized to develop the general landscape characterization. The objective of the general characterization is to describe the landscape's primary structural elements and characteristics to reflect its key visual and spatial features, functions and uses, typicality or uniqueness, as well as the perception of the landscape. The general landscape characterization is necessary to conduct the landscape assessment, identify qualities, and provide recommendations for landscape management following landscape quality objectives.

II Landscape values (qualities)

Subsequently, the following landscape values or qualities are evaluated.

Landscape Ecological Qualities. The landscape structures and elements of SPNAs should be evaluated

not only as visual aesthetic, cultural, and socio-economic resources, but also as features ensuring landscape ecological quality due to the specifics of these areas. For the determination and assessment of landscape ecological qualities, both cartographic materials and various available data sources (such as Ozols.lv (Ozols, 2025), Mantojums.lv (Mantojums, 2025), lvm.geo.lv (LVM GEO, 2025), and biodiversity protection plans for the specially protected natural areas, if available) are analyzed, as well as field surveys conducted on-site. The assessment results are to be represented cartographically and supplemented with descriptions, including evaluations according to the following assessment criteria:

- landscape structures that provide significant landscape ecological functions (ecological connections with surrounding natural areas outside the SPNA; green network throughout the entire SPNA; habitat diversity and density; landscape structure diversity; fragmentation (visually observable)) (Figure 4);
- landscape elements that provide significant landscape ecological functions (mature trees, trees with multiple trunks and cavities, fallen mature trees, rare local species, alleys, edges, ruins of old houses, stones, topography variations, water streams, etc.) (Figure 5);
- naturalness (proportions of natural vegetation and land cover, biologically valuable grasslands, etc.);
- pollution (noise and light from roads, other infrastructure elements).

Historical and Cultural Qualities. These qualities are closely linked to a place's identity and recognizability, encompassing both material and immaterial values, such as traditional practices, processes, and customs (e.g., agricultural traditions, forestry, human-made structures, peat extraction/quarries, such as the remnants of old railway lines now transformed into greenways, as well as war/military heritage, including trenches and bunkers). The criteria groups utilized for the assessment include:

1) historical significance (presence of historic spatial structures – old roads, ancient villages, historic buildings; visually noticeable historic elements - anchor elements – manor houses, sacral buildings, mills, bridges, fort hill, etc.) (Figure 6);
2) uniqueness and recognizability (landscape of national importance, landscape protected areas);
3) cultural monuments (density, types, conditions);
4) sacred heritage (types and density of sacral buildings, cemeteries, conditions);
5) traditions, and processes (traditional land use for the definite region, other elements creating identity of the places).

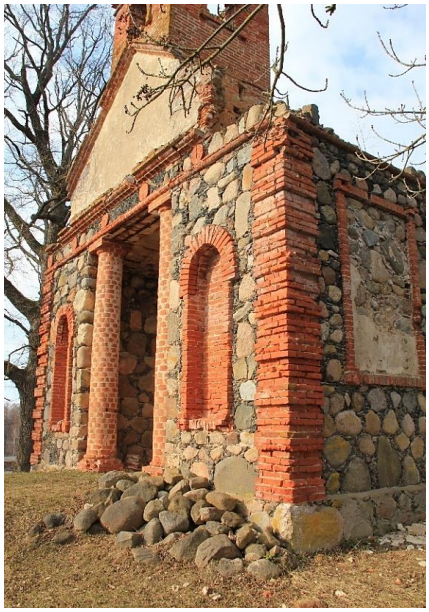
Visual Aesthetic Qualities are analyzed using view analysis in the context of human perception. These individuals can include residents traversing the area as well as tourists.

Figure 4
Fragmentation of landscape structures that provide significant landscape ecological functions – clear cutting patches. Forest in nature park '*Istra*'

Figure 5
Landscape elements that provide significant landscape ecological functions – an alley from mature trees (Tilia) that represents also cultural heritage value – an old alley to Istra manor's house

Within the framework of view analysis, viewpoints, vistas, and the landscape structures and elements that determine the visual aesthetic quality of the view (high or low) are mapped and described. In natural areas, the most significant from a landscape perspective are the primary roads and routes frequented by tourists (Figure 7). The criteria groups utilized for the assessment include viewpoints, views from roads and river corridors, characterization of view expressiveness and visual quality, scenic landscapes (areas with high visual aesthetic view density) (Figure 8), and proportion of visually attractive roads.

Figure 6
Landscape elements representing historic significance and recognition of the place – sacral building – Vecslabada's church



Socio-economic qualities of a landscape are associated with its potential uses and the public benefits derived from the landscape as a significant resource. Considering that not all areas permit economic activities, with a priority placed on protecting nature and landscapes, the socio-economic qualities of the specially protected natural areas are evaluated in the context of their usage possibilities, primarily concerning tourism and recreation (Figure 8).

Figure 7
Scenic landscape of lake Dzilezers of the nature park Istra. View from the Tiskova hill

The criteria groups utilized for the assessment include:

- function and purpose of use (diversity of land use types; purpose of establishment and protection of the definite SPNA);
- accessibility (density of populated places, distance to cities, public transport, bicycle routs);
- recreation, and tourism (location and density of recreation and tourism objects, elements and infrastructure; seasonal usage, public involvement).

Figure 8
Scenic road in the forest serves as bicycle route through the area of the nature park '*Istra*'

Conclusions

1. The developed methodology can be applied as a document and guidelines for landscape assessment within the framework of a nature conservation plan and for developing thematic landscape plans in municipalities and planning regions.
2. Territorial and landscape planners and landscape architects can use the methodology to conduct landscape assessments in specific areas.
3. Obtaining missing data, involving specialists from relevant fields, and utilizing various digital tools are essential.
4. Possible limitations of the method are connected to the data availability and subjectivity in the evaluation of some criteria, for example, scenic and aesthetic quality.

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EVALUATING THERMAL PROPERTIES OF NORWAY SPRUCE CROSS-LAMINATED TIMBER PANELS AT DIFFERENT WOOD MOISTURE CONTENTS

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Abstract
This study explores the thermal conductivity of cross-laminated timber made from Norway spruce (*Picea abies* L.), emphasizing the impact of varying wood moisture content, density, and temperature. A comprehensive set of eighty specimens was prepared, grouped into four clusters of twenty specimens each, categorized by average density to ensure consistent representation. Measurements were conducted at equilibrium temperatures 10 °C, 20 °C and 23 °C (temperature difference 10 °C) using Heat Flow Meter HFM 436/3. The study identified a quadratic relationship between thermal conductivity and bulk density, with conductivity increasing non-linearly. Dispersion and regression analysis comparing results to ISO 10456 standard showed experimental values were consistently lower, highlighting potential overestimation in standardized data. Density-dependent trends at 23 °C demonstrated better alignment, but deviation from historical models for solid wood thermal conductivity dependence to wood density and moisture content (e.g., MacLean, Tenwolde) emphasized the need for updated, cross-laminated timber specific data. This research enhances energy efficiency modelling for building with cross-laminated timber products in the external envelope of the building by providing more precise conductivity values. The findings emphasize equilibrium moisture content of wood dependence of climatic conditions and its impact on energy performance of mass timber structures. The findings support updates to thermal performance standards. Addressing variable conditions, this work lays the groundwork for accurate modelling of specific cross-laminated timber product behaviour in real-world applications.
Keywords: cross-laminated timber (CLT), thermal conductivity, Norway spruce, *Picea abies* L., moisture content.

Introduction

Cross-laminated timber (CLT) is a known construction product that has gained significant attention in recent years in the context of sustainable building. The thermal properties of CLT are crucial factor influencing the energy efficiency of buildings, especially in external envelope applications. While the thermal conductivity of natural solid wood depends on various factors, including wood species, density, porosity, anisotropy and moisture content, these factors may manifest differently in CLT due to its specific structure. Previous studies (MacLean, 1941; Wilkes, 1988; Tenwolde et al., 1988) give solid background for prediction solid wood thermal performance, however, standards such as ISO 10456 (International Organization for Standardization, 2007) and ISO 10077-2 (International Organization for Standardization, 2017) give only partial guidance for wood and wood-based products, CLT as material category is not even mentioned. Other product assessment guidance documents such as EAD 130005-00-0304 (European Organisation for Technical Assessment, 2015) recommend to use design values as declared for solid wood materials, when no testing is done. Recent study suggested (Flexeder et al., 2021) that CLT panels might have different thermal conductivity values as tabulated values in standards.

The service conditions of buildings significantly impact the equilibrium moisture content (EMC) of solid wood materials, which can vary substantially throughout the year, dynamically influencing the energy efficiency indicators of a building. Earlier studies (Hunt et al., 2008; Avramidis & Liadis, 2005) have shown that moisture redistribution within wood can alter its heat transfer properties, necessitating careful consideration of moisture dynamics in thermal conductivity models. The work of Flexeder et al. (2021) further highlights the need for long-term monitoring of CLT structures to evaluate their hygrothermal performance under real-world conditions.

The HFM 436/3 Lambda (NETZSCH-Gerätebau GmbH., n.d.) heat flow meter is widely used in research for measuring thermal conductivity, contributing to data accuracy and comparability across different studies. The standards serve as benchmarks for evaluating CLT's thermal performance under varied environmental criteria.

Therefore, it is essential to determine precise parameters characterizing the changes in CLT thermal conductivity under different moisture and thermal conditions. This study analyses the thermal conductivity of Norway spruce (*Picea abies* L.) CLT panels at various wood moisture contents to understand how moisture and density affect the thermal behaviour of the material. The aim of this study is to verify whether a statistically significant and practically relevant dependence exists between the thermal conductivity of industrial cross-laminated timber panels and their wood-moisture content and bulk density under typical service temperatures.

The study employs an experimental approach, conducting thermal conductivity measurements at different equilibrium moisture levels and temperatures. The methodology follows prior research on thermal conductivity models (Hunt et al., 2008) and compares empirical findings with existing standardized values and computational predictions. By integrating past empirical data (MacLean, 1941) with modern modelling techniques and real-world monitoring insights from Flexeder et al. (2021), this research aims to refine thermal property predictions for CLT. The study's findings can be valuable for designers and building

regulation developers seeking to improve the energy efficiency modelling of mass timber constructions and enhance the accuracy of existing standards. The novelty of the work lies in providing the first coherent experimental dataset for CLT across the range of 10 % to 21 % equilibrium wood moisture content and demonstrating how the measured values deviate from ISO 10456 reference data.

Materials and Methods

This study investigated the thermal conductivity of Cross Laminated Timber (CLT) panels under different conditioning regimes. The specimens were prepared based on the technical constraints of Heat Flow Meter (HFM 436/3 Lambda), which have fixed sample chamber size. Three-layer CLT panel cutoffs were selected randomly. Each panel was approximately 60 mm thick, composed of 20 mm thick and 120 mm wide Norway spruce (*Picea abies* L.) lamellas, bonded with polyurethane (PU) adhesive. The adhesive layer thickness was approximately 0.1 mm. The lamellas were manufactured from strength-graded sawn timber according to EN 14081-1 (European Committee for Standardization, 2020), with a characteristic strength class of C24 according to EN 338 (European Committee for Standardization, 2016a). Square-shaped specimens with side length of 290 mm were cut, yielding a total of 80 samples.

To analyse the effect of moisture content on thermal conductivity, four conditioning regimes were applied:

1. **Conditioning regime 1** – Temperature 18 °C / Relative air humidity (RH) 90 %: Target Equilibrium Moisture Content of wood (EMC) ~ 21 %;
2. **Conditioning regime 2** – Oven dried samples at temperature 103 °C till constant weight (European Committee for Standardization, 2002a);
3. **Conditioning regime 3** – Temperature 23 °C / RH 50 %: EMC ~ 10 % (ISO 10456 reference conditions);
4. **Conditioning regime 4** – Temperature 20°C / RH 65 %: EMC ~ 12 % (Service Class 1 reference conditions according EN 1995-1-1 (European Committee for Standardization, 2005), also reference conditions for tabulated design thermal conductivity (λ) values of solid wood in ISO 10456).

Wood moisture content (MC) measurements were performed using the Brookhuis FMD v5.0 wood moisture meter equipped with Teflon-coated electrode needles, following the recommendations of EN 13183-2 (European Committee for Standardization, 2002b). Measurements were taken from both sided of each sample. The electrode needles were oriented parallel to the wood grain and inserted at the centre of the specimen, approximately 30 mm deep, as suggested in EAD 130005-00-0304. The Second group of specimens (oven-dried) did not undergo moisture measurements; instead, they were immediately wrapped in LDPE plastic film and transferred to the thermal conductivity test setup.

Thermal conductivity measurements were conducted using the HFM 436/3 Lambda apparatus according to EN 12667 standard method (European Committee for Standardization, 2001). Apart from varying the plate-equilibrium temperatures to study their influence on CLT, all operational parameters followed the standard procedure (NETZSCH-Gerätebau GmbH., n.d.). Each specimen was measured at three equilibrium temperatures: 10 °C, 20 °C and 23 °C with a temperature gradient (ΔT) of 10 °C between the hot and cold plates. Since the specimen dimensions exceeded the measurement area, perimeter insulation was not applied. To ensure proper contact with the measurement plates, the sample surfaces were lightly sanded.

Data from 72 successfully conditioned specimens were analysed. Microsoft Excel was used for data compilation, while statistical analysis was performed using R 4.4.3 in RStudio 2024.12.1+563. The analysis included correlation and regression modelling, as well as ANOVA testing to assess the influence of Moisture content (MC), density (ρ) and equilibrium temperature on CLT thermal conductivity. Experimental results were compared with ISO 10456 and ISO 10077-2 reference values. Characteristic density values were calculated according EN 14358 (European Committee for Standardization, 2016b), and thermal conductivity reference values were derived using ISO 10456.

Results and Discussion

To evaluate the relationship between density and thermal conductivity, regression analysis was performed for each conditioning regime and equilibrium temperature. The results are summarized in Table 1, which presents the regression equations, correlation coefficients (r), coefficients of determination (R^2), average measured thermal conductivity ($\bar{\lambda}$), 90%-percentile of measured data according ISO 10456 (λ_D), measured average densities ($\bar{\rho}$), 5%-percentile values of measured sample densities according to EN 14358 (ρ_k), measured average CLT moisture content (MC) and corresponding standard deviations (s).

These values illustrate how moisture content influences the strength of the density and thermal conductivity relationship, with higher humidity levels generally leading to stronger correlations. Stronger correlation (r > 0.75) was observed in conditioning regimes with higher relative moisture (RH = 90 %), confirming that moisture amplifies density effect on thermal conductivity. R^2 values varied between 0.13 (oven-dried group of samples) and 0.77 (samples conditioned at high RH), suggesting that moisture increases the predictability of density effects. Conditioning regimes significantly affected thermal conductivity, with the highest thermal conductivity measurement values obtained from samples conditioned at environment with high RH.

Table 1
Regression Analysis Summary

Cond. Regime	*Regression Equation at Equilibrium temperature*	*Correlation coefficient, r*	*Coefficient of determination, R^2*	*Measured average thermal conductivity, $\bar{\lambda}$ (W/m·K)*	*Declared thermal conductivity, λ_D (W/m·K)*	*Standard deviation, s*	*Measured average density, $\bar{\rho}$ (kg/m³)*	*Calculated characteristic density, ρ_k(kg/m³)*	*Standard deviation, s*	*Measured average wood moisture content, MC (%)*	*Standard deviation, s (%)*
1	λ_{10} = 0.00013*ρ + 0.0478	0.80	0.64	0.111	0.132	0.011	498	376	66.9	18	4.7
1	λ_{20} = 0.00015*ρ + 0.0389	0.88	0.77	0.113	0.136	0.011	498	376	66.9	18	4.7
1	λ_{23} = 0.00013*ρ + 0.0451	0.86	0.73	0.108	0.128	0.010	498	376	66.9	18	4.7
2	λ_{10} = 0.00011*ρ + 0.0390	0.40	0.16	0.083	0.090	0.004	411	374	20.5	NA	NA
2	λ_{20} = 0.0001034*ρ + 0.0420	0.36	0.13	0.084	0.092	0.004	411	374	20.5	NA	NA
2	λ_{23} = 0.00009383*ρ + 0.0450	0.34	0.12	0.084	0.091	0.004	411	374	20.5	NA	NA
3	λ_{10} = 0.00015*ρ + 0.0311	0.66	0.43	0.099	0.107	0.005	451	411	22.6	11	0.6
3	λ_{20} = 0.00016*ρ + 0.0279	0.63	0.40	0.100	0.109	0.005	451	411	22.6	11	0.6
3	λ_{23} = 0.0001979*ρ + 0.0101	0.82	0.67	0.099	0.109	0.005	451	411	22.6	11	0.6
4	λ_{10} = 0.00017*ρ + 0.0262	0.69	0.48	0.102	0.103	0.004	455	414	22.8	12	0.5
4	λ_{20} = 0.00016*ρ + 0.0323	0.66	0.44	0.103	0.111	0.004	455	414	22.8	12	0.5
4	λ_{23} = 0.00016*ρ + 0.0275	0.76	0.57	0.103	0.110	0.004	455	414	22.8	12	0.5

The highest slope (~ 0.00017) was observed with samples conditioned in 20 °C / 65 % RH, indicating that in moderate humidity, defined as limit value for Service Class 1 (SC1) environmental conditions in Eurocode 5, density exerts the greatest effect. This highlights the importance of classifying environmental exposure classes correctly when modelling thermal performance in buildings using CLT construction products. Moisture levels not only shift the mean conductivity values but also affect the sensitivity of conductivity to density variations, thereby impacting predictive modelling.

Furthermore, comparison of regression intercepts across conditioning regimes revealed how base thermal conductivity changes independently of density. Higher intercepts in high relative humidity conditions suggest intrinsic conductivity increase due to bound water content in the wood structure. This aligns with previously observed effects in solid wood studies and reinforces the necessity for CLT-specific datasets.

Figure 1
Thermal Conductivity Distribution at 10 °C, 20 °C and 23 °C Equilibrium Temperatures for Conditioning Regime 4

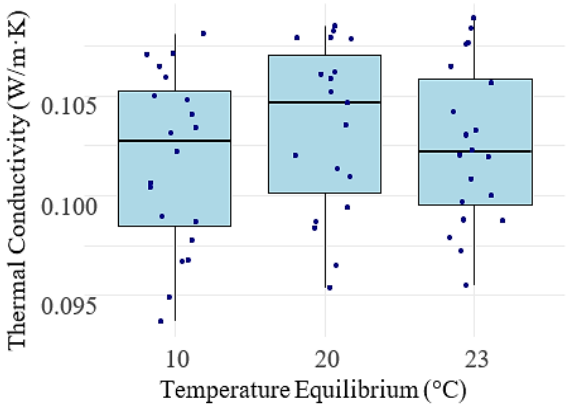
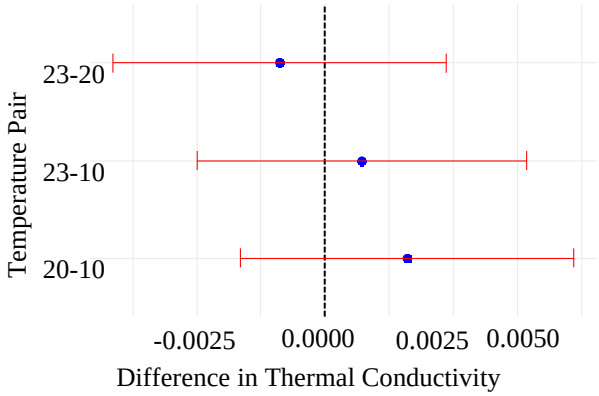


Table 1 provides an overview of how environmental conditions alter the role of density in thermal conductivity predictions, offering insight into potential modifications for CLT-based structures of building external envelope, playing role as part of thermal insulation and energy performance modelling.

To examine the effect of thermal equilibrium temperature on CLT thermal conductivity, boxplots were generated for each conditioning regime, and Tukey's Honestly Significant Difference (HSD) test was conducted. The results provide insights into whether temperature variations within the studied range significantly impact heat transfer properties.

Figure 2
Tukey's (HSD) test for Temperature Equilibrium Differences at Conditioning Regime 4



A representative boxplot 'Figure 1' shows the thermal conductivity distribution at 10 °C, 20 °C, and 23 °C equilibrium temperatures, highlighting differences across conditioning regimes. The Tukey HSD results 'Figure 2' illustrate statistical groupings, showing whether conductivity changes significantly with temperature.

The data suggest that while temperature has a secondary role compared to moisture and density, it can introduce measurable differences, particularly in samples with elevated MC. This implies that simplified models assuming constant λ across narrow temperature bands may overlook relevant variability in real-world application. These findings (Table 2) indicate that thermal equilibrium temperatures do not have a statistically significant impact on CLT thermal conductivity, suggesting that other parameters such as moisture and density are the primary influencing factors.

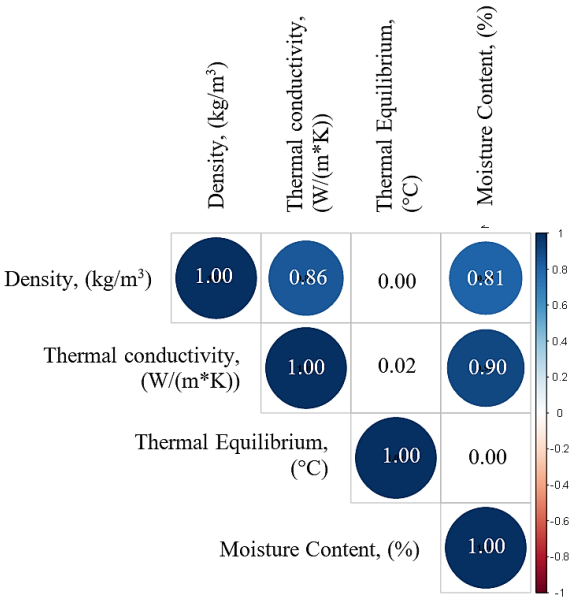
In all conditioning regimes, mean conductivity values remain stable across the tested equilibrium temperatures, as confirmed by Tukey's Honestly Significant Difference (HSD) test. This stability implies that within typical indoor climate conditions, temperature variation alone does not introduce meaningful fluctuations in CLT thermal performance.

Table 2
Dispersion Analysis Summary

Conditioning Regime	*Measured average thermal conductivity at 10 °C thermal equilibrium, $\overline{\lambda_{10°C}}$ (W/m·K)*	*Measured average thermal conductivity at 20 °C thermal equilibrium, $\overline{\lambda_{20°C}}$ (W/m·K)*	*Measured average thermal conductivity at 23 °C thermal equilibrium, $\overline{\lambda_{23°C}}$ (W/m·K)*	*Tukey significance ($p < 0.05$)*
1	0.111	0.113	0.108	No significant difference
2	0.083	0.084	0.084	No significant difference
3	0.099	0.100	0.099	No significant difference
4	0.102	0.103	0.103	No significant difference

To evaluate the accuracy of standardized thermal conductivity values, the experimentally measured data was compared against ISO 10456 reference values. The scatter plot 'Figure 3' illustrates deviations between measured values and standard predictions, highlighting systematic discrepancies across different density ranges.

Figure 3
Thermal Conductivity Influencing Key Factor Correlation Matrix



In particular, the trend of overestimation becomes more evident at lower densities, where measured values deviate furthest from the ISO reference line.

The ISO 10456 model consistently overestimates thermal conductivity values across the tested density range. The experimental data follows a quadratic regression trend, deviating from the similar ISO 10456 assumptions. This discrepancy suggests that ISO models may not fully capture other factors (e.g. knots, splits, resin pockets, fissures between laminations, adhesive dependant effects, not evaluated in this paper) and the moisture-dependent variations in CLT thermal conductivity.

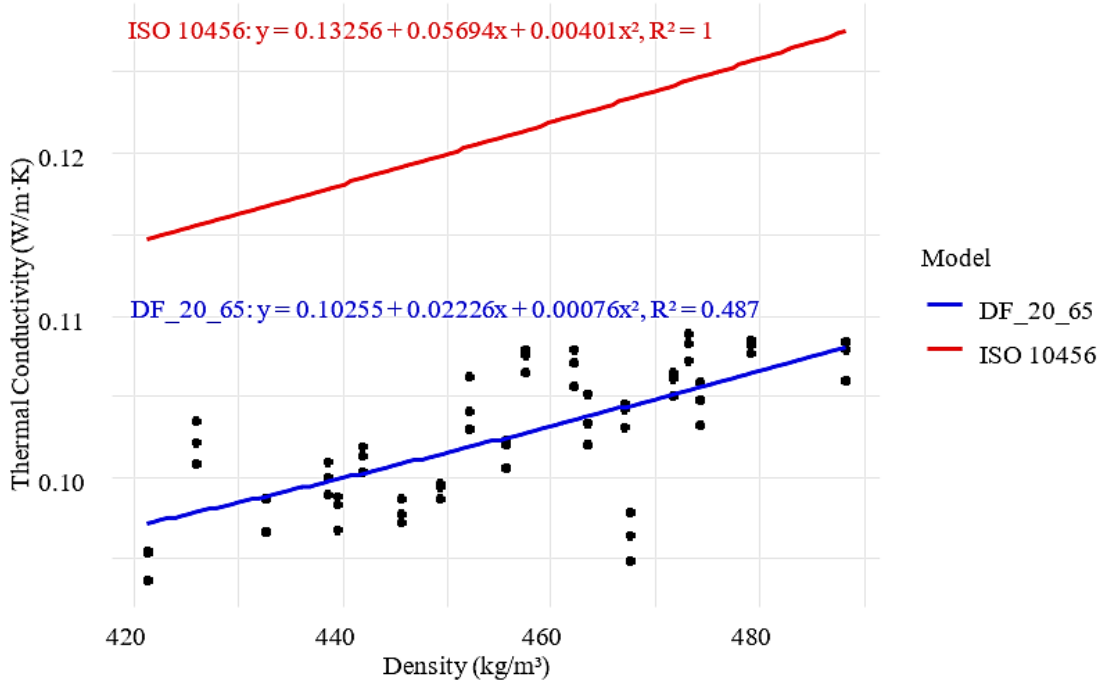
To identify key factors influencing thermal conductivity measured during experiment, a correlation matrix was generated ‘Figure 4’.

The correlation analysis confirms that:

- Density strongly correlates with thermal conductivity (r = 0.85);
- Moisture content exhibits a high correlation with thermal conductivity (r = 0.90), reinforcing its significance as contributing factor;
- Equilibrium temperature has a negligible effect ($r \approx 0.02$), further validating previous findings that temperature variations within the tested range have minimal impact.

Figure 4

Comparison of Theoretical ISO 10456 Model with Experimental Data Obtained from Samples Conditioned at Reference Conditions 20 °C and 65 % RH



To improve predictive accuracy, multiple regression models were tested using density and moisture content as key independent variables. The best-performing models are summarized in Table 3.

Table 3

Multifactor Regression Analysis Summary

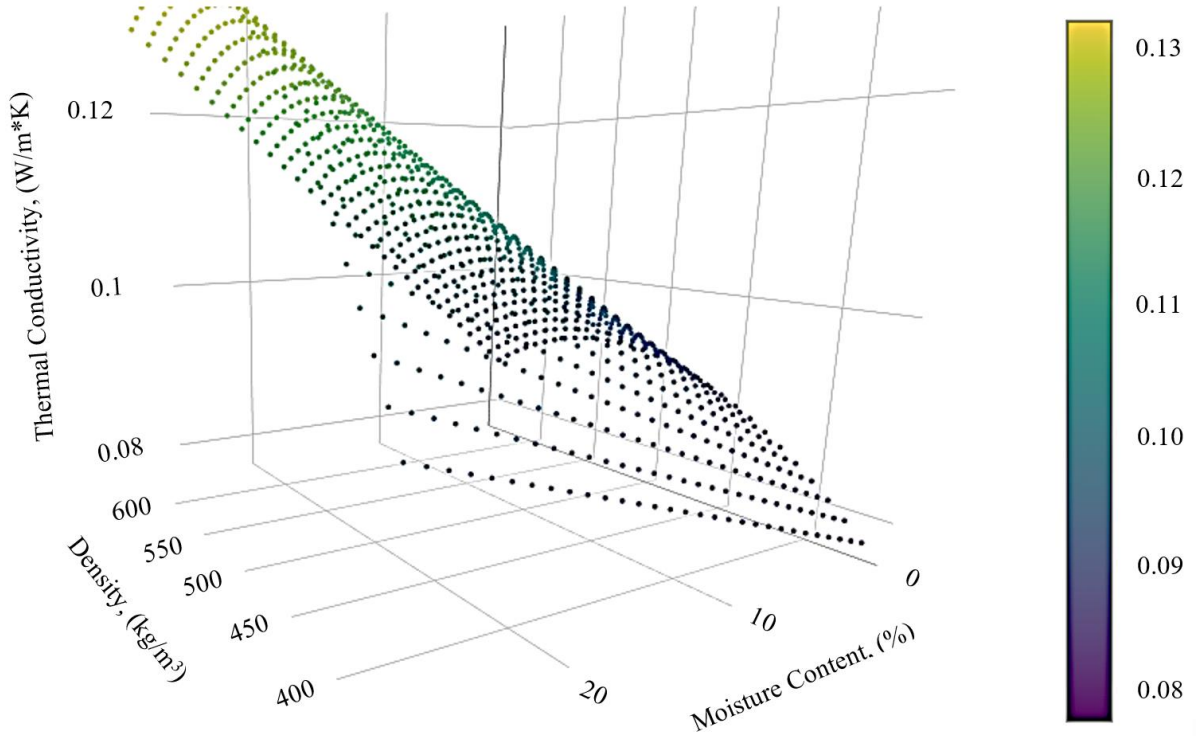
Model	***Regression Equation***	R^2
Without MC	$\lambda = 0.137\rho^2 + 0.098$	0.78
With MC	$\lambda = 0.066\rho^2 + 0.089\text{-}0.022MC$	0.87
With MC interaction	$\lambda = 0.029\rho^2 + 0.088\text{-}0.034MC + 0.102\rho\ MC$	0.88

The model incorporating moisture interaction effects provided the highest accuracy ($R^2 = 0.876$), demonstrating that moisture moderates the density-conductivity relationship. Notably, the interaction term suggests a nonlinear dependence on both factors. To better illustrate the combined influence of density and moisture content of wood on thermal conductivity, a 3D regression surface plot ‘Figure 5’ was generated using best-performing model. The surface plot visually confirms that:

- Higher wood moisture content levels amplify thermal conductivity increase, particularly in denser specimens;
- At lower moisture contents, density is dominant factor, while at higher moisture levels, both variables interact significantly.

These findings suggests that future revisions to ISO thermal conductivity models should incorporate moisture-density interactions for wood-based products to improve predictive accuracy, including CLT construction products.

Figure 5
Combined influence of Density and MC of Wood on CLT Thermal Conductivity



Consistent with the fundamental solid-wood studies of MacLean (1941), Kollmann & Côté (1968) and Tenwolde et al. (1988), we observed that thermal conductivity rises with both density and wood moisture content; however, our CLT-specific data reveal λ-values at 20 °C equilibrium temperature that are roughly 10 to 15 % lower than those prescribed by ISO 10456, a divergence that mirrors the field findings of Flexeder et al. (2021) and signals that the standard reference data tables may need updating for modern mass-timber products.

Conclusions

1. Experimental results confirm that CLT thermal conductivity is strongly correlated with density and wood moisture content, while thermal equilibrium effects on the measurements were found to be insignificant.
2. An increase in moisture content leads to a rise of CLT thermal conductivity, with this effect being more pronounced in higher density samples.
3. When comparing experimental data with ISO 10456 standard values, systematic discrepancies were observed – the standard models overestimate thermal conductivity across different density categories, potentially leading to inaccuracies in building energy efficiency calculations.
4. The obtained data suggest that interaction between moisture and density in CLT is a significant factor that should be considered when designing buildings, particularly in external envelope applications.
5. The study's findings provide a contribution to refining the thermal properties of CLT and offer improvements for updating standards and regulations related to the energy efficiency of mass timber structures.
6. The results contribute to a better understanding of how moisture and density influence CLT thermal conductivity and offer practical guidance for further investigation of laminated wood-based products.

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SHAPING THE FUTURE OF FOOD: GLOBAL INFLUENCES AND STAKEHOLDER ROLES

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Abstract
The food and beverage industry (F&BI) has traditionally been perceived as less innovative than high-tech sectors. This perception largely stems from the critical role of food in public health, which necessitates stringent and often protracted approval processes for novel products and technologies. Additionally, consumer adoption of food-related innovations tends to be cautious, influenced by safety concerns and a general aversion to risk. Recent advancements in food processing technologies, such as automation, digitalization, and novel preservation techniques, offer significant improvements in food quality, shelf life, and production efficiency. The food and beverage industry (F&BI) demonstrates significant variation in innovation dynamics, characterized by differences in innovation focus and acceptance, as well as in the intensity of drivers and barriers across diverse environmental contexts. This study seeks to investigate the underlying factors and contextual conditions that may account for these divergences. It aims to identify and analyze the drivers shaping innovation trends and dynamics within the F&BI. Drawing on a systematic review of 48 peer-reviewed publications, the research examines these drivers at two levels: global macro-level trends and sector-specific factors influenced by key stakeholders: consumers, companies, and public authorities. The paper further introduces a conceptual model that outlines the hierarchy and interrelations among these factors, emphasizing their combined influence on the direction and intensity of innovation within the sector. The model suggests that the predominant focus - whether on consumers, businesses, or state authorities - shapes differential responses to the identified factors.
Keywords: food and beverage industry, innovation, future food trends, food-processing factors.

Introduction

The food and beverage industry (F&BI) is one of the largest manufacturing sectors globally. In Europe, it generated a turnover of €1.196 trillion and contributed €249 billion in added value in 2021, employing approximately 4.7 million people and attracting €45 billion in investments (FoodDrinkEurope, 2024).

Despite its economic significance, the industry has a substantial environmental footprint, characterized by high resource consumption and considerable greenhouse gas (GHG) emissions. It ranks as the fifth-largest contributor to GHG emissions within the EU manufacturing sector, with an estimated 59 million tonnes of food waste recorded in 2022 (FoodDrinkEurope, 2024). In response to these environmental challenges, policy initiatives such as the Farm to Fork Strategy have been introduced to promote sustainable production, reduce waste, and support the transition toward a circular economy. Concurrently, industry actors are increasingly adopting advanced technologies, such as the Internet of Things (IoT), blockchain, and artificial intelligence (AI) - to enhance supply chain transparency and reduce inefficiencies (Arowosegbe et al., 2024).

As a strategically important sector, the F&BI represents a convergence of traditional manufacturing practices and emerging technologies, aimed at improving food safety, quality, and sustainability.

This study conducts a structured literature review to examine the key factors influencing current innovation trends in the F&BI. It explores the hierarchy, interdependencies, and interactions among these factors, with a primary focus on the European context, complemented by global comparisons. The aim is to identify future opportunities for development and transformation within the industry.

Factors Influencing the Development of the F&BI

A total of 48 peer-reviewed publications were analyzed to identify the key drivers shaping the development of the F&BI. Based on the literature review, this study categorizes these drivers into two principal groups: Global Framework Factors and Stakeholder-Driven Factors, emerging from the actions and responses of key industry stakeholders: consumers, companies, and public authorities (Table 1).

This classification aims to clarify the subordination and interconnections between the global and stakeholder-level influences, thereby providing a more nuanced understanding of their collective impact on innovation within the sector.

Table 1
Number of reviewed articles

Factor	***Papers***
Global factors	**15**
Economic and Demographic Factors	5
Regional and ethnic culture	2
Climate changes	3
Global crises	5
Key stakeholders	**33**
Customer demand	14
Business interest	7
Public authorities	12

1. Global Framework Factors

Global framework factors define the structural conditions that shape the functioning of the F&BI. Within the existing literature, we have identified and categorized the following factors as global:

1.1. Economic and Demographic Factors

Economic and demographic factors significantly impact the F&BI on both global and regional scales.

The growing population is expected to lead to a substantial increase in global food demand, projected to rise by 102% by 2050, driven by both population growth and rising per capita income, particularly in developing countries, which in turn generates heightened demand for food products and necessitates the adoption of sustainable production methods. (Fukase & Martin, 2020).

Addressing **food security** concerns requires strategies that ensure the availability of sufficient, high-quality food while addressing malnutrition and equitable distribution. This demand places pressure on land, water, and energy resources, exacerbated by climate change and the need to mitigate the environmental impact of food systems (Godfray et al., 2010).

Demographic shifts represent another global factor impacting the trends in the F&BI. The aging population stimulates the so-called 'silver economy', which encompasses the production, distribution, and consumption of goods and services tailored to the needs of older consumers. This demographic shift increases the demand for products that address health, nutrition, and quality of life (Delalay et al., 2024).

Sustained migration introduces diverse culinary traditions to host countries, leading to increased demand for a variety of food products. This diversification prompts the F&BI to adapt by expanding product lines to cater to new tastes and preferences. For instance, in the United States, demographic trends, including increased diversity brought about by immigration, may cause overall consumer demand for certain types of foods to grow faster than others. This shift necessitates adjustments in food production to meet the evolving demands of a diverse consumer base (Dong & Stewart, 2022). As immigrants acculturate, their food consumption patterns may begin to resemble those of the native-born population. This process can lead to changes in demand for certain food products.

Economic factors are the next group influencing the food-processing trends. Higher income levels lead to a shift in consumer demand from food quantity to quality, driving innovations focused on enhancing food attributes and quality (Figiel & Kufel-Gajda, 2017). **Inflation** affects the relative prices of goods, which can influence the demand for certain food products and subsequently drive innovation in those areas. A decrease in the relative price of a good due to inflationary pressures can lead to increased demand and innovation in that product category.

1.2. The regional and ethnic culture

The F&BI is deeply affected by **cultural heritage and local habits**, which shape consumer preferences and are a driver or a barrier to innovation. Food choices are deeply tied to cultural identity, values, and lifestyle. Consumers often select foods that reflect their cultural heritage, which in turn influences food production systems to cater to these preferences. This connection between food and cultural identity can drive demand for traditional and ethnic foods, impacting the types of products that F&BIs prioritize. The food industry faces the challenge of balancing innovation with the **preservation of traditional foods**. While there is a push to develop new products that align with modern trends, maintaining the authenticity and identity of traditional foods remains important. This duality influences how F&BIs innovate while respecting cultural heritage (Csergo, 2018). **Globalization** is another driver. The increasing interconnectedness of global markets fosters the spread of diverse food cultures, fuelled by immigration and travel. This process introduces new food preferences and dietary habits into local markets. For example, the influx of immigrants into Europe and the USA has expanded the demand for kosher, halal, and ethnic foods, prompting local producers to diversify their product portfolios. Furthermore, globalization stimulates innovation by facilitating cross-border collaboration between research institutions, technology developers, and food producers. Cultural globalization affects how food is marketed and consumed, blending local and global influences. This 'glocalization' can lead to the adaptation of traditional foods to fit global tastes, impacting how F&BIs develop and market their products (Csergo, 2018). The impact of globalization and innovation in the F&BI extends to social and cultural transformations. These innovations can modify consumer eating patterns and affect broader social and cultural domains, underscoring the necessity for strategies that integrate both technological advancements and social dynamics (Earle, 1997).

1.3. Climate change

Climate change exerts a profound influence on the global food supply and its future development, significantly affecting the trend in the F&BI as part of the food supply chain.

Rising global temperatures contribute to the increased frequency and intensity of droughts, wildfires, and extreme weather events such as hurricanes, floods, and hailstorms. These phenomena accelerate the depletion of natural resources, degrade arable land, and impair both the quality and adequacy of food, ultimately resulting in reduced agricultural yields. An illustrative example is the adverse impact on olive production due to persistent drought conditions in 2023. Consequently, olive oil production in Europe experienced a significant decline, with prices rising by 69.29% compared to 2022 (EUROSTAT, 2025).

Rising temperatures and **shifting aquatic ecosystems** are expected to alter the distribution and abundance of fish and shellfish populations, further threatening food supplies derived from marine and freshwater sources (Myers et al., 2017).

The excessive use of chemical fertilizers poses another challenge, as it contributes to environmental pollution, including soil contamination and nutrient leaching. The detrimental effects of chemical fertilizers begin with the processing of chemicals,

which release harmful by-products and gases such as NH4, CO2, and CH4, contributing to air pollution (Bisht & Chauhan, 2020). Furthermore, **the untreated disposal of industrial waste** into nearby water bodies leads to water pollution and eutrophication - an accumulation of chemical waste in aquatic environments that depletes oxygen levels and threatens biodiversity. Prolonged application of chemical fertilizers degrades soil health and quality, resulting in soil contamination and reduced agricultural productivity (Bisht & Chauhan, 2020).

Climate change not only affects food quantity but also its nutritional quality. Crops may yield smaller harvests with lower nutrient concentrations, potentially exacerbating nutritional deficiencies. The overall reduction in consumable food calories reduces the availability of energy-providing food, increasing health risks such as malnutrition and anemia (Leisner, 2020). Consequently, food scarcity and concerns about food security escalate, particularly in vulnerable communities that struggle to access essential resources such as water, fertile land, and food.

The consequences of climate change stimulate extensive research and innovation within the food and beverage industry, focusing on improving nutritional value across the entire food supply chain. Additional focal points of development include minimizing food waste, optimizing storage methods, and extending the preservation of nutritional qualities.

1.4. Global crises

The COVID-19 pandemic has posed economic and structural challenges to the F&BI, disrupting supply chains and increasing operational costs, leading to food price volatility. This volatility affected both producers and consumers, highlighting the fragility of global food supply systems under crisis conditions. Vasylieva (2021) reports stable prices for bread and vegetable oil in Eastern Europe, while fruit and potato prices declined due to distribution issues. In Ukraine, sugar prices rose amid economic hardship, while eggs became a key protein alternative, contrasting with price drops for pork, poultry, and eggs in Poland and Slovakia. Concurrently, demand for home meal replacements, meal-kit services, and online food ordering surged, driven by consumer preferences for convenience and safety (Lee & Ham, 2021).

The pandemic accelerated consumer interest in alternative proteins and sustainable food practices, leading to increased investments in bioactive food compounds and environmentally responsible supply chains (Galanakis et al., 2021).

The war conflicts further destabilized supply chains, raising food prices and exacerbating food insecurity. Ukraine's reduced capacity to produce essential crops, such as wheat and maize, and rising input costs, notably for fertilizers, have strained global food availability and increased prices (Countryman et al., 2024).

Historical evidence suggests that military conflicts drive innovations in logistics, with local food supply solutions fostering advancements later applied to civilian food systems (Danzer et al., 2023). The combined effects of the pandemic and ongoing conflicts underscore the need for innovative, sustainable, and localized food-processing solutions to ensure food security in times of crisis.

2. Stakeholder-Driven Factors

2.1. Customer demand

Global trends shape consumer preferences in the food industry. The COVID-19 pandemic, in particular, has influenced a resurgence in home cooking, increasing the demand for staple foods and healthier alternatives. Consumers now exhibit a greater preference for nutritious, sustainable, and ethically produced food options while reducing food waste. This shift aligns with changes in food choice motives, emphasizing health, natural ingredients, and ethical considerations (Borsellino et al., 2020).

Lifestyle changes, particularly in developed economies, have contributed to the increasing demand for convenience foods. Studies indicate that when selecting these products, consumers prioritize sensory appeal, nutritional value, and safety, as these factors significantly impact purchase intentions and overall satisfaction (Imtiyaz et al., 2021). The demand for high-quality, convenient meat and fish products that retain natural flavor and nutritional integrity has increased, supporting findings that highlight the importance of convenience without compromising health (Banerjee & Verma, 2014). However, research indicates that the convenience of processed foods may come at the cost of nutritional quality and safety. Regular consumption of processed convenience foods has been associated with suboptimal dietary choices, raising concerns regarding consumers' prioritization of nutrition and food safety (Jackson & Viehoff, 2016). Additionally, studies indicate that while consumers seek convenience, they frequently select foods high in sugar, fat, sodium, and cholesterol, negatively impacting dietary quality and health (Zhang & Gallardo, 2022).

A growing trend towards healthier and more pleasurable eating experiences is driven by **increased health awareness**. The food industry is responding by reformulating products with healthier ingredients and leveraging health claims to attract consumers. For example, beverages labeled as 'no/low sugar' or 'no artificial sweeteners' have gained popularity (Zhou & Liu, 2024). Younger consumers, particularly university students, prefer functional beverages aligned with their health values. Studies indicate a willingness to pay a premium for healthier food options, particularly those rich in whole grains, reduced fat, and added fruits and vegetables, with variations based on age, gender, and health consciousness (Alsubhi et al., 2022).

Consumer preference for healthy food is closely linked to ingredients and production process transparency. **Concerns over food safety, environmental impact, and ethical production** drive the demand for clearer labeling and supply

chain traceability (Meijer et al., 2021). Transparency plays a critical role in restoring consumer trust, particularly regarding food processing and ingredient sourcing (Meijer et al., 2021). In complex food supply chains, transparency is essential for ensuring food quality and safety. Sustainability and clean-label products are gaining traction, requiring simpler ingredient lists and transparent sourcing practices (Choi et al., 2023). This trend has led companies to adopt more responsible ingredient sourcing and production methods. For instance, clean-label antimicrobials in dairy products reflect this shift toward consumer-friendly labeling (Choi et al., 2023).

Animal welfare considerations are also playing an increasing role in consumer purchasing decisions. Studies indicate that many consumers are willing to pay a premium for products that meet higher welfare standards (Napolitano et al., 2010). Labels indicating compliance with animal welfare standards are gaining relevance in the retail sector, enhancing informed consumer choices and positively impacting sales (Akaichi & Revoredo-Giha, 2020). The rise of innovations in alternative protein sources, particularly plant-based products and cultured meat, is driving a significant transformation within the food industry. These advancements address the concerns related to animal welfare and also environmental and health challenges associated with conventional meat production. **Sensory attributes, such as taste and color,** also influence consumer acceptance of new food products with preferences shaped by demographic factors including age, health status, and cultural background (Ueland et al., 2020).

Food customization is emerging as a trend allowing consumers to tailor products to their preferences, thereby increasing purchase intentions. Research indicates that consumers with greater food expertise exhibit a stronger inclination toward customized products, making personalization strategies an effective market approach (Li et al., 2022). This shift is driving mass customization within the food industry, balancing product variety with efficient production processes to cater to diverse consumer demands (Kanama, 2018).

2.2. The business perspective

In their innovation and business strategies, producers in the F&BI are influenced by factors such as **operational efficiency, profit margins, overall profitability, market share, and long-term strategic objectives**. These determinants drive innovation, strategic partnerships, and competitive positioning.

Manufacturers within the F&BI prioritize both profit expansion and customer profitability, though the emphasis varies according to specific strategic approaches and prevailing market conditions (Wetzel et al., 2024). The focus on profitability is influenced by various factors, including operational efficiency, market power, and financial management.

Technological determinants, including the availability of research infrastructure, resources, and complementary expertise, are other factors influencing the trends within the F&BI. These elements facilitate the adoption and advancement of innovative technologies, which, in turn, influence industry evolution. Firms with strong technological capabilities and absorptive capacity are more likely to integrate new technologies, thereby enhancing food preservation, quality, and safety (Priyadarshini et al., 2018). Industry 4.0, characterized by advancements such as artificial intelligence (AI), the Internet of Things (IoT), and robotics, is transforming food production, distribution, and consumption. These technological advancements have enabled the emergence of novel food trends, including 3D-printed foods and personalized nutrition while addressing global challenges such as climate change and food security (Hassoun et al., 2022).

The impact of a **skilled workforce** on trends within the European F&BI is substantial, as it influences innovation, strategic management, and overall sector performance. Skilled employees are fundamental drivers of innovation, facilitating the development of differentiated, high-value products that enhance competitiveness in the European market (Brickau et al., 1994). Moreover, skilled labor enables firms to respond effectively to evolving consumer preferences and market dynamics. This adaptability is crucial for addressing emerging trends in food supply chains and consumer expectations.

Pressures from large retailers and the dynamics of open markets further influence the European F&BI. The high concentration of retailers exerts considerable influence on food processors, fostering intense competition and reducing profit persistence relative to other sectors (Hirsch & Gschwandtnerq, 2013). Retailer dominance necessitates continuous innovation and product differentiation among manufacturers to maintain market share (Brickau et al., 1994).

Firm size is a key determinant of profitability and competitive advantage within the F&BI. Larger firms generally exhibit higher profitability due to economies of scale, enabling them to allocate greater resources toward innovation, workforce development, and market resilience. Consequently, they are better equipped to withstand market fluctuations (Hirsch et al., 2014). Conversely, small and medium enterprises (SMEs) frequently encounter challenges related to resource allocation, thereby constraining their competitive capabilities. To maintain competitiveness, SMEs in the F&BI are increasingly engaging in strategic alliances to augment internal competencies and enhance market management capabilities (O'Dwyer & Gilmore, 2018). Strategic alliances enable firms to strengthen internal capabilities, foster innovation, and differentiate their products, which is essential for sustaining competitiveness in the European market (Brickau et al., 1994).

2.3. Public authorities

Regulatory frameworks shape the F&BI by establishing food safety, quality, and sustainability standards. European legislation enforces stringent requirements concerning traceability, production practices, and consumer protection, often exceeding international benchmarks (Curtis, 2019). Compliance requires substantial effort from businesses, impacting resource allocation and operational strategies (Curtis, 2019). However, regulatory harmonization across the European Union (EU) fosters trade, competition, and industry efficiency (Vancauteren & Henry de Frahan, 2011). The EU regulations emphasize sustainability, encouraging food businesses to adopt environmentally responsible practices, such as utilizing food processing by-products and integrating sustainability criteria into food safety standards (Rao et al., 2021).

Regulations can either facilitate or hinder innovation. Legal clarity supports high food safety and consumer protection standards, fostering an environment conducive to innovation, as seen in the dairy alternatives sector (Leialohilani & De Boer, 2020). Additionally, the revised Novel Food regulations incentivize innovation by enhancing data protection (Grimsby, 2022). However, regulatory constraints, such as high compliance costs, may impede the adoption of novel products, particularly for SMEs (Lähteenmäki-Uutela et al., 2021).

A comparative analysis of global regulatory environments reveals differing approaches. The U.S. regulatory framework is generally more flexible, fostering rapid adaptation and innovation (Roberts & Leibovitch, 2010). China's regulatory measures prioritize economic development, influencing investment in food-processing technologies (Song & Zhang, 2023). While European regulations focus on consumer protection, their complexity may slow innovation compared to more adaptable frameworks in the U.S. and China.

State support strategies also impact innovation. In Europe, collaboration with universities and industry stakeholders plays a crucial role in fostering innovation, whereas financial support mechanisms have been less effective (Ciliberti et al., 2015). Eco-innovation is central to transitioning towards a circular economy, with product and process innovations shaping sustainability efforts (Hamam et al., 2022). In the U.S., market-driven strategies and substantial private-sector R&D investments dominate (Mohamedshah et al., 2020). Meanwhile, China's innovation-driven economic policies emphasize high-tech sectors, influencing food-processing advancements (Xiao et al., 2022). These regulatory and economic dynamics highlight the intricate relationship between policy, innovation, and market development in the global food industry.

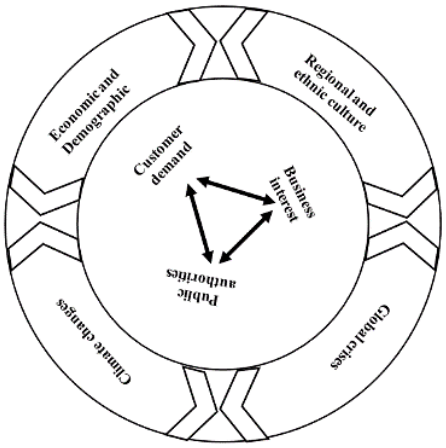
Results and Discussion

The analysis aims to systematically structure the factors influencing trends in the food and beverage industry, drawing on a comprehensive systematic literature review. The proposed framework, illustrated in Figure 1, outlines the hierarchical relationship and interdependence between global drivers and stakeholder-dependent factors.

The framework serves as a foundation for forecasting the future development of food technologies and products, while also enhancing the understanding of existing constraints and barriers.

Figure 1

Subordination and Interdependence of the factors



Key emerging trends include a growing focus on environmental sustainability, enhanced quality of life, and a transition toward healthier dietary patterns. The aging population - linked to the concept of the 'Silver Economy' - further underscores the relevance of personalized nutrition. Current market dynamics reflect a heightened demand for convenient yet health-conscious food options, including functional foods, reduced meat consumption, and personalized diets. These changes are motivated by both ethical concerns and a broader pursuit of healthier lifestyles. The increased access to information and advancements in artificial intelligence are expected to accelerate these shifts.

Cultural and traditional values play a significant role in shaping regional regulatory frameworks. For instance, Europe generally adopts a more conservative regulatory approach, particularly in limiting the adoption of technologies such as genetically modified organisms (GMOs), despite potential inefficiencies and elevated costs. Conversely, the United States maintains a more liberal regulatory environment, where innovation is often driven by business interests rather than consumer demand. While this facilitates technological progress, it can also lead to the production of nutritionally suboptimal or potentially harmful food products. In China, a centralized, state-driven policy model prioritizes food security and economic growth, influencing the direction of industry development.

These divergent policy approaches are reflected in the intensity of regional R&D activities. In 2021, R&D expenditures in the food and beverage industry as a percentage of turnover were 1.6% in China, 0.7% in

the United States, and 0.3% in the EU27 (FoodDrinkEurope, 2024).
Potential limitations of this study include the omission of certain influencing factors and the need for further refinement of the framework's classification and hierarchy. Future research should aim to expand and validate the model through empirical investigation and the integration of additional variables.

Conclusions

1. Global factors (Table 2) - economic and demographic trends, regional and ethnic cultures, climate change, and global crises—collectively shape the environment in which the F&BI evolves. These factors influence the direction, dynamics, and impact of key stakeholders, namely consumers, companies, and state authorities (Table 3).

2. The predominant stakeholder focus - whether on consumers (as in the EU), businesses (as in the US), or the state (as in China) - further defines the response to changes in these global factors.

3. The proposed model provides a framework to explain the varying dynamics, priorities, and levels of acceptance of innovation within the F&BI across different regions. Despite Bulgaria's integration in the EU and access to the Single Market, including support mechanisms for innovation and R&D, companies in the sector invested on average only 0.06% of their output in R&D between 2019–2021 - well below the EU average of 0.24% (FoodDrinkEurope, 2024). This disparity may reflect the influence of factors outlined in the proposed model. Further research is required to test this hypothesis and substantiate the observed trends.

Table 2

Global Factors

Economic and Demographic Factors	***Regional and ethnic culture***	***Climate changes***	***Global crises***
• growing population • rising income per capita • food security • demographic shifts • sustained migration • inflation	• cultural identity, values, and lifestyle • preservation of traditional foods • globalization and 'glocalization'	• rising global temperatures • shifting aquatic ecosystems • excessive use of chemical fertilizers • untreated disposal of industrial waste	• the COVID-19 pandemic • the war conflicts

Table 3

Stakeholder-Driven Factors

Customer demand	***Business interest***	***The state authority***
• demand for nutritious, sustainable, and ethically produced food • lifestyle changes • increased health awareness • concerns over food safety, environmental impact, and ethical production • animal welfare considerations • sensory attributes, such as taste and color	• operational efficiency • profit margins • overall profitability • market share • long-term strategic objectives • technological determinants • skilled workforce • pressures from large retailers and the dynamics of open markets • firm size	• regulatory frameworks • state support

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DEFENCE INNOVATION ECOSYSTEMS AND RURAL ECONOMIC DEVELOPMENT: PATHWAYS TO SUSTAINABLE GROWTH AND MILITARY ADAPTATION

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Abstract
The full-scale war in Ukraine and the shifting geopolitical landscape have prompted European nations to reassess their defence strategies. Latvia has identified defence innovation as a strategic priority, with growing emphasis on integrating rural regions into its Defence Innovation Ecosystem (DIE). This study examines the structure, mechanisms, and development pathways of Latvia's DIE specifically focusing on the role of rural integration in regions such as Latgale. Through a systematic review of academic literature and national policy documents, the paper analyzes stakeholder roles, institutional coordination, and policy frameworks. It highlights concrete measures including the establishment of test and evaluation sites in Latgale, targeted Ministry of Defence grant programs for dual-use technologies, and national action plans aimed at decentralizing innovation. While public investment has increased, rural engagement remains constrained by infrastructural limitations, low SME participation, and funding disparities. The paper offers targeted policy recommendations to enhance rural innovation potential, align with NATO and EU frameworks, and support sustainable, innovation-led defence development in small states.
Keywords: defence innovation ecosystem, national security, rural development, public-private partnerships.

Introduction

In response to escalating geopolitical risks, particularly Russia's actions in Ukraine, European leaders have emphasized the urgent need to enhance defence readiness (Centrone & Fernandes, 2024). Innovation plays a critical role in strengthening national security, serving as a catalyst for advanced defence capabilities (Langham & Wrigley, 2020). Reflecting this global trend, the United States increased its research, development, test, and evaluation (RDT&E) spending by 9.4% in 2023, continuing a focus on advanced systems since 2014 (Tian et al., 2024). Sustained investment in research and development (R&D) remains essential for fostering defence innovation.

Innovation ecosystems dynamic networks of diverse stakeholders are key drivers of economic growth and competitiveness. Their resilience depends on consistent government support and legal frameworks (Abdi et al., 2024). As collaborative platforms, they enable technological advancement across sectors (Caliari et al., 2024; Thomas & Autio, 2019).

Rural regions are integral to national economies and are increasingly relevant to defence innovation efforts (Cabinet of Ministers of the Republic of Latvia, 2025). Regional development in the Baltic States is supported by international actors like the World Bank and European Commission, especially in vulnerable border areas. Digitalisation and community engagement are essential for rural resilience and autonomy (Nasution et al., 2025).

Defence Innovation Ecosystems (DIEs) vary significantly across countries based on strategic needs, policy frameworks, and geopolitical context (Budden & Murray, 2019). Studies from Ukraine, Armenia, Malaysia, and others illustrate different models shaped by national priorities (Hmyria et al., 2024; Harutyunyan, 2024; Balakrishnan & Johar, 2023). The DIE's form reflects assessments of threat levels, military readiness, and regional security dynamics (Kumar, 2017).

Latvia's DIE is rooted in its post-1990 independence trajectory and NATO/EU membership since 2004, relying on allied security guarantees (North Atlantic Treaty Organization, 1949). Its defence policy reflects geographic proximity to Russia, modest size, and strategic alliances. Though Latvia committed to a 2% GDP defence target by 2020, economic constraints delayed progress (Rublovskis, 2014). More recently, growing U.S. pressure to increase defence spending to 5% of GDP (Hendrix, 2025) has prompted Latvia to adopt a more proactive security strategy (Sprūds, 2025). While defence innovation spending is increasing, research on DIE mechanisms especially in rural integration remains limited. Understanding Latvia's DIE structure and its link to regional development is essential for informed policymaking. Most existing studies focus on broader defence policy, not ecosystem dynamics or rural contributions.

Research question: How does the DIE in Latvia function, and what are its implications for rural development and economic growth?

Aim: To analyze the structure, mechanisms, and policy frameworks of Latvia's DIE, with a focus on its impact on rural development.

Objectives: 1) Define key concepts and frameworks; 2) Identify primary stakeholders; 3) Propose policy recommendations to enhance innovation-driven military adaptation.

This paper concludes with strategic recommendations for aligning Latvia's DIE with NATO and EU priorities and identifies future research directions.

Limitations: Due to limited scholarly focus and the confidentiality of defence data, the study relies heavily on grey literature and policy analysis. Latvia's small research community and the scarcity of defence-specific academic publications further constrain comprehensive insights. Notably, no prior research has

addressed rural contributions to Latvia's DIE or benchmarked it internationally.

Materials and Methods

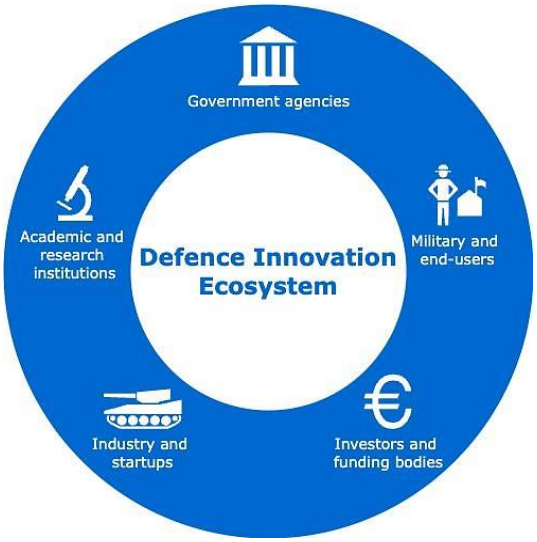
This scientific article adopts realism as its ontological stance and positivism as its epistemological foundation. The research object is the development and functioning of defence innovation ecosystems, with a particular focus on their impact on rural economic development within NATO and EU member states. This study is qualitative in nature and is based on a narrative literature review combined with grey literature analysis. These methods are particularly suited for exploring complex and evolving phenomena where primary data collection is not feasible. A narrative literature review is used to provide a broad, interpretive synthesis of existing scientific and policy knowledge, rather than to systematically analyze all available data. Relevant scientific studies and grey literature were identified through a systematic search in the Scopus academic database and via Google search, using keywords such as 'defence innovation ecosystem', 'rural development', 'rural economic development', 'defence expenditure', 'innovation ecosystem', 'defence industry', and 'national security and military capabilities'. The search focused on the subject areas of Social Sciences, Economics, Econometrics, and Finance, and was geographically limited to exclude Russia and Belarus. Only English-language publications from 2019 to 2025 were considered. While this approach provides a comprehensive overview of the topic using publicly available data, it has certain limitations. Chief among these is the lack of primary data, which constrains the ability to validate findings through empirical fieldwork or stakeholder interviews. Furthermore, the reliance on policy documents and secondary sources may introduce bias or restrict the depth of insight into real-world implementation dynamics.

Definition and conceptual framework

The author proposes the concept of a DIE to highlight the necessity of strengthening national security and military capabilities through technological advancements and cross-sector collaboration. As illustrated in Figure 1, an innovation ecosystem is a dynamic network of actors including government agencies, academic institutions, private industry, military and investors working together to drive technological breakthroughs and economic growth (Caliari et al., 2024). While the general principles of innovation ecosystems have been widely studied (Thomas & Autio, 2019; Granstrand & Holgersson, 2020; Alka et al., 2024; Sotirofski, 2024), DIEs exhibit distinct characteristics due to their reliance on national security policies, strategic alliances, and military needs. An innovation ecosystem consists of actors, artifacts, and activities interconnected through complementary and substitute relations. Additionally, institutions and the evolving nature of these ecosystems play a crucial role (Granstrand & Holgersson, 2020). The key definitions of the study's main concepts are outlined in Table 1. While the list could be expanded and refined, these represent the most essential concepts.

Figure 1

Key stakeholders in Defence Innovation Ecosystem



Conceptual framework of the defence innovation ecosystem

The DIE framework builds upon existing innovation ecosystem theories but integrates security-related constraints, regulatory mechanisms, and strategic imperatives. It is influenced by national policies, defence budgets, geopolitical pressures, and technological advancements.

Figure 2

Innovation mechanisms within Defence Innovation Ecosystem

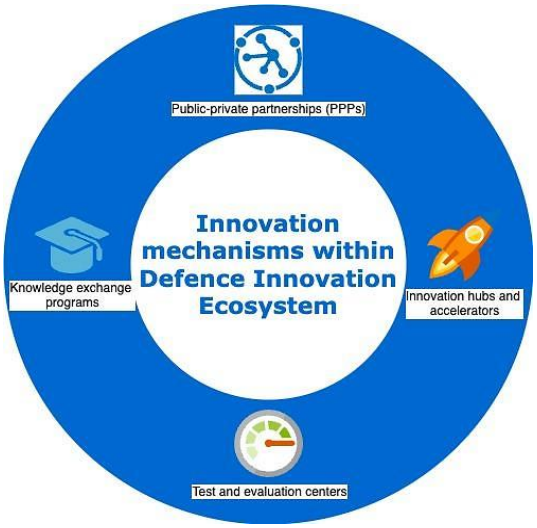


Table 1
Definition of key concepts

Concept	***Definition***	***Reference***
Defence Innovation Ecosystem	Network of stakeholders (gov., industry, academia, NGOs) collaborating on defence tech.	Authors definition
National Security and Military Capabilities	Ensures sovereignty and safety through policy and military strength.	Szpyra, 2014
Rural Economic Development	Enhancing rural economies via agriculture, infrastructure, and sustainability.	Wang, 2023
Innovation Ecosystem Resilience	Ecosystem's ability to adapt and recover from disruptions.	Abdi et al., 2024
Triple Helix Model	Collaboration between academia, industry, and government for innovation.	Cai & Amaral, 2021
Technology Transfer	Movement of tech/knowledge across entities to boost development.	Günsel, 2015
Dual-Use Technologies	Technologies with both civilian and military applications.	Vaynman & Volpe, 2023

Governance and policy frameworks
National and international regulations influence the structure of DIEs. For instance, in the European context, the European Defence Fund (EDF) plays a crucial role in funding defence R&D and fostering collaboration across member states (Lawrenson & Sabatino, 2024). Strategic initiatives such as NATO's Defence Innovation Accelerator for the North Atlantic (DIANA) encourage the development of cutting-edge military technologies by leveraging startups and small enterprises (NATO DIANA, 2024; Szkurłat, 2024). Beyond military applications, DIEs contribute to broader economic development, particularly in rural regions where defence industries can drive employment and infrastructure investments. A strong DIE fosters supply chain resilience, reducing dependency on foreign defence suppliers.

Results and Discussion
This research explored interconnected areas to better understand the DIE. To achieve this, it was essential to first comprehend what constitutes an innovation ecosystem, its components, various models, operational mechanisms, and resilience assessment. Rural development plays a crucial role in the DIE, as innovation can emerge in any region nationally, in capital cities, urban centers, or rural areas. R&D spending on defence is a key factor, encompassing both national and international support aimed at fostering defence innovation. Understanding the impact of innovation on national security and capabilities, as well as its economic influence particularly on rural development is vital. To achieve this, further in-depth and focused studies are needed, examining specific use cases across the innovation lifecycle, assessing their implications for security and economic growth.

Comparative concentration of defence innovation infrastructure: Urban vs. rural
Despite the Latvian government's efforts to promote regional development, defence innovation infrastructure remains largely concentrated in urban areas, particularly in and around Riga. Rural regions like Latgale, though emphasized in strategic documents, still face significant infrastructure and capacity gaps. While urban centres host the majority of defence companies, accelerators, and university-linked R&D hubs, rural regions have only recently begun to see the emergence of test sites or minor manufacturing capacity.

Table 2
Approximate distribution of defence innovation infrastructure in Latvia

Type of Infrastructure	***Urban (e.g., Riga, Jelgava)***	***Rural (e.g., Latgale)***
R&D centres	80%	20%
Dual-use industrial capacity	70%	30%
Startups engaged in DIE	85%	15%
Test sites and proving grounds	40%	60%
Public-private innovation initiatives	90%	10%

These are estimated figures outlined in Table 2 based on policy document content, hackathon locations, and known investments from Ministry of Defence (e.g., Rezekne Hackathon 2025). They illustrate a stark imbalance in innovation density and accessibility.

Regional disparities in defence grant funding

Grant funding provided by the Ministry of Defence between 2020–2024 has been predominantly awarded to organizations located in or near urban areas. Precise geospatial data is not publicly available; however, anecdotal evidence from news releases and project announcements suggests that rural applicants are significantly underrepresented among successful recipients. Key observations: 1) In 2024, out of 5 grant beneficiaries, only 1 was from a rural region (Rezekne); 2) In previous years (2020–2022), no rural-based projects were highlighted in MOD publications; 3) There is no dedicated rural stream or priority indicator in existing grant calls.

Policy gap analysis: Rural barriers and enablers in defence innovation (SWOT)

In the absence of fully disaggregated data, the following SWOT analysis (Table 3) outlines systemic issues and opportunities affecting rural engagement in the defence innovation ecosystem.

Table 3

SWOT analysis: Rural participation in Latvia's DIE

Strengths	**Weaknesses**
Strategic assets (test sites, low-cost land)	Limited access to R&D funding
Community interest and motivation	Talent drain to urban areas
Emerging infrastructure in Latgale	Low awareness of MOD programs
Government policy support (Action Plan 2025–2027)	Few linkages with industry leaders
Opportunities	**Threats**
EU and NATO funding for rural tech	Continued concentration of innovation in Riga
Dual-use tech deployment for civilian use	Infrastructure decay without investment
International collaborations (e.g., NATO DIANA)	Bureaucratic barriers for SMEs in periphery

Policy gap analysis reveals that despite strategic potential and emerging initiatives in rural regions, systemic barriers such as limited funding access, low institutional connectivity, and talent outmigration continue to hinder their full integration into Latvia's Defence Innovation Ecosystem.

Key mechanisms of defence innovation ecosystem

The evolving technological landscape and shifting geopolitical dynamics influence the long-term relevance and applicability of defence innovation (Girardi, 2024). As noted by the Massachusetts Institute of Technology (MIT) report (Budden & Murray, 2019), there is no universal approach to defence innovation. Countries are adapting established practices, and the Defence Innovation Ecosystem (DIE) described by MIT includes entrepreneurs, government agencies, universities, corporations, and risk capital providers. In Malaysia, key R&D stakeholders include the government, end-users, industry, and academia, who collaborate to advance technology through policy, research, development, and funding (Balakrishnan & Johar, 2023). The traditional Triple Helix model falls short in defence, as globalization necessitates international collaboration, especially in Europe (Cai & Amaral, 2021). The Quintuple Helix model better reflects modern needs by integrating environmental and technological factors, while emphasizing R&D investment and cooperation among defence firms, academia, and military centers (Reis et al., 2022). In the Dutch defence sector, spin-ins from civilian R&D dominate, with SMEs playing a leading role. Civilian-developed IT, supported by the Triple Helix framework, sustains both defence innovation and the national economy (Sezal & Giumelli, 2022). To overcome current gaps, deeper civilian-military integration and international cooperation are essential. The Russo-Ukrainian war has spurred innovation, enabling SMEs to enter the defence sector, though funding remains a hurdle (Mészáros, 2024). Partnerships are critical for implementing external innovations (Langham & Wrigley, 2020). The Estonian anti-armor mine case supports the value of a national innovation system and multi-stakeholder approach in procurement success (Ploom et al., 2024). Warfare continues to drive innovation by challenging developers to support armed forces. Studying DIE culture is vital. Bloomberg emphasized flexibility and risk-taking in U.S. DOD technology adoption, advocating for 'failing fast' to improve battlefield performance. Both he and General Milley linked innovation to military superiority (Dew & Lewis, 2024). While large defence contractors dominate integration and production, smaller firms focus on innovation. Many DOD-funded projects fail to transition to production due to limited fielding budgets creating the so-called 'valley of death' (Dew & Lewis, 2024). This study thus examines DIEs in the context of leading military powers.

Ukraine's DIE relies on government, defence enterprises, research institutions, and startups, supported by procurement policies, PPPs, and international cooperation (Hmyria et al., 2024). Innovation is costly but critical for battlefield advantage. Armenia's DIE includes state and private actors in R&D and weapons production, geared toward security and economic growth (Harutyunyan, 2024). With growing global uncertainty, Europe must invest

in defence innovation to ensure technological leadership and reduce reliance on U.S. support (Bērziņš, 2024). Figure 2 highlights core innovation mechanisms in DIEs: PPPs, knowledge exchange, innovation hubs, and testing centers.

Rural development integration

The successful integration of newcomers into rural Latvia enhances local communities by leveraging their vision, knowledge, and skills, fostering remote work, driving new economic practices, and revitalizing remote and depopulated areas as valuable human resources (Kruzmetra & Bite, 2023). Financial capital within a network influences the ties actors form, with less prosperous communities creating more bridging ties to secure funding (Rahe et al., 2025).

Recent studies from Ukraine underscore the strategic relevance of agricultural and rural land for dual-use defence infrastructure. Tonkha et al. (2021) emphasize the importance of geospatial assessments in optimizing land use for both agricultural productivity and defence infrastructure planning. Their methodology, which integrates satellite imagery and GIS analysis, highlights how terrain suitability can be leveraged to identify optimal locations for test ranges, logistics hubs, or surveillance installations. Similarly, Tykhenko et al. (2024) explore how soil quality and land valuation can inform national strategies for preserving high-value farmland while enabling military use on marginal or underutilized land. Applying these insights to Latvia, particularly in sparsely populated areas like Latgale, suggests the potential for coexistence between traditional land use and strategically planned defence innovation zones.

The Ukrainian Agricultural War Damages, Losses, and Needs Review (Kyiv School of Economics, 2023) further illustrates the vulnerability and importance of rural land during conflict, detailing extensive damage to arable land, infrastructure, and ecosystems due to military operations. While Latvia is not currently experiencing armed conflict, these findings serve as a warning and a planning opportunity. By proactively integrating rural land into the defence innovation ecosystem—through resilient infrastructure, redundant supply chains, and dual-use installations Latvia can enhance both national security and rural economic resilience. Strategic land use planning, informed by environmental and economic data, will be crucial in safeguarding Latvia's food security, rural livelihoods, and territorial integrity under future threat scenarios.

The U.S. Department of Defense and major prime defence contractors are actively seeking deeper collaboration with allied and partner nations, recognizing that integrating international industrial capabilities is essential for maintaining technological superiority, strengthening global security networks, and ensuring a resilient defence supply chain (Defense Innovation Board, 2024). Integrating rural regions into the DIE requires close collaboration between the Ministry of Defence, industry associations, and regional planning authorities (Langham & Wrigley, 2020). The first step is to identify regional industrial capabilities, compile them into a centralized database, and inform the Ministry of Defence. Military production in rural areas is viable when there is a clear long-term demand (Garin & Rothbaum, 2025). Based on the Cabinet of Ministers 2025 Action Plan, the Latvian government emphasizes the development of strategic infrastructure in regions like Latgale including industrial parks, transport and dual-use facilities to attract investment, support emerging rural startups, and create conditions for job creation, talent retention, and potential test and evaluation capabilities aligned with national security objectives (Cabinet of Ministers of the Republic of Latvia, 2025). Defence innovation initiatives are being actively promoted in rural regions of Latvia, exemplified by the EUDIS Defence Hackathon 2025 held at Riga Technical University's Rezekne Academy, which brought together innovators to develop rapid defence solutions tailored to Ukraine's operational needs (Latvia's Official Legal Information Portal, 2025a). Ministry of Defence engages with NATO defence attachés to present the Defence Industry and Innovation Support Strategy 2025–2036, which aims to enhance local industrial capacities and foster innovation beyond urban centres (Latvia's Official Legal Information Portal, 2025b). The Plan for the Development of a Cohesive and Civically Active Society 2024–2027 includes measures that indirectly support innovation in rural regions by strengthening civil society, enhancing the capacity of regional NGOs, promoting volunteerism and local solidarity, and fostering civic engagement through forums and think tanks, thereby creating a supportive environment for grassroots innovation (Cabinet of Ministers of the Republic of Latvia, 2024).

Defence innovation ecosystem in Latvia

Latvia's national defence budget for 2025 is 3.45% of GDP, making it the largest defence budget in the country's history and the 4th highest defence expenditure as a share of GDP among NATO member states (NATO, 2024b). The defence budget is allocated not only to the development of military capabilities, personnel and maintenance costs, and military infrastructure but also to fostering the DIE. Latvia plans to increase funding for defence research, technology development, and innovation to 1.5% of the defence budget by 2028 (Ministry of Defence of the Republic of Latvia, 2024). However, publicly available and consolidated data on defence spending for R&D is lacking.

The Ministry of Defence's Industry and Services Policy, as defined in national strategic documents, stresses the urgent need to strengthen Latvia's defence industry in response to rising geopolitical threats. The ability of the industry to scale production rapidly is essential for the National Armed Forces (NAF) to fulfil

their roles during peace, crises, and war, while also contributing to EU and NATO capabilities. Enhancing industrial capacity ensures both operational sustainability and innovation, even in conflict situations (Ministry of Defence of the Republic of Latvia, 2024).

The Defence Industry Law (Parliament of the Republic of Latvia, 2024), adopted in 2024, creates a legal framework for fostering innovation and cooperation among government, industry, and research institutions. It promotes defence R&D, supports public-private partnerships, and facilitates the integration of emerging technologies into military use. The law also encourages local production, strengthens resilience, improves funding access, and simplifies procurement to support a robust and competitive defence ecosystem.

Table 4
Latvian defence budget

Year	*% from GDP*	*Million EUR*
2020	2.20%	700
2021	2.20%	758
2022	2.20%	800
2023	2.25%	987
2024	3.20%	1 367
2025	3.45%	1 559

Table 4 presents Latvia's defence budget as a percentage of GDP and in million EUR. However, information on defence R&D expenditures is not publicly available. To obtain this data, expert interviews with the Ministry of Defence would be required. The Central Statistical Bureau of Latvia does not have data on the use of the Ministry of Defence budget, including specifically for research.

Table 5 presents the funding amounts allocated in the **Ministry of Defence grant program** for the development of military or dual-use products, along with the number of applications submitted and the number of recipients.

The grant competition serves as the primary national support mechanism within Latvia's DIE. The Ministry of Defence grant program has provided financial support to a total of 25 beneficiaries between 2020 and 2024.

The total available funding over these years amounts to 2.15 million EUR, with annual grants ranging from 450,000 EUR to 600,000 EUR. The number of applicants has varied each year, with the highest recorded in 2024 (37 applicants), while data for 2023 is unavailable.

Table 5
Ministry of defence grant program in numbers

Year	*Available funding in thousands EUR*	*Number of applicants*	*Number of beneficiaries*
2020	500	31	9
2021	450	Unknown	7
2022	600	33	4
2023	-	-	-
2024	600	37	5

This program plays a crucial role in fostering defence-related innovation and strengthening national security through targeted financial support (Ministry of Defence of the Republic of Latvia, 2025a).

The Defence Innovation Research Program is a key government initiative that supports technological advancements and strengthens national security. With a budget of 1.5 million EUR, it funds research institutions and businesses developing cutting-edge defence solutions. In 2021, three projects were approved in areas such as cybersecurity, unmanned systems, and advanced soldier equipment. These include innovations like electromagnetic shielding, hybrid composites for drone protection, and smart ballistic vests, reinforcing Latvia's Defence Innovation Ecosystem (Ministry of Defence of the Republic of Latvia, 2021).

Descriptive Statistics was used to summarize key characteristics of the dataset, as presented in Table 6, providing insights into trends in defence budget allocation, grant funding, and industry participation over time. This method allowed for the identification of central tendencies, variability, and missing data points, highlighting fluctuations in defence spending and grant distribution while offering a quantitative foundation for further analysis.

The Latvian Ministry of Defence allocated €5.5 million for R&D in 2024 and €6.8 million for 2025, supporting innovation initiatives including drone grants, defence research, NATO contributions, and European Defence Fund co-financing. Priority areas include autonomous systems, AI, and quantum technologies (Ministry of Defence, 2024). NATO countries allocate a large share of defence budgets to R&D; the 2024 NATO defence budget is estimated at $1.18 trillion, with Europe and Canada contributing about $430 billion (NATO, 2024b).

The literature identifies three knowledge gaps. First, more research is needed on evolving defence culture to better integrate SMEs, start-ups, and disruptive innovation (Mészáros, 2024).

Second, the lack of public data on failed projects limits learning opportunities; analyzing such cases could help identify promising ideas sooner (Langham & Wrigley, 2020). Third, there's no robust model for measuring innovation ecosystem resilience using System Dynamics or Agent-Based Modeling (Abdi et al., 2024). Each country's Defence Innovation Ecosystem (DIE) reflects its strategic priorities, shaped by national defence policy.

Table 6

Descriptive statistics summary of defence innovation ecosystem data

	Year	***Defence Budget (% GDP)***	***Defence Budget (Million EUR)***	***Available Grant Funding (Thousand EUR)***	***Number of Applicants***	***Number of Beneficiaries***
count	6	6	6	4	3	4
mean	2022	2.58	1028.5	537.5	33.67	6.25
std	1.87	0.58	355.25	75	3.06	2.22
min	2020	2.2	700	450	31	4
25%	2021	2.2	768.5	487.5	32	4.75
50%	2022	2.23	893.5	550	33	6
75%	2023	2.96	1272	600	35	7.5
max	2025	3.45	1559	600	37	9

In Latvia, key DIE stakeholders are listed in the National Defence Policy report and shown in Figure 3. Latvia's DIE includes government, military, academia, industry, and associations. The Ministry of Defence leads policy and funding; the Ministry of Economics promotes industrial growth. The Investment and Development Agency supports businesses, and the Defence Logistics and Procurement Center manages procurement. The National Armed Forces are key end-users, shaping capability development. The Latvian Science Council (LZP) fosters research in defence technologies alongside universities and institutes specializing in cybersecurity, materials science, and advanced tech. Industry, including start-ups, drives dual-use and military tech development.

The State Defence Corporation was established to build national industrial capacity (Ministry of Defence, 2025b).

Industry associations and competence centres promote collaboration and public-private partnerships. Internationally, Latvia engages through platforms like NATO DIANA, supporting defence start-ups (NATO, 2024a). These actors form a dynamic ecosystem that drives innovation and strengthens national and allied security.

Comparative Perspective: Latvia and Ukraine's Defence Innovation Ecosystems

To contextualize Latvia's DIE trajectory, a brief comparative perspective with Ukraine's wartime innovation ecosystem reveals instructive parallels and divergences. Table 7 summarizes selected features of both systems:

Table 7

Comparative Overview of Latvia's and Ukraine's Defence Innovation Ecosystems

Feature	***Latvia DIE (2020–2025)***	***Ukraine DIE (2022–2024)***
Strategic driver	NATO/EU integration, deterrence policy	Full-scale invasion and urgent battlefield needs
Key rural integration approach	Regional test sites (e.g., Latgale), MOD hackathons	Rural-based production hubs, field R&D in frontline
Governance model	Policy-driven, grant-based	State-led procurement, wartime executive authority
Innovation mechanisms	Grants, public-private initiatives, EU co-funding	Dual-use innovation under conflict, startup-military partnerships
Speed of transformation	Gradual	Rapid and responsive (Hmyria et al., 2024)
International collaboration	NATO DIANA, EDF projects	Bilateral support, Lend-Lease, multilateral R&D

Ukraine's defence innovation ecosystem, transformed by existential urgency, illustrates how war catalyzes system-wide shifts in innovation management, stakeholder roles, and rural integration. Rural areas in Ukraine, particularly underutilized farmland and remote zones, became strategic assets for both conventional logistics and experimental technology deployments (Hmyria et al., 2024; Tykhenko et al., 2024). Latvia's rural innovation push particularly in regions like Latgale can draw valuable insights from Ukraine's rapid establishment of local innovation hubs. These included makeshift fabrication labs, drone-testing ranges, and logistics nodes situated in rural settings far from

urban frontlines. While Latvia operates under peacetime constraints, the Ukrainian case emphasizes the importance of agility, decentralized innovation, and the dual civil-defence use of rural territories (Harutyunyan, 2024).

Figure 3
Defence innovation ecosystem stakeholders in Latvia

The defence sector is inherently confidential for justified reasons, as it involves not only commercial secrecy but also national security concerns. Disclosing information about vulnerabilities and weaknesses in defence systems can pose significant risks to national security (Cardona, 2018). The analysis of the defence innovation ecosystem was based on scientific literature, policy documents, and reliable industry research. However, given the time required for the publication of scientific articles, the information available in academic journals may not always reflect the most current developments. This is particularly relevant in the context of shifting global dynamics, where geopolitical changes influence the evolving needs of the innovation ecosystem (Cochrane & Zaidan, 2024).

Future Research Directions

To build upon these findings, future DIE research should employ alternative methodologies, including expert interviews, observations, surveys, and case studies, to capture a more nuanced understanding of ecosystem dynamics. A comparative analysis of DIE frameworks across different nations is necessary to establish best practices and explore the feasibility of an international alliance-scale DIE framework at the NATO and EU levels. Further studies should focus on the collaboration mechanisms among DIE stakeholders, using the innovation lifecycle as a foundation to assess efficiency, adaptability, and long-term sustainability. Additionally, research should determine whether any critical stakeholders are absent in Latvia's DIE, drawing lessons from other innovation ecosystems to enhance governance and operational effectiveness.

From a policy perspective, Latvia can strengthen its DIE by:

- Incentivizing private-sector R&D investment;
- Enhancing SME participation in defence procurement;
- Strengthening international partnerships through NATO and the EU.

By addressing these challenges and leveraging international best practices, Latvia can build a more resilient and effective DIE that supports both national security and economic growth.

Conclusions

1. Latvia's Defence Innovation Ecosystem (DIE) operates within a small, strategically positioned economy where national security imperatives and innovation goals are increasingly interlinked. Despite the establishment of supportive frameworks such as the Defence Industry Law and national funding mechanisms, systemic gaps remain particularly in rural participation, inter-institutional coordination, and ecosystem transparency (Ministry of Defence of the Republic of Latvia, 2024). Rural regions, especially Latgale, present untapped innovation potential yet remain underrepresented in funding allocations and stakeholder networks (Tables 2 and 3).
2. Rural areas such as Latgale possess key strategic enablers including available land, emerging infrastructure, and growing community engagement that could support decentralization of defence R&D and production. These areas are well-positioned for establishing dual-use industrial zones, test and evaluation sites, and localized innovation hubs (Tykhenko et al., 2024; Garin & Rothbaum, 2025). Government initiatives like the Action Plan for the Eastern Border Region and the EUDIS Defence Hackathon 2025 in Rezekne represent promising steps toward harnessing rural innovation capacity (Cabinet of Ministers of the Republic of Latvia, 2025; Latvia's Official Legal Information Portal, 2025a).
3. Targeted investment and cross-sector collaboration are essential to close existing urban–rural innovation gaps. Enhanced data collection, grant streamlining, and the inclusion of rural-specific priorities in MOD programming would create incentives for SME participation and build local capacity. Lessons from Ukraine demonstrate the strategic value of rural regions for logistical, production, and rapid prototyping functions under stress conditions insights Latvia can proactively apply in peacetime (Hmyria et al., 2024; Tonkha et al., 2021).
4. Latvia's DIE lacks transparency on innovation failures and resilience metrics. The absence of systematic evaluation tools limits the ability to learn from past initiatives or forecast future adaptability. Integrating underutilized modeling techniques and rural innovation indicators would enhance ecosystem governance. Future research should prioritize the development of rural innovation readiness frameworks, informed by community-driven, data-rich approaches (Abdi et al., 2024; Rahe et al., 2025).

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PUBLIC PROCUREMENT IN VILLAGE COUNCILS: ORGANISATION, CONTROL AND AREAS FOR IMPROVEMENT

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Abstract
Public procurement in village councils plays a pivotal role in addressing the socio-economic needs of rural communities. Effective organisation and efficient control of public procurement are crucial conditions for the development of rural areas. The article is aimed at finding and developing ways to improve the efficiency of public procurement in village councils. The study applies analytical tools, survey methods, and draws upon practical experience to assess procurement indicators and control mechanisms. The emphasis is placed on the importance of public procurement which enables rural communities to function, meet their social and economic needs and develop. The study analyses key indicators of public procurement of rural councils, identifies problematic questions. The article identifies ways to improve the efficiency of public procurement as a key condition for the development of rural areas. Key findings highlight the need for improved internal control systems, the strategic use of analytical tools, and enhanced professionalisation in procurement roles. Effective control correlates with improved procurement efficiency, cost savings, and transparency. The article proposes structured directions for preliminary, ongoing and subsequent internal control and emphasises the necessity of aligning the professional standard 'Public Procurement Specialist' with contemporary procurement challenges. The study concludes that optimised internal control and professionalisation are fundamental for the sustainable development of rural areas.
Keywords: public procurement, rural council, rural area, social and economic needs, professionalisation.

Introduction

Procurement activities have always been relevant from both theoretical and practical perspectives. Their significance has grown even more in the current context when Ukraine is in a state of war and procurement for rural areas plays a critically important role.

Rural councils, acting as representatives of public procurement contracting authorities, have special features not only in terms of carrying out their activities and fulfilling their functions but also in terms of conducting public procurement. The importance of the procurement activities of rural councils is determined by their impact on the development of the rural areas which they represent. The relevance of this study is further emphasised by the fact that, in recent years, there has been a limited amount of scientific research into the organisation and control of public procurement of specifically rural councils. This can be explained by the fact that such research requires practical experience and direct involvement in the studied process. At the same time, there are several problematic questions in this area that need to be addressed. In particular, it is conducting procurement to meet the needs under conditions of limited funding, which, in its turn, requires greater efficiency in procurement processes, effective internal control and professionalisation. Therefore, there is a need for more in-depth study to ensure the proper execution of procurement functions and adherence to procurement principles in rural councils.

The article is aimed at finding and developing ways to improve the efficiency of public procurement in village councils.

To achieve this aim, the following tasks have been set:

- to analyse the key indicators of the organisation and control of public procurement in rural councils;
- to identify the specific features and the directions of internal control in rural councils to enhance procurement processes;
- to characterise and identify the main capabilities for using analytical tools to improve the efficiency of public procurement;
- to outline the importance of the professionalisation of public procurement and the main directions for its enhancement.

Materials and Methods

The organisation and control of the public procurement process in rural councils, which serve as a condition for the development of rural areas, have been studied with the help of commonly accepted scientific methods. The main methods include: historical method (used to examine trends and changes in the formation of procurement organisation specific features); systematic approach (applied to analyse the links between procurement phenomena and processes; abstract-logical method (used to identify and specify main components of the studied relations); sociological method (used for conducting surveys); monographic method (applied to consider best practices of specific rural councils); systematization method (used for summarizing and forming conclusions); graphical method (used for visualizing information), etc.

The research was conducted in Mykolaiv Oblast, Ukraine. The object of the research is the process of organising, conducting, documenting, controlling and analysing public procurement in rural councils. The subject of the research is the combination of theoretical, methodological and practical aspects of organisation and control of public procurement in rural councils.

The survey respondents were public procurement specialists from rural councils in Mykolaiv Oblast, Ukraine. The conducted survey reflects the specific features, key indicators and challenges in organisation

and control of public procurement in rural councils and their impact on the development of territorial communities. The survey covered 20 rural councils of Mykolaiv Oblast. They represent all the territorial districts of the oblast. The questionnaire included 25 questions divided into three sections: the organisation of procurement, internal control practices, and use of analytical tools. The survey was conducted in two formats - face-to-face interviews and completing the questionnaire. The survey period lasted for two months - November and December 2024.

Results and Discussion

According to the Law of Ukraine 'About Local Self-Government in Ukraine' (Verkhovna Rada of Ukraine, 1997), a rural council is a local self-government body, and it represents the rural territorial community. A rural council performs its functions on behalf of and in the interests of the community. The rural council is a legal entity and has an approved structure. It directly contributes to the development of the community, primarily by meeting the economic and social needs of the community. It happens through the public procurement of certain goods, works and services for schools, kindergartens, hospitals, the council itself.

Thus, the procurement process is shaped by the needs of the rural council, which arise from its main functions and responsibilities. The main functions of rural councils are: organisational and managerial (approval of the council's work plan, approval of the territorial community statute, establishment and dissolution of executive bodies); administrative (addressing administrative-territorial issues); legal (adoption and repeal of bylaws, contract work, establishment of institutions to provide free primary legal aid); supervisory (review of reports from the village head, heads of executive bodies and officials, consideration of deputy inquiries, decision-making on inquiries); electoral (organisation of elections to the rural council); informational (use of the community's official and social mass media); financial (approval of the local budget, its amendment; establishment of local taxes and fees, creation of target funds, attraction of additional funds, public finance control); property management (management of communal property); economic (providing directly with goods, works and services); property (regulation of land relations, use of local natural resources); environmental protection and recreation (organisation of territories and objects of local nature reserve funds, improvement of the territory); extraordinary (management of natural disaster and epidemics, establishment of a municipal emergency rescue service) and others.

Mykolaiv Oblast has 44 rural territorial communities in its administrative structure. Each community comprises from 5 to 45 villages. Every rural territorial community has a rural council. According to the Law of Ukraine 'On Public Procurement' (Verkhovna Rada of Ukraine, 2015), a rural council acts as a contracting authority for goods, works and services.

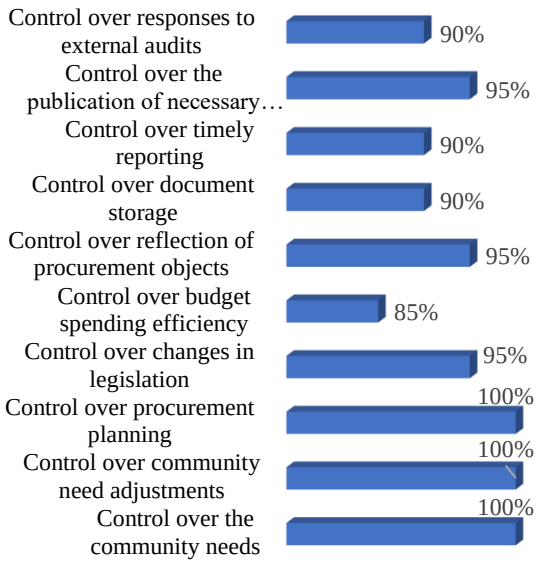
As a contracting authority, the rural council strictly adheres to the procurement process organisation, principles and documentation requirements during the procurement process. The organisation of the procurement process consists of the following stages: financing, planning, procurement, accounting and reporting.

Thus, according to the survey results and analysis of the electronic procurement system, the main goods, works and services procured by rural councils include: electricity and distribution services; gas and distribution services; centralised water supply services; project and cost estimation services; capital and current repairs of buildings, structures and roads; vehicles; insurance services; street lighting equipment; stationery and household chemicals; waste management services; transportation services; diesel fuel and gasoline; food products; medicines and pharmaceutical products; toys; educational equipment and materials; furniture; spare parts, etc.

The procurement process is accompanied by both internal and external control. Internal procurement control is carried out by the executive committee of the rural council, the procurement specialist and the head of the rural council. According to the survey of 20 rural councils in Mykolaiv Oblast, the respondents identified the internal control directions, shown in 'Figure 1'.

Figure 1

Directions of Internal Control of the Procurement Process



Apart from that, we consider that internal control tasks include control over training and qualification improvement of public procurement specialists; control over the procurement process using analytical tools; control over contract work and fulfilment of obligations; control over execution of decisions.

External control is carried out by government authorities:
- State Audit Service of Ukraine – monitoring, scheduled and unscheduled checks of compliance with principles and legislation while conducting the procurement;
- State Treasury Service of Ukraine – control of procurement documentation and its compliance with legal requirements, control of payment processing for procured goods, works and services;
- Antimonopoly Committee of Ukraine – consideration and decision-making on complaints regarding violations of procurement participants' rights.

Ensuring effective and transparent procurement, prevention of corruption, development of bona fide competition is the purpose of state regulation and control of procurement, including monitoring (Dubinina et al., 2022).

During procurement planning, rural councils take into consideration their financial capabilities.

The priority is given to critically essential procurement items. We have analysed them by categories in 20 rural councils in Mykolaiv Oblast. We have identified the critical priority procurement items and the specific weight of each category:
- education sector (45%) - procurement of educational materials, food, water, repairs, etc.;
- healthcare sector (32%) - procurement of medical equipment, medicines, medical supplies, repairs of medical institutions, etc.;
- infrastructure sector (12%) - road maintenance and repair, bridge and water pipeline repair, installation, or modernization of street lighting, etc.;
- social assistance sector (11%) - support programs for low-income families, procurement of social services for people with disabilities, social assistance for internally displaced persons, etc.

It should be noted that these are the results of actual procurements financed from local budgets on average for the period 2023-2024 in the surveyed communities. The infrastructure sector in some communities requires significant restoration due to the consequences of military aggression. The financing of this sector during the study period was primarily provided by the communities' local non-restricted revenues or grants and donor contributions.

Based on the analysis of information from the Prozorro electronic procurement system, the use of analytical tools and the analysis of survey responses, the key indicators of procurement organisation and control in 20 rural councils of Mykolaiv Oblast, Ukraine, for 2023-2024 have been compiled (Table 1).

Table 1

The Main Indicators of Organisation and Control of Public Procurement of the Researched Rural Councils in Mykolaiv Oblast, Ukraine in 2023-2024

Indicator	***Year 2023***	***Year 2024***
Number of completed procurements, as a percentage relative to announced procurements	90.1	92.3
Cost savings as a percentage of the expected value	6.4	7.8
Number of complaints received, units	18	23
Decisions of the Antimonopoly Committee of Ukraine in favour of the contracting authority (rural council), as a percentage of total complaints received	83.3	65.2
Number of decisions by the State Audit Service of Ukraine to initiate procurement monitoring, units	27	39
Cases of the procurement law violations, as a percentage relative to the number of monitoring initiation decision	25.9	43.6

Taking into account the geographical location of the studied rural councils, which operate under the martial law conditions, we consider the percentage of completed procurements to be sufficient. The cost savings resulting from procurements in rural councils are not often higher because the procurement volumes, the amount of funding and specific characteristics of procurement items are more limited compared to other contracting authorities. The presence of the facts of law violations and violations of the procurement process indicates the need for organisational and control measures. The main goal of these measures is to ensure timely and efficient procurement of goods, works and services to meet the needs of the territorial community.

The observed cost savings align with findings from researchers (Bosio et al., 2022), who associate internal control quality with procurement performance. However, unlike in more centralised systems, rural councils often lack both analytical capacity and dedicated control units, which may account for the increase in detected violations.

Therefore, effective internal control of public procurement in rural councils serves as the foundation for the optimal organisation of the public procurement process and its rationalisation. Proper procurement procedures guarantee cost savings. These costs can then be allocated to procure additional goods, works and services essential for the community operations, development and additional benefits. Internal control primarily aims at complying with current legislation, efficient use of budgetary funds and achieving priority goals of the territorial community development.

In our view, the effectiveness of internal control

depends on two key factors: the level of staff training and the rational distribution of responsibilities according to the set objectives. To ensure a positive impact on the development of the territorial community, internal control must be systematic. It should include control over community needs and procurement prices, contract analysis, analysis of successful and cancelled procurements, analysis of procurement appeals and external audit results.

Based on the practical research, the key directions of internal control for public procurement in rural councils have been identified (Table 2).

Table 2

Proposed Directions of Internal Control for Public Procurement for Rural Councils of Ukraine

Type of Control	***Direction of Control***
Preliminary Control	Identification of community needs; analysis of financial and other capabilities to meet needs; formation of procurement planning; informational, analytical and professional procurement support; analysis of key potential suppliers; consideration of problems and mistakes from the previous procurement period; analysis of modern appeal practices and decisions of control authorities; control of changes in legislation; distribution of responsibilities; organisation of internal document flow; coverage of procurement information for public discussion
Ongoing Control	Control of documentary support, adherence to procurement principles, compliance with deadlines, implementation of decisions, contract work, financial settlements, accountability and coverage of factual information
Subsequent Control	Analysis of the rationality and execution of the procurement plan; identification of contract deficiencies; analysis of suppliers and their performance obligations; analysis of document flow; analysis of the most effective procurements; review of procurement appeal causes and monitoring of procurement

According to the results of the survey of public procurement specialists, it has been established that internal control of public procurement in rural councils has a predominantly ongoing character (100% of respondents). We should note that external control is also primarily conducted during the procurement process.

Thus, in our view, effectively organised internal control, based on the suggested directions, is one of the key prerequisites for efficient procurement and consequently, one of the preconditions for the development of rural areas. At the same time, greater attention to preliminary and subsequent control will only enhance the efficiency and effectiveness of procurement. The use of analytical tools plays a crucial role at these stages.

Ukrainian public procurement has been characterised by significant modernisation over the last 10 years. It includes the development of the electronic procurement system, improvement of the appeal process, creation and adoption of regulatory and methodological documents, implementation of automatic risk indicators for external control, public relations, professionalisation of procurement specialists, etc. The martial law period has brought substantial adjustments to the procurement process. These changes have become the foundation for the temporary optimisation of procurement; however, they have not violated procurement principles, the control process and have not stopped the process of further development. As a result, public procurement continues to fulfil its functions, in particular regarding the reconstruction and development of rural areas.

International donor organisations, government authorities, ministries and public organisations have developed information and analytical tools which enable optimisation and improvement of the public procurement organisation and its control.

The key information tools are state registers. They are open to procurement contracting authorities and contain data regarding control of the supplier's conformity to legal requirements.

In our view, analytical tools are becoming increasingly important to carry out effective procurement and control. These tools are constantly expanding and improving to fulfil informational and control functions. The reliance on such tools is especially important in village councils, as highlighted by scholars (Osmirko et al., 2021), who stress the strategic role of automated systems in reducing procurement risks.

Brief characteristics of key analytical tools and their actual use in rural councils during procurement processes are provided in Table 3.

As regards the Use of Analytical Tools Based on survey responses, the most commonly used tools were YouControl (90%) and the Public Procurement Module of Prozorro (60%). Limited usage of Clarity Project (25%) reflects low awareness or access to paid tools. Respondents identified training and user-friendly design as a key to broader adoption.

Ukraine is among the countries with the highest transparency in public procurement. This was influenced by the functioning of the electronic procurement system since 2016 and its continuous improvement, as well as by information technology (Khorana et al., 2024).

Table 3
Characteristics of Key Analytical Tools and Their Actual Use in Rural Councils of Mykolaiv Oblast, Ukraine During Procurement Processes in 2023-2024

Analytical Tool	***Capabilities and Advantages***	***Usage by Public Procurement Specialists (%) in the Surveyed Rural Councils***
Public Procurement Module	Information is provided through easy-to-use tables, analytical charts and diagrams from the Prozorro electronic procurement system. For example, appeals, monitoring, supplier and buyer profiles, pricing, procurement items and cost savings. Analysis of planning stages, procurement processes and contracts. Free of charge tool.	60% (12 out of 20)
YouControl	There is a possibility to verify procurement participants based on general parameters (history, beneficiaries, owners, capital, financial indicators, affiliations, debts, lawsuits, etc.) and to analyse procurement activities of a particular participant (offers, pricing, complaint submissions, obligations fulfilment, etc.). Registration is required. Information is free; additional information is behind a paywall.	90% (18 out of 20)
Clarity Project	Contains analytical indicators for all territorial communities (free access). There is a possibility to filter groups of suppliers (paid tool). It offers a service to make a report about a supplier from official registers, mass media, social media, etc. (paid tool). It contains a database of all decisions from the Antimonopoly Committee of Ukraine and the State Audit Service of Ukraine. There is a possibility to search by filters - procurement item, supplier, buyer and type of violation (paid tool). It includes analytical indicators of public procurement with 23 filters, such as procurement item, price, supplier, reason for rejection, complaint, region, procurement type, payment method, funding type, etc. (paid tool).	25% (5 out of 20)

That is why the use of analytical tools should contribute to the effectiveness of internal control, transparency, and competitiveness of public procurement.

Thus, the main capabilities of the proposed analytical tools can help to increase the efficiency of public procurement. These main capabilities are: detailed market and price analysis; comprehensive study of potential suppliers and tenderers; analysis of the practice of making and correcting mistakes in procurement; analysis and implementation of best practices of other village councils for more efficient procurement; attraction of other sources of funding, etc. This will allow for effective procurement planning; ensuring competitive procurement and cost savings; timely procurement and completion; guaranteeing the supply of goods, services and works; avoiding the selection of dishonest suppliers; determining the financial condition of suppliers; using positive experience; avoiding mistakes in procurement, etc.

The concept of procurement efficiency is not limited to cost savings alone (Psota et al., 2020). These findings support our view that procurement efficiency is influenced by a number of factors. Effective internal control and professionalisation of public procurement can increase the positive impact of such factors and reduce the negative impact.

One of the key conditions for the organisation and effective carrying out of procurement is the presence of highly qualified specialists in public procurement. Professionalisation of procurement is an important factor in procurement efficiency (Mischenko, 2011; Khorana et al., 2024). A professional in public procurement should respond timely to frequent changes in procurement legislation, understand the needs of the territorial community, have a good command of analytical tools in procurement and take responsibility for quite a low salary (an average rural council cannot afford to pay a high salary). Additionally, the field of procurement organisation and control in rural councils is included as a subject in the insufficient number of educational programmes of Ukrainian higher education institutions. As a result, professionals already working in rural councils often need to learn it by themselves.

The public procurement sphere has undergone significant reforms in accordance with the Agreement Association between Ukraine and the EU, and the 'Strategy of Public Procurement System Reform ('Roadmap')' (Cabinet of Ministers of Ukraine, 2016) developed under this agreement. The implementation

period of the strategy has already passed. The predominant majority of this strategy's provisions have been fulfilled and implemented. However, Ukraine was unable to complete its full implementation due to the full-scale invasion of the aggressor state.

One of the main directions of the strategy was the development of a professional training system for public procurement specialists and the professionalisation in the sphere of public procurement. Incorporating empirical data, it was established that 70% of procurement specialists in rural councils lack formal education in procurement, and over 60% acquired skills through informal learning or peer exchange. This direction has been developed, implemented in the practical activity and continues to be improved. Thus, we believe that public procurement professionalisation is an essential component of improving the procurement sphere. In addition, educational institutions and organisations which provide opportunities for enhancing the qualification play a significant role in this process. Professionalisation in public procurement is relevant for the labour market, education, rural councils, territorial communities and rural areas, which are studied in this article.

Given the constant changes and improvements in public procurement, adapting the professional standard 'Public Procurement Specialist' (Ministry of Economy of Ukraine, 2023) to modern reality and career growth requirements in this field has become an important initiative. Thus, between October 2024 and January 2025, we periodically analysed the labour market and employer demands for public procurement specialists, in particular for rural councils. The results are presented in Table 4.

Table 4

The results of the Research into Professional Requirements for Public Procurement Specialists in the Labour Market of Ukraine for October 2024 - January 2025

Requirements from Contracting Authorities for Public Procurement Professionals	Among them – Requirements from Rural Councils	Requirements from Participants for Public Procurement Professionals
Higher education in Economics or Law (some contracting authorities allow either, while others specify this or that field)		A higher education in Economics or Law is desirable, but technical or other education is also valid
Work experience in the field from 1 year (sometimes specified in detail, such as experience with procurement platforms, contracts, audits, etc.)	Not always required	Not always required
Knowledge of public procurement legislation; Proficiency in the state language; Ability to work with office software		
-	-	Ability to analyse the market and identify new opportunities
High responsibility, attention to detail; Stress resistance and multitasking skills; Ability to work in a team and avoid conflict situations; Willingness to defend their own position in the competitive environment		

Thus, we can state that the primary requirements set by contracting authorities align with the current professional standard. Rural councils have slightly simplified requirements, considering the conditions in which they are located and operate, but education and professional knowledge remain mandatory. There is also a difference in salaries offered by rural councils and other contracting authorities. There are two limiting factors. This is limitation in funding and the institution's revenue levels, not forbidden by the state. In general, if to take contracting authorities, the salary of a public procurement specialist ranges from 9,000 to 20,000 UAH, while in rural councils, it ranges from 9,000 to 16,000 UAH. The participants do not limit the salary. Offers exceeding 60,000 UAH can be also found.

We believe that the requirements for the position of public procurement specialist should also include an understanding of internal control and response to external control results. This is especially important for procurement specialists who intend to work in rural areas where significant needs are closely connected with a limited budget.

The personnel policy of local self-government bodies should provide for a systematic approach to professionalisation, focusing on the opportunity to enhance knowledge and professional experience of professionals. Therefore, the professional competency requirements for candidates applying to local self-government positions remain unchanged. They are defined according to a traditional methodology - based on professional qualifications established by legislative regulations, depending on their functions and responsibilities.

Thus, educational institutions which include procurement-related components into educational programs for various economic specialties play a significant role in the professionalisation of public procurement.

The professionalisation of personnel is a crucial criterion in shaping the positive image of a rural council, which, in its turn, influences the perception of the rural area itself. Professional human resource is

the primary prerequisite for implementing the planned programs because the activity of a rural council is primarily aimed at developing and improving the territorial community, meeting the needs and interests of its residents.

We should emphasise that many other professionals are directly or indirectly involved in procurement processes. For example, management personnel, a lawyer, an accountant, a quantity surveyor, an economist, a logistics specialist, technical experts, etc. Therefore, the above-mentioned professionals should have minimal knowledge of public procurement to effectively contribute when needed, in compliance with all the key principles and legal requirements.

Thus, not only public procurement specialists but also a significant part of rural council employees should be familiar with the procurement process. It contributes to the efficient budget use, organisation and effective carrying out procurement processes, effective internal control in the context of development of a specific rural area.

We are convinced that the understanding of the connection between such concepts as a qualified procurement specialist, organisation and control of procurement process and territorial community development is one of the key steps towards the development of rural areas.

Conclusions

1. The functional responsibilities of rural councils are aimed at meeting the social and economic needs of the community and developing the rural area in which they operate. The role of public procurement is crucial in this process, as the provision of goods, works and services is fundamental for meeting the above-mentioned needs and rural area development.

2. The analysis of main indicators regarding the organisation and control of public procurement of the surveyed rural councils indicate the need to improve the internal control system to ensure a timely and effective procurement process.

3. Based on the analytical research and survey results, the specific features of internal control in rural councils have been identified. They have become the foundation to the formation of key directions of preliminary, ongoing and subsequent internal control in procurement. The implementation of these will enhance the procurement process and increase its efficiency.

4. The use of analytical tools will increase the effectiveness of control and efficiency of public procurement, namely: optimize the procurement planning and pricing process; ensure cost savings; facilitate the selection of bona fide suppliers; guarantee timely completion of procurement and execution of contracts and help avoid errors and violations.

5. The professionalisation of public procurement has a direct impact on the efficiency of procurement and compliance with the law in the context of the functioning of village councils. The following areas of its improvement are proposed: advanced training of employees, participation in professional groups, acquisition of knowledge in the field of procurement by other specialists of village councils involved in the organisation of this process, and increasing the role of educational institutions.

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FINANCIAL AND ENVIRONMENTAL ASPECTS OF CARBON FARMING: PROSPECTS FOR FARMERS IN UKRAINE

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Abstract
In the context of global climate change and soil degradation, carbon farming is viewed as a promising tool for ensuring the sustainable development of the agricultural sector. This study focuses on assessing the financial and environmental dimensions of implementing such practices in Ukraine - a subject still underexplored in the national academic discourse, particularly in terms of economic feasibility for farmers. The objective is to identify potential benefits, challenges, and the level of readiness among agricultural producers to adopt this approach. The analysis also considers financial incentives, including mechanisms for generating income through the sale of carbon credits on international markets. To evaluate farmers' acceptance of these technologies, the study employs comparative analysis, a sociological survey conducted among farmers in the Mykolaiv region, and the CARVER Plus SHOCK method, which enables quantitative assessment of economic and environmental risks associated with implementation. The findings reveal major barriers to the advancement of carbon farming in Ukraine, including high initial investment costs, an underdeveloped regulatory framework, and limited access to carbon credit markets. The results suggest that, with sufficient government support, appropriate financial incentives, and developed infrastructure, this practice can become an effective instrument for enhancing the economic resilience of farming enterprises while simultaneously promoting environmental sustainability.
Keywords: financial support, carbon credits, climate change, greenhouse gases, environmentally friendly products.

Introduction

Ukraine's agricultural sector, a vital part of the national economy, is facing major challenges, including climate change, declining soil fertility, rising production costs, and the need to adapt to global environmental shifts. In this context, exploring innovative approaches that boost both economic efficiency and environmental sustainability is essential. One such approach is carbon farming, which provides both financial and ecological benefits.

Carbon farming uses agronomic practices to sequester carbon from the atmosphere and store it in the soil, lowering greenhouse gas levels. It also improves soil structure, reduces the use of chemical fertilizers, and enhances fertility. A key financial aspect is the potential to earn income by selling carbon credits on international markets, offering farmers new revenue streams.

Research confirms that financial instruments are vital for encouraging sustainable agricultural practices. Financial support can reduce carbon emissions, especially in countries with strong environmental policies (Gao et al., 2023). Likewise, tools such as green bonds, subsidies, and insurance systems are seen as essential for supporting agriculture in a changing climate (Opalchuk et al., 2024).

Carbon farming is highly relevant for Ukraine. As one of Europe's largest agricultural producers, the country has strong potential for wide-scale adoption. Moreover, climate change forces farmers to adapt, and carbon farming can help reduce agriculture's environmental footprint, improve resilience, and support sustainable growth.

However, its implementation faces obstacles, including high initial costs and the need for continuous monitoring. Small and medium-sized farms often lack the resources to adopt such practices. Government support - through subsidies, tax incentives, and carbon credit market infrastructure - is crucial for advancing this field.

International experience from the U.S., France, and Germany shows carbon farming can lower fertilizer costs, increase yields, and open new markets for eco-friendly products. For Ukraine, these practices offer valuable opportunities. With proper state support, carbon farming could become a key strategy for environmental protection and economic stability in the sector.

This study aims to assess the prospects of carbon farming in Ukraine from financial and environmental perspectives and to highlight key directions for its nationwide implementation.

To achieve this, the study sets the following tasks: analyze international experience with carbon farming; evaluate Ukraine's regulatory and financial frameworks for such practices; assess Ukrainian farmers' readiness to adopt carbon technologies; identify major barriers and risks to the development of carbon farming.

Materials and Methods

A range of methods was used to achieve the research objective. These included the analysis of scientific literature and regulatory acts to assess the legal framework governing carbon markets and environmental policy in Ukraine. Comparative analysis was applied to examine carbon farming practices in Ukraine and in developed countries such as the United States, France, and Germany, identifying both opportunities and barriers to adopting this technology domestically. Economic analysis was used to model potential benefits for farmers, including income from carbon credits and reduced agrochemical costs. Risk and barrier analysis focused on estimating potential farmer income assuming relevant infrastructure development.

Sociological methods helped gather data on the perception of carbon farming among farmers in the Mykolaiv region and identify key obstacles to its implementation. The case study method examined successful examples of carbon farming in Ukraine and abroad to adapt best practices to local conditions. In the final research stage, the CARVER Plus SHOCK method assessed the influence of economic, environmental, and political factors on carbon farming under global changes and domestic economic conditions.

The study was conducted in Mykolaiv region, Ukraine. The object of the study is the organization and implementation of carbon farming in local agricultural enterprises, as well as its economic and environmental outcomes. The subject includes theoretical, methodological, and practical aspects of carbon farming in Ukraine, with a focus on financial support for farmers and ecological effects.

The survey involved farmers, agronomists, and other experts engaged in carbon farming practices in the Mykolaiv region. It covered 47 farms across various districts and included both personal interviews and questionnaires. Conducted over three months (August to October 2024), the survey provided a comprehensive view of the characteristics and challenges of carbon farming in the region.

Results and Discussion

One of the key challenges of modern agriculture is the need to adapt to climate change and reduce greenhouse gas emissions. Carbon farming, as a strategy aimed at increasing the organic carbon content of the soil, can play an important role in ensuring sustainable production. Research (Droste et al., 2020) confirms that carbon storage in soils not only improves their fertility but also provides crop insurance against adverse weather conditions that are becoming more frequent due to climate change.

The importance of restoring soil functions and increasing their resilience to degradation is emphasized in a review of European research (Hamidov et al., 2018). The authors analyze climate change adaptation measures, including minimizing tillage, using cover crops and organic fertilizers, which helps preserve soil structure and increase carbon sequestration. The implementation of these methods on farms in Mykolaiv region allows us to assess their effectiveness in local agroclimatic conditions.

According to the latest IPCC report (2023), climate change is already affecting agricultural production, in particular through rising average annual temperatures and an increase in the number of extreme weather events. This reinforces the need to introduce carbon farming as one of the key tools for adapting to change and mitigating its negative effects.

The study (Paustian et al., 2016) focuses on the concept of 'climate-smart soils' that provide carbon storage, improve water balance, and increase biodiversity. The implementation of such approaches can contribute to both reducing CO_2 emissions and increasing the economic efficiency of agricultural production.

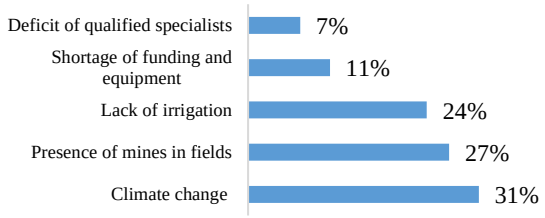
According to research, carbon farming holds great potential for climate change mitigation; however, large-scale implementation depends on strong governmental backing and financial incentives (Smith et al., 2008).

From an economic perspective, a study (Tang et al., 2016) shows that the economics of carbon farming remains challenging due to high upfront investments and uncertainty in carbon credit markets. In Mykolaiv oblast, farmers show interest in new financial instruments, but lack effective mechanisms for their implementation.

In order to analyze the real challenges and opportunities for implementing carbon farming in Mykolaiv region, a survey of 47 local farmers and agronomists was conducted. The results of the survey allowed us to identify the main risks that affect the activities of farms in the region 'Figure 1'. According to the data, the main critical risk factors are climate change (31%), presence of mines in fields (27%), lack of irrigation (24%), shortage of funding and equipment (11%), and deficit of qualified specialists (7%).

Figure 1

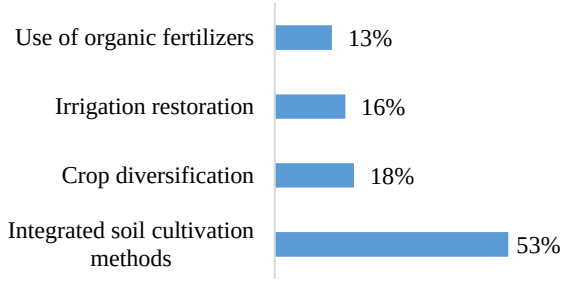
Critical risk factors for farms in Mykolaiv region



According to the survey results, farmers implement various agroecological practices to adapt to new farming conditions 'Figure 2'.

Figure 2

Agro-ecological practices of farmers' adaptation to the current economic conditions



The most common approach is integrated soil cultivation methods (53%), which includes combined minimum and no-till technologies. A significant number of farmers use crop diversification (18%) as a strategy to reduce the risk of crop loss. Irrigation

restoration (16%) remains an important priority for farms, especially in arid areas. The use of organic fertilizers (13%) is also a common practice aimed at improving soil fertility and maintaining its environmental sustainability.

The results show that although farmers in Mykolaiv region are actively implementing adaptive agroecological practices, their effectiveness remains limited due to structural and financial barriers. In particular, the high level of threats, such as field mines and water shortages, requires not only individual adaptive solutions, but also a systemic approach at the level of public policy. Compared to developed countries, where carbon farming is supported at the legislative level through subsidies and tax breaks (Paustian et al., 2016), such mechanisms are only beginning to develop in Ukraine.

Table 1

Comparative Analysis of Approaches to Carbon Farming: International Experience and Prospects for Implementation in Ukraine (based on Paustian et al., 2016; Smith et al., 2008; Tang et al., 2016)

Criteria	***Countries***			
	Ukraine	***USA***	***France***	***Germany***
State support	The initial stage of development of carbon farming, some initiatives to integrate farmers into international carbon markets.	Public and private financial support programs, incentives to reduce emissions and store carbon in the soil.	Active government support through programs to reduce emissions and improve soil quality.	Significant government subsidies for sustainable agricultural practices, emphasis on environmental sustainability and resource conservation.
Carbon credit market	Farmers get access to the international carbon credit market through special programs.	Mandatory and voluntary markets are in place, allowing farmers to sell credits to companies seeking to offset their emissions.	A developed carbon credit market provides farmers with additional income from sustainable practices.	An active market that promotes the monetization of sustainable agricultural technologies through the sale of carbon credits.
Agricultural technologies	Practices to increase the carbon content of the soil are being implemented, including cover crops, minimal tillage and organic fertilizers.	No-till technologies covering crops and crop rotation to conserve carbon and improve soil fertility are used.	Agroforestry, cover crops and organic farming are used to maintain the carbon balance.	Popular organic farming practices, crop rotations, and cover crops to maintain the carbon balance in the soil.
Barriers	Insufficient awareness of farmers about the possibilities of carbon farming, lack of government support and financial incentives.	High initial costs and volatility of the carbon credit market.	Complexity of certification procedures and lack of awareness of farmers about the benefits of carbon farming.	Bureaucratic obstacles and difficulty in accessing the carbon credit market.

The economic analysis shows that despite the potential benefits of carbon farming, its implementation requires significant initial investments, access to information on international carbon credit markets, and a stable regulatory environment. As international practices show, effective integration of farmers into this sector is possible if clear certification mechanisms and financial incentives are created (Smith et al., 2008). Therefore, the development of carbon farming in Ukraine requires a comprehensive approach that includes the adaptation of successful international practices, the creation of appropriate infrastructure, and raising awareness of farmers about the economic benefits of this management model.

Based on international experience, in countries with developed carbon credit markets (e.g., the US, France, and Germany), farmers can earn additional income by selling certified emission reduction units (Smith et al., 2008). In Ukraine, this mechanism remains at the development stage, as the legal framework does not yet ensure transparent and massive access of farmers to carbon markets. An analysis of legislative initiatives and

prospective regulations shows that it is necessary to create incentives, such as tax breaks or government subsidies, to actively engage farmers in this system (Table 1).

Our analysis of the barriers to financial adoption of carbon farming in this study points to several key economic and institutional constraints that hinder the adoption of this technology in Ukraine. In particular, one of the biggest barriers is the lack of adequate financial support from the state, which prevents farmers from making initial investments in adapting to carbon practices. The absence of well-established mechanisms for monitoring, certification, and trading of carbon credits creates uncertainty in the market and reduces interest in these instruments among agricultural producers. As a result, farmers do not have a clear idea of the economic feasibility of such investments and the possibility of benefiting from the sale of carbon credits.

Additionally, legal issues and insufficient infrastructure for carbon farming significantly complicate the process of its implementation. In the absence of a stable and transparent legal framework that would regulate the carbon credit market, farmers face legal uncertainty, which creates risks when participating in carbon trading mechanisms. Given these factors, adapting to carbon practices becomes unattractive without adequate legal and economic support from the state.

It is worth noting that with the development of appropriate infrastructure and improvement of the legislative framework, carbon farming can become a powerful tool not only for mitigating climate change, but also for economic development of the agricultural sector. Given the potential for increased revenues from carbon credits and reduced costs of agrochemicals through the implementation of sustainable agroecological practices, farmers can reap significant economic benefits. However, to achieve this, it is necessary to overcome existing barriers through the introduction of appropriate financial and legal mechanisms that will ensure the transparency and stability of carbon markets in Ukraine (Dubinina & Tyvonchuk, 2024).

For a more detailed analysis of the implementation of carbon farming in Mykolaiv region, as well as to illustrate real examples of agroecological practices, Table 2 presents farms that use methods aimed at increasing the organic carbon content of the soil. The assessment of these practices allows us to highlight both positive and negative experiences in their implementation, which is important for understanding the potential benefits and challenges.

Table 2

Examples of farms in Mykolaiv region implementing carbon farming practices and their impact on soil fertility and yields

The name of the farm farms	***Implemented agroecological practices***	***Impact on soil fertility***	***Impact on yields***	***Results***
ʻOsnova – 2006ʼ, Yelanets district	Cover crops, minimal tillage	Improving soil structure, preserving moisture	Increasing crop yields	Positive experience, improved fertility
ʻAgroLeader-Dʼ, Voznesensky district	Use of organic fertilizers, restoration of irrigation	Improving soil fertility, increasing biodiversity	Increased yields, reduced fertilizer costs	Important experience in the use of organic technologies
ʻMarykovskyʼ, Pervomaisky district	Integrated soil cultivation methods, organic fertilizers	Improving the structural properties of the soil	Stable level of yields	Use of minimal tillage for conservation

Note: Source: authors' own data, based on a 2024 survey of farms in the Mykolaiv region.

The analysis of Table 2 illustrates that the introduction of carbon farming in Mykolaiv region has the potential to improve soil fertility and increase crop yields, in particular through the use of cover crops, organic fertilizers, and minimal tillage.

At the same time, the introduction of such innovations requires a thorough assessment of possible risks related to environmental and financial aspects, as well as other factors that may affect the stability of farms. One of the most effective tools for such an assessment is the CARVER Plus SHOCK methodology, which allows to determine the vulnerability of farms to various threats. This methodology takes into account various aspects, from environmental to economic risks, and allows to assess the likelihood of their impact on farms in the context of carbon farming (Table 3). According to the assessment in the table, key factors such as criticality, availability, renewability, vulnerability, effect, recognizability, and shock help to determine the level of potential vulnerability at different stages of carbon farming implementation. Given the specifics of agricultural production in Ukraine, where carbon farming is a relatively new trend, a high score on the criticality criterion indicates the importance of this process for the long-term development of the agricultural sector and the stability of food security in the country.

Table 3
Assessment of farms using the CARVER Plus SHOCK methodology in the context of carbon farming in Ukraine

Criterion	***Description***	***Points (1-10)***
C (Criticality)	The importance of carbon farming for farm economics and food security.	9
A (Accessibility)	Ease of access to resources and infrastructure for the implementation of carbon technologies (agricultural machinery, farmer training).	7
R (Recuperability)	The time it takes for a farm to recover from environmental or financial losses (e.g., from reduced yields due to incorrectly implemented technology).	6
V (Vulnerability)	Vulnerability of farms to environmental changes or climate change (impact on soil fertility, fluctuations in weather conditions).	8
E (Effect)	The potential impact of environmental or financial issues (e.g., reduced productivity, increased costs due to improper use of technology).	9
R (Recognizability)	Ease of identification of the farm as responsible for environmental practices that may affect its reputation (green image).	8
Plus (Shock)	The psychological impact of failures to implement carbon farming technologies (e.g., impact on confidence in investment or climate change).	7

However, the importance of applying this approach lies in the analysis of accessibility and recoverability, indicators that are directly related to infrastructure and financial support. For an effective transition to carbon farming, farms must have access to the necessary resources and be able to recover from possible environmental or financial shocks. Assessment of these parameters allows us to identify at what stages the greatest difficulties arise in ensuring stability and development in the context of the introduction of environmentally sustainable technologies.

The methodology also helps to analyze vulnerability to various environmental risks, from climate change to environmental pollution, which is especially relevant for agricultural enterprises seeking to integrate the principles of carbon farming. Assessment of the effect on farm productivity, in particular, on reduced yields or deterioration of crop quality due to unstable environmental conditions, emphasizes the need to adapt to climate change and develop risk minimization strategies.

Table 4
Assessment of potential risks using the CARVER Plus SHOCK methodology for each stage of carbon farming

Stage	***Criticality (C)***	***Accessibility (A)***	***Renewability (R)***	***Vulnerability (V)***	***Effect (E)***	***Recognizability (R)***	***Shock effect (S)***	***Over all risk***
Land plot selection and soil preparation	9	7	6	8	9	7	8	54
Implementation of carbon storage technologies	8	6	6	7	8	6	7	48
Use of agricultural machinery	7	8	7	6	7	7	7	48
Monitoring and evaluation of results	9	6	5	7	9	6	7	49
Adaptation to climate change	9	7	6	8	9	8	8	55
Environmental and economic losses	8	6	7	9	9	7	8	54
Attracting investments and partners	8	7	6	6	8	7	6	48

In general, the use of CARVER Plus SHOCK allows not only to collect comprehensive information on farm vulnerabilities, but also to develop recommendations for reducing these risks. Given the importance of such a comprehensive approach to assessing potential threats, the table above illustrates the CARVER Plus SHOCK assessment of farm vulnerability at each stage of carbon farming implementation. Table 4 provides a

detailed risk analysis for each stage of this process, which allows to identify the most vulnerable stages and develop strategies to minimize them.

The assessment of potential risks using the CARVER Plus SHOCK methodology for each stage of carbon farming in Ukraine, presented in Table 4, allows for a deeper understanding of the specifics of farmers' vulnerability at different stages of implementation of this innovative technology. This approach makes it possible to comprehensively assess the risks associated not only with environmental and financial factors, but also with organizational and technical aspects that may affect the efficiency of carbon farming in Ukraine.

According to the assessment, the greatest vulnerabilities were identified in the stages of organic fertilizer application and cover crop management. These stages, in particular, are characterized by high scores in terms of vulnerability (V) and effect (E), indicating a high probability of risks associated with potential technological disruptions or non-compliance with environmental standards. For example, at the stage of applying organic fertilizers, there is a high risk of negative environmental impacts and reduced efficiency of carbon farming due to possible soil or water contamination.

The cover crops and minimum tillage stages show moderate vulnerability to technical and economic threats, which may be due to imperfect infrastructure, lack of financial support, and the need to adapt to new tillage practices. These stages are marked by average values for the criteria of renewability (R) and accessibility (A), indicating the need to improve infrastructure and financing systems to ensure sustainability in the transition to sustainable agriculture.

Particular attention should be paid to the stage of monitoring and evaluation of the results of carbon farming implementation. Here, it is critical to ensure an adequate level of availability (A) of information and effective data management for timely detection of problems and correction of technological processes. The CARVER Plus SHOCK assessment of this stage indicates the need to integrate modern information systems to monitor soil conditions, carbon emissions, and other environmental parameters.

The risks associated with the financial costs of implementing carbon farming are also not insignificant. The high investment requirements for technologies that ensure minimal tillage and the use of cover crops can be a significant barrier for many farms, especially in the context of unstable financing and lack of government support.

In general, the results of the CARVER Plus SHOCK assessment for each stage of carbon farming emphasize the importance of a systematic approach to risk assessment at all stages of the implementation of this technology. They point to the need to develop comprehensive risk management strategies that cover both environmental and economic aspects. Given the specifics of agricultural production in Ukraine, it is necessary to increase the effectiveness of state policy to support farmers, in particular through financing sustainable agricultural practices, improving infrastructure and investing in innovative technologies that ensure the stability and efficiency of carbon farming.

Conclusions

1. Carbon farming is an important tool for adapting agriculture to climate change and reducing greenhouse gas emissions. The use of strategies aimed at increasing the organic carbon content in the soil improves fertility, increases resilience to adverse weather conditions, and contributes to biodiversity conservation. Effective implementation of such practices requires support at the state level and the development of financial mechanisms, particularly in the context of local agro-climatic conditions, as the experience of Mykolaiv region shows.
2. Based on the results of the analytical study and the survey, the main problems affecting farmers' activities were identified, among which the most significant are climate change, field mining, and lack of irrigation. Farmers are actively adopting agroecological practices, such as integrated tillage and crop diversification, to adapt to the new conditions. However, despite these efforts, the effectiveness of their practices remains limited due to financial and structural constraints.
3. Although Ukraine is only beginning to develop its carbon credit system, with major obstacles including limited financial support, regulatory gaps, and certification issues, the introduction of incentives like subsidies, tax relief, and transparent market rules is essential to make carbon farming economically viable and attractive for farmers.
4. An analysis of the adoption of carbon farming by farmers in Mykolaiv region shows that the use of agroecological practices, such as cover crops, organic fertilizers, and minimum tillage, has a positive impact on soil fertility and yields. These practices help to improve soil structure, retain moisture, and increase yields.
5. The CARVER Plus SHOCK risk analysis of carbon farming in Ukraine allowed for a comprehensive assessment of environmental, financial, and technical risks that are critical for a successful transition to sustainable agriculture. Risks related to insufficient infrastructure support, financing, and potential environmental losses require the development of detailed management strategies, including improving the effectiveness of government support and investments in technology.

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CIRCULAR ECONOMY IMPLEMENTATION IN THE AGRICULTURAL SECTOR, EGGSHELLS APPLICATION

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Abstract
Innovative and sustainable solutions are necessary to tackle the global food security issue, ensuring adequate and nutritious food for an expanding population. Eggshells (ES) have multiple applications that can help reduce their impact on environmental contamination. The ES consist of a part of protein fibres along with some mineral compounds like calcium carbonate ($CaCO^3$), magnesium carbonate ($MgCO^3$) and calcium phosphate $Ca^3(PO^4)^2$. This research investigates the most effective use of ES in a circular economy farming model for local poultry, emphasizing circular economy (CE) principles, and sustainable agricultural practices to enhance food security. The prevailing linear production and consumption model is not sustainable in the long term. The food industry heavily utilizes precious natural resources in its production and distribution processes, yet little attention is given to recycling the waste produced along the production chain. Technological applications play a pivotal role in realizing the potential of eggshells as a circular resource. Key innovations include grinding and pulverization systems for producing microfine calcium powders, bioactive extraction methods for isolating proteins and enzymes from eggshell membranes, and waste-to-energy systems incorporating eggshells into biogas production. The primary goals of this research are to assess the feasibility and benefits of utilizing eggshells as fertilizers and biomaterials and evaluate their application in processing eggshells into high-value agricultural products. The study employs a multidisciplinary approach, incorporating qualitative and quantitative data from agricultural enterprises, policy documents, and scientific literature.
Keywords: eggshells, circularity, poultry, economy, sustainability.

Introduction

Over the last five decades, the worldwide appetite for animal-derived goods has consistently risen, propelled by swift population expansion and economic growth. This trend is anticipated to persist in the foreseeable future (FAOSTAT, 2022). Animal food products significantly contribute to environmental issues, including climate change, water and air pollution, land degradation, and biodiversity loss (Poore & Nemecek, 2018a). The poultry industry, a leader among the supply chains of animal products, has been identified as the most environmentally efficient (Crenna et al., 2019a). This recognition should reassure stakeholders about the industry's commitment to sustainable practices. However, the industry's rapid growth and the associated environmental concerns have put its sustainability under the spotlight (Notarnicola et al., 2015).

The circular economy in egg production across Europe has been increasingly adopted to enhance sustainability and reduce waste. Key initiatives of implementation include Circular Feed Practices, Policy and Regulation Support, Recycling Waste Products, Reducing Food Losses, Research and Collaboration and Country-Specific Innovations. The concept of 'Circular Feed' for animals is relatively new, despite the European feed industry's long-standing practice of reclaiming nutrients from secondary raw materials in other industrial processes (Randall et al., 2022). The recovery of nutrients and minimization of nutrient waste are crucial in ensuring that feed production contributes to the circular economy in livestock farming. By adopting this innovative approach, resource efficiency is optimized, aligning with sustainable farming methods (Spoelstra et al., 2013). Consequently, this paves the way for a more environmentally responsible and economically sustainable livestock industry. Animal products such as meat, dairy, and eggs, along with farmed fish, provide humans with highly nutritious food sources. Livestock are raised on feed composed of plant materials that humans cannot consume, including grass and byproducts from food processing (Crenna et al., 2019b). The EU's Circular Economy Action Plan (CEAP) provides a framework for integrating circular economy principles across the food system, including eggs (Aina, 2023). Member States are encouraged to adopt policies that support local circular systems, reduce packaging waste, and promote nutrient recycling. Countries like the Netherlands and Denmark are leading with advanced systems for managing organic waste and optimizing egg production efficiency **(**ETC/CE Reports, 2022). According to the most recent Food and Agricultural Organization (FAOSTAT, 2022) report on hen egg production for 2021 and considering the most conservative estimate that eggshell waste comprises 10% of total egg mass, it is calculated that approximately 8.638,779 tons of eggshell are produced globally, with 1.111,751 tons generated in the European Union. Eggshells, often discarded as waste, are increasingly being repurposed for calcium-rich products or as an additive in construction materials. Other by-products of egg production, such as waste from poultry farming, are converted into bioenergy or compost European initiatives, such as Horizon 2020 projects, focus on identifying risks and optimizing circular economy practices in food production 'Figure 1'. This includes partnerships with universities and industries to improve technologies for recycling and waste management in the egg production supply chain (Harchaoui et al., 2023).

Figure 1
Eggshells and their valuable mineral (Leroma, 2025)

The circular economy is becoming an essential part of the egg industry in Europe, where efforts focus on reducing waste and reusing by-products to enhance environmental sustainability.

Netherlands: Pioneering circular agriculture with closed-loop systems in egg production, including the use of organic waste as feed. The Netherlands has implemented strict animal welfare policies, banned conventional and enriched cages and setting high standards for layer housing systems. The government and private sector encourage innovation in sustainable poultry farming (Spoelstra et al., 2013).

Germany: Investments in biogas facilities where poultry waste is converted into renewable energy. Germany has developed advanced systems for managing poultry by-products. Germany implements sustainable housing systems aligned with animal welfare standards, which support higher resource efficiency and reduced environmental footprint.

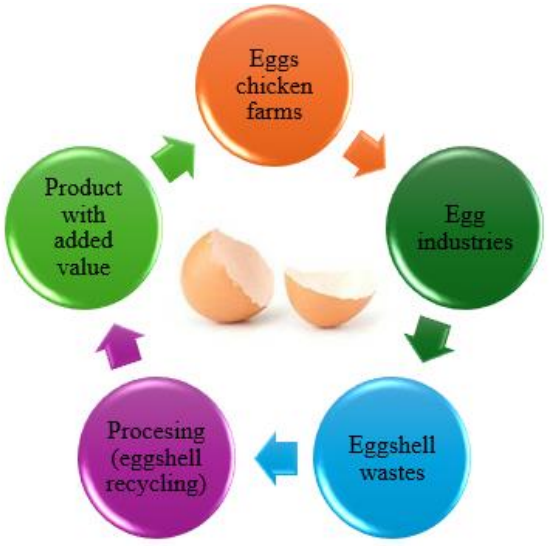
France: Integration of regional policies encouraging circularity in agricultural sectors, including poultry farming **(**ETC/CE Reports 2022). France produces approximately 840,000 metric tons of eggs annually, supported by 46 million laying hens. The French egg supply chain is integrated into broader poultry production, optimizing resources such as feed and waste management. Circular practices in France include the reuse of poultry manure for fertilization and the potential for biogas production. Nitrogen flow analyses in poultry systems show room for improvement in balancing feed inputs and waste outputs to reduce environmental impacts. Italy, one of Europe's top egg producers, focuses on valorising spent hens and by-products through material flow analysis (Harchaoui et al., 2023). With 41 million laying hens, the industry emphasizes sustainable management of spent hens, which are often composted or incinerated. Innovative approaches include using spent hens for human consumption, anaerobic digestion for energy recovery, and microbial fermentation to extract proteins. This circular approach can recover over 13,000 tons of proteins annually, promoting both environmental and economic benefits (Figge et al., 2018).

European countries are adopting alternative housing systems for hens, such as enriched cages and free-range systems, to meet sustainability and welfare directives. Efforts also include the recovery of eggshells and other waste streams for industrial applications, such as calcium extraction or compost materials. The transition away from traditional battery cages aligns with the EU Directive 1999/74/EC, promoting eco-friendly production models across the sector (EU Directive 1999/74/EC).

The Baltic countries: Latvia, Lithuania, and Estonia—are progressively integrating circular economy principles into their policies, including efforts relevant to the egg production and agriculture sectors, though the focus is broader across industries (Griniece et al., 2020). Latvia is actively promoting circularity in waste management and packaging, which indirectly supports agriculture by encouraging more sustainable practices. A key strategy includes enhancing infrastructure for segregating and recycling materials, which could be relevant for agricultural waste management, such as egg cartons or by-products. Moreover, policymakers are working on balancing economic efficiency with environmental responsibility under the 'polluter pays' principle (ETC CE Report 2022/5, Latvia). Lithuania has set ambitious targets for recycling and the use of secondary raw materials, including packaging. The country promotes the reuse of packaging and supports food-sharing initiatives that minimize food waste. These efforts align with the broader goals of resource

efficiency in agriculture. Notable measures include encouraging short food supply chains, which may benefit egg producers by reducing transportation emissions and costs. Additionally, Lithuania is focusing on increasing its circularity rate (currently below the EU average) and reducing landfilling rates by 2030 (ETC CE Report 2022/5, Lithuania). Estonia's circular economy strategy highlights bio-circular initiatives and sustainable resource management, which can influence the egg production sector. The country is working to improve recycling rates and adopt sustainable production practices. However, Estonia faces challenges due to its small population and limited processing capacity for secondary materials. These limitations affect the scalability of solutions such as composting or recycling agricultural waste. Policies are being developed to address these issues, particularly focusing on food waste reduction and the valorisation of organic by-products (ETC CE Report 2022/5, Estonia). While direct applications to egg production are not yet explicitly detailed in these countries, their policies create a supportive framework for integrating circular economy principles into agricultural sectors, including sustainable egg production. Investments in food waste reduction, packaging reuse, and resource efficiency could significantly benefit the industry (Poore & Nemecek, 2018b).

Figure 2
Eggshells used in circular economy principal (Author)



This research aims to investigate the properties of eggshells, determine their application in various industries, and assess the economic and environmental benefits of processing and using eggshells 'Figure 2'.

Materials and Methods
The theoretical part is based on an analysis of strategic documents concerning the production capacity of poultry industries, and on experimental studies that will reveal the potential of eggshells as a valuable resource by applying the monographic, induction and deduction methods. Statistical analysis shows the possible efficient use of eggshells and demonstrates the circular economic efficiency of recycling eggshells as a raw material.
Without recycling, eggshell waste must be disposed of in landfills or specialized waste facilities.

$$C_{disposal} = Q_{eggshells} \times P_{disposal} \quad (1)$$

where:
$C_{disposal}$ – total disposal costs (EUR),
$Q_{eggshells}$ – volume of eggshells (tons/year),
$P_{disposal}$ – disposal cost per ton (EUR).

Eeggshells contain 95% calcium carbonate ($CaCO_3$), which is widely used in agriculture and industry.

$$R_{sales} = Q_{processed} \times P_{selling} \quad (2)$$

where:
R_{sales} – total revenue from selling recycled products (EUR),
$Q_{processed}$ – amount of processed eggshells,
$P_{selling}$ – average selling price per ton of processed product (EUR/ton).

Recycled eggshells can replace calcium carbonate used in agriculture and industry. Cost savings on purchasing substitute materials can be calculated as follows:

$$S_{savings}=Q_{substitution}\times(P_{imported}- P_{recycling}) \quad (3)$$

where:
$S_{savings}$ – cost savings from substituting imported $CaCO_3$ (EUR),
$Q_{substitution}$ – amount of eggshell-derived $CaCO_3$ replacing imports (tons/year),
$P_{imported}$ – price of imported calcium carbonate (EUR/ton),
$P_{recycling}$ – cost of producing eggshell-derived $CaCO_3$ (EUR/ton).

The total economic effect of eggshell recycling can be calculated using the formula:

$$E_{recycling}=R_{sales}+S_{savings}+C_{disposal}-C_{investment}-C_{operational} \quad (4)$$

where:
$C_{investment}$ – capital investment in recycling equipment (EUR),
$C_{operational}$ – annual operational costs (EUR).

Results and Discussion
In developed nations, approximately 30–35% of eggs produced for consumption are sent to processing facilities, resulting in a significant amount of eggshells waste. Considering that about 8.7 million metric tons of eggshell was produced globally in 2023. This waste is

now being increasingly investigated for its potential in various value-added applications. The treatment of ES encompasses cleaning, disinfection, and various mechanical processes such as slicing, grinding, and pulverizing, which facilitate the extraction of ES suitable for high-value applications. Additionally, ES can be carved using mechanical or laser techniques, opening possibilities in art and decorative fields. Moreover, the whole ES can be employed for serving food. The rapid growth in innovative techniques for screening, sorting, gathering, and processing ES demonstrates industry's eagerness to upgrade low-value ES waste, marking a critical initial phase in the development of advanced technologies that harness ES for biomedical, chemical, engineering, and environmental purposes (Ahmed et al., 2021).

The study of eggshells has a wide range of practical applications, which include the following areas: fertilizers, construction: cement and concrete production, medicine and pharmacy: calcium supplements and biomaterials. Also, it includes the following environmental improvement processe: waste reduction, water purification and food industry (Mignardi et al., 2020). Eggshells can be used as a natural calcium supplement in food products, an essential trace element for human health. Eggshells consist of 9-10% of the eggs weight or 5.22–5.80 g. assuming an average egg weight of 56–58 g. One egg consists of 8-9% eggshell or 4.5-5 g (Kocetkovs et al., 2022).

Fertilizers. Eggshells, rich in calcium, can stimulate the growth of root and seed hairs while also enhancing stem strength (Kocetkovs et al., 2022). Additionally, calcium serves to counteract unfavourable soil conditions and substances. Fertilizers derived from eggshells waste, containing a full spectrum of nutrients, have the potential to command high prices and compete in global markets. Furthermore, these fertilizers can be utilized in the production of eco-friendly goods (Faridi & Arabhosseini, 2018).

Eggshells contain a lot of calcium, a crucial nutrient for many plants, and can help neutralize the acidity or pH of the substrate. Organic fertilizer made from eggshells affects the growth of red clover plants fertilized with eggshell pieces. This indicates that plants treated with eggshells grow at an average of more than 10 mm, and eggshells are more effective than sand as a growth fertilizer. (Chandrappa & Kamath, 2021).

Construction: cement and concrete production. The production of building materials has a considerable environmental impact. The need for cementitious materials has expanded with the fast growth of infrastructural development (Yang et al., 2022). Cement, aggregates and water are the three main components of binders. Cement production needs extensive energy and emits considerable CO^2 to the environment. Researchers are currently focusing on using alternate materials instead of cement and natural aggregates, promoting environmentally responsible construction. Eggshells, the hard exterior coating of an egg, are agro waste. Calcium carbonate ($CaCO^3$) is a significant chemical component of eggshells; it is necessary for the growth of binder gel (calcium-silicate hydrate (C-S-H)) in cementitious materials. As a result, this component can be utilized in powder form construction materials as a replacement for cement fine aggregate (Aina, 2023). One effective approach to address environmental concerns is the utilization of waste materials as a substitute for cement, either partially or fully. By repurposing waste into a cement alternative, it is possible to mitigate the environmental problems associated with the uncontrolled disposal of such materials (Sathiparan, 2021). Recent research has explored the use of eggshell powder as a replacement for cement in concrete production, with proportions ranging from 0% to 30%. Most studies have focused on combining eggshell powder with materials such as fly ash, metakaolin, and rice husk ash to create high-strength concrete and cement mortar (Okonkwo & Odiong, 2012; Yang et al., 2022).

Medicine and pharmacy: calcium supplements and biomaterials. Eggshells and their associated membranes, often considered waste products, have emerged as valuable materials in medicine and pharmacy (Macharia & Ori, 2017a). Their high calcium carbonate content and unique biological properties make them ideal for various applications, including calcium supplements and biomaterials. A calcium salt of carbonic acid makes up calcium carbonate, often known as calcite. Solid dosage forms frequently use calcium carbonate, a pharmaceutical excipient, as a diluent (Liang et al., 2024). Additionally, it serves as a basis for pharmaceutical and dental preparations, a food additive, a calcium supplement, and a buffering and dissolution aid for dispersible tablets. Mineral salts are abundant in eggshells, especially calcium carbonate, which makes up around 94% of the shell. Eggshells calcium is probably the best natural source of calcium, and it is about 90% absorbable (Macharia & Ori, 2017a). It is a much better source of calcium than limestone or coral sources. One whole medium sized eggshell makes about one teaspoon of powder, which yields about 750-800 mgs of elemental calcium (Liang et al., 2024; Rouabhi et al., 2023). The composition of an eggshells is very similar to that of our bones and teeth. It is recommended that people with osteoporosis take 400-500 mg calcium per day to supplement dietary sources. The powder should be taken together with some added magnesium, zinc, vitamin D3, K1, K2, strontium and boron for efficient utilization (Nakano et al., 2003). The researchers indicate that healthy people with an adequate calcium intake at baseline may increase the bone mineral density of the hip within 12 months following supplementation with the chicken eggshells powder-enriched supplement. The presence of hydroxyproline in the hydrolysates of the eggshell's membrane has been confirmed through biochemical and immunological tests to be composed of collagen. They primarily consist of type I, V and X collagen (Limroongreungrat et al., n.d.). The eggshells membrane is one of the supplements that has been showing promising results in joint disease and is mainly

composed of collagen, predominantly type I, among other metabolites that have demonstrated action on joint problems such as Glycosaminoglycans and proteins responsible for the mineralization of eggshells, as well as others that play a significant role in microbial resistance (Aguirre et al., 2017). Collagen is a protein found in all body structures: skin, cartilage, tendons, ligaments, and connective tissues. It makes up 30% to 35% of the body's total proteins and provides cohesion, elasticity, and regeneration to these tissues. Poultry eggshells and membranes are valuable, sustainable resources with significant potential in medicine and pharmacy. From calcium supplements that address dietary deficiencies to advanced biomaterials for regenerative medicine, their applications continue to expand, highlighting the importance of innovative recycling and utilization (Kodali et al., 2011).

The versatility of calcium carbonate ($CaCO^3$) is truly impressive. It is used as a natural calcium supplement in food and serves as an effective leavening agent and pH regulator in baking powder for various bakery products. Additionally, $CaCO^3$ is commonly included in pharmaceutical products, such as antacids, calcium supplements, and certain antibiotics. In personal care, calcium carbonate is primarily used in toothpaste as a thickener and mild abrasive (Macharia & Ori, 2017b). Moreover, it plays a significant role in the beauty industry, where it is utilized in the production of face powders, baby powders, eye shadows, and cosmetic foundations due to its whitening effect and ability to promote regular cell renewal. $CaCO^3$ is favoured not only for its effectiveness but also because it can be produced through a relatively simple, fast, and economical reaction (Kodali et al., 2011; Limroongreungrat et al., n.d.).

Farming has been actively developing in the Baltic countries over the last 20 years. The growth was 3-5% per five years. Producers from countries such as Lithuania and Latvia provided their products to domestic markets and actively developed exports. In the countries of Latvia and Lithuania, liquid egg products and powder are produced Table 1. As a result, a by-product of eggshells is formed. Each manufacturer is looking for optimal solutions for processing eggshells and subsequent use. New technologies will allow the consolidation of the principles of circular economy. Example Calculation:

A poultry farm produces 1,500 tons of eggshell waste annually, and disposal costs 30 EUR per ton.

$$C_{\text{disposal}} = 1{,}500 \times 30 = 45{,}000 \text{ EUR}$$

Thus, recycling can save 45,000 EUR per year.

If a company processes 1,500 tons of eggshells into fine calcium carbonate and sells it for 120 EUR per ton, revenue would be:

$$R_{\text{sales}} = 1{,}500 \times 120 = 180{,}000 \text{ EUR}$$

Imported $CaCO_3$ costs 180 EUR per ton, and locally processed eggshell $CaCO_3$ costs 90 EUR per ton, replacing 1,000 tons would yield savings of:

$$S_{\text{savings}} = 1{,}000 \times (180 - 90) = 90{,}000 \text{ EUR}$$

- ✓ Revenue from sales: 180,000 EUR;
- ✓ Savings from import substitution: 90,000 EUR;
- ✓ Savings on waste disposal: 45,000 EUR;
- ✓ Investment in recycling equipment: 250,000 EUR (amortized over 10 years = 25,000 EUR per year);
- ✓ Operational costs: 40,000 EUR per year.

$$E_{\text{recycling}} = 180{,}000 + 90{,}000 + 45{,}000 - 25{,}000 - 40{,}000 = 250{,}000 \text{ EUR}$$

Thus, the net economic benefit from eggshell recycling amounts to 250,000 EUR per year.

In Esonia and Latvia, a notable study conducted by Riddhi Hirenkumar Shukla, a PhD candidate at Tallinn University of Technology (TalTech), focuses on repurposing eggshell waste for orthopedic bio-implants. Eggshells, which are primarily composed of calcium carbonate along with trace elements such as sodium (Na), potassium (K), magnesium (Mg), and strontium (Sr), resemble the composition of natural bone. The research explores the integration of porous titanium with materials derived from eggshells to create bioactive implants. This approach aims to enhance bone integration while also reducing environmental impact (Shukla et al., 2023).

The eggshell project, a collaboration between Riga Technical University (Latvia), Tallinn University of Technology (Estonia), and partners from Norway and Iceland, aims to convert eggshell waste into advanced biomaterials for bone regeneration. The project focuses on synthesizing amorphous calcium phosphate (ACP) from eggshells to develop porous ceramic scaffolds that promote bone growth. Additionally, proteins extracted from eggshell membranes are utilized for their antibacterial properties, further enhancing the scaffolds' effectiveness. These initiatives highlight Estonia's commitment to sustainable waste management and the development of high-value applications from eggshell by-products, contributing to advancements in medical technology and environmental conservation (RTU, 2021). The project successfully synthesized ACP from chicken eggshells, creating porous ceramic scaffolds with potential applications in bone regeneration.

The project resulted in several peer-reviewed publications and joint project proposals, advancing research-based knowledge in Latvia and Estonia. Proteins with high bioactivity and antibacterial properties were extracted from eggshell membranes and applied as coatings on the developed scaffolds, further enhancing their properties. These efforts address environmental concerns associated with eggshell waste and contribute to advancements in medical technology, showcasing a successful integration of waste management and biomedical innovation (Shukla et al., 2023). In Lithuania, while specific scientific research on eggshell waste solutions is limited, the country has been actively engaged in

sustainable waste management practices, aligning with broader European initiatives as Činčikaitė, 2025 in the study of Lithuania's efforts in waste management mentioned.

Table 1
Eggshell potential in ton raw material in the Baltic countries (EEPA, 2024)

Countries	***Total laying hens***	***% of Europe Union***	***Potentional of eggshell, t***	***Eggshell waste potentional resource Yes / No***
EU countries total laying hens	387 509 904	100%	1 1117 751	Yes
Lithuania	2 926 891	0.76%	2 605	Yes
Latvia	3 568 353	0.92%	2 137	Yes
Estonia	888 773	0.23%	649	No

The research reveals that Lithuania ranks 16th globally in this area, with a focus on sustainable practices and the circular economy. The study emphasizes the importance of integrating legal, economic, social, and environmental measures to achieve effective waste management. Although the research does not specifically address eggshell waste, it underscores the country's commitment to innovative waste management solutions (Činčikaitė, 2025). Although direct studies from Lithuania are scarce, international research offers insights into potential applications for eggshell waste. Calcined eggshells have been investigated as a lime source in leather processing, providing an effective alternative to commercial lime in tannery operations (Abul et al., 2024). Additional studies in Lithuania were oriented on nanoparticle synthesis. Research has demonstrated the feasibility of transforming eggshell waste into calcium oxide nanoparticles, which have applications in environmental remediation and as catalysts in various industrial processes (Hemmami et al., 2024). By leveraging such innovative applications, Lithuania can further its commitment to environmental conservation and resource efficiency.

The research highlights that moving towards a circular economy necessitates a systematic change, which includes innovative technologies, collaboration among stakeholders, and supportive policy frameworks. Although the use of eggshells presents a promising model, the wider adoption of circular practices in agriculture will rely on ongoing research, increased public awareness, and investments in infrastructure and education.

Conclusions

1. Eggshells, traditionally considered agricultural waste, emerge as a valuable resource within this framework, demonstrating significant potential for diverse applications.
2. Economic feasibility of recycling: An approximate calculation shows that recycling 1,500 tons of eggshells can bring a net economic benefit of up to 250,000 euros per year through product sales, import substitution and reduced disposal costs.
3. Thesis demonstrates that the application of circular economy principles through the utilization of eggshells offers a sustainable pathway for transforming agricultural waste into valuable resources.
4. Eggshells are used to produce environmentally friendly fertilizers, substitute cement in construction, and create calcium supplements, biomaterials, and implants in medicine, which demonstrates their broad functionality and high value.
5. Implementing circular economy principles in agriculture requires investment in technology, raising awareness, promoting cross-sector cooperation, and establishing supportive policies, especially for recycling biowaste like eggshells.

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METHODOLOGICAL ASPECTS OF THE FORMATION AND DEVELOPMENT OF SECTORAL MARKETS

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Abstract
The aim of the paper is to study the methodological aspects of the formation, enhancement and strategic development of industrial markets. Currently, the industrial market theory is a field of economic analysis that studies the functioning of markets, considering all their diversity and peculiarities. This scientific direction is currently developing very intensively; in the literature it is known as the 'industrial economics', 'industrial organisation', but some sources also utilize the 'economics of industry markets', 'organisation of industry markets', as well as the 'theory of industrial organisation'. The theoretical and methodological aspects of enhancing the efficiency of functioning and development of industry markets are examined. Within the study, general scientific methods of analysis and synthesis, generalization, comparison, abstract-logical analysis, etc. were used. A systemic approach is the common methodological basis of the economy of industry markets. The main conclusion is that modern markets are the imperfect competition markets, and therefore various factors that restrict freedom of competition and to some extent regulate the activities of organisations in industry markets must be considered and introduced into the models. When analysing the efficiency of industrial markets, the achievements of modern institutionalism must be considered and the influence of market institutions on the behaviour of economic entities, which will affect the social-and-economic efficiency of the market, must be included in the analysis.
Keywords: cluster, industrial economics, organisation of industry markets.

Introduction

In world economic science, there are two approaches to research of the industry markets: the Structure-Conduct-Performance approach and the Price Theory approach. The first approach was proposed by E. Mason and Joe S. Bain and later became known as 'structure-conduct-performance'. The second approach employs the microeconomic models to explain the behaviour of firms and the structure of markets. Within the framework of the first paradigm (this concept is also called the Harvard tradition in industry organisation), the functioning of the industry (and the industry and the market in the framework of the theory of industry organisation, unless specifically stated otherwise, are treated as interchangeable concepts) depends on the behaviour of sellers and buyers, which is determined by the market structure (Jacquemin, 1999).

Roy L. V. and Tretyak V. P. distinguish the 'industry' and 'industry market' notions. According to them, 'pursuant to the theory of industry organisation, the market is a phenomenon analysed from the standpoint of demand. The industry, on the other hand, is considered from the perspective of the supply of goods on the market. An industry market comprises numerous firms that produce products within its boundaries, often based on similar resources and technologies. The distinction between an industry market and an industry is that the market is defined by the satisfaction of the needwhile the industry is defined by the nature of the assets utilised' (L. V. Roy & V. P. Roy, 2008).

Entry barriers to the market, preventing the emergence of new competitors, are important for the structure of the modern market. Industry barriers (entry-exit barriers) are a combination of objective and subjective factors that either prevent the incoming enterprise(s) from organising profitable production in the industry market or prevent an established organisation (firm) from leaving it without significant losses.

In economics, there are two main approaches to the definition of the concept of industry entry barriers: from the point of view of the theory of industry markets (Industrial Organisation) and from the standpoint of strategic management (Strategic Management). The first approach aims at identifying entry barriers and analysing the characteristics of the industry in which such barriers exist.

The second approach involves assessing the existence of barriers in terms of the company's strategic decisions within the framework of strategic management policy. Joe S. Bain, the founder of the barrier study, defines barriers to entry as anything that allows advantaged firms to earn excess profits without the threat of entry (Doyle & Stern, 2006).

Strategic types of barriers are a combination of objective and subjective factors that either prevent the incoming firm from organising profitable production in the industry market or prevent it from leaving the market without significant losses. Formation of strategic barriers depends on the behaviour of an active firm in the industry market.

The objective is to study the methodological aspects of the formation, enhancement and strategic development of industrial markets.

Materials and Methods

Within the study, general scientific methods of analysis and synthesis, generalization, comparison, abstract-logical analysis, etc. were used. A systemic approach is the common methodological basis of the economy of industry markets. In this regard, when analysing an industry or market, a complex of cause-effect relationships within the framework of the paradigm (structure-conduct-

performance) is explored, both in statics and in dynamics, and the existence of a connection between the parameters characterising the blocks of the paradigm is revealed. Herewith, it is important to investigate the existence of a connection between paradigm blocks in various industries (or markets), as well as the relationship between theory and practice of the actual functioning of industries and markets, as well as conduct a comprehensive study of each individual industry (market).

Modern economics tries to consider the problem of the efficiency of industrial markets from the standpoint of classical economic theory, which considers the microeconomic foundations of the behaviour of an economic entity. This is since the new industry market can be considered as an activity of a single firm that has begun to produce a new product or service.

Results and Discussion

Conditions of production of products and services, pricing principles, the need for government regulation are determined by the 'market model'. The main features of market models are summarized in Table 1.

Table 1

Main features of market models

Feature	***Market models***			
	Perfect competition	***Monopolistic competition***	***Oligopoly***	***Monopoly***
Number of firms	Unlimited number	Multiple	Several (2–6)	One
Type of production	Same	Differentiated	Traditional or differentiated	Unique or close substitutes
Price control	None	Some, but within narrow bounds	Limited by mutual dependence significant in case of conspiracy	Significant
Conditions for joining the industry	Very easily, there are no obstacles	Comparatively easier	Significant obstacles	Blocked
Non-price competition	None	Emphasis on advertising, trademarks, brands	Typical for production differentiation	Promotion of communication with public organisations

Traditionally, the efficiency of the market is considered from a market perspective of perfect competition in two aspects. The first one is the distribution efficiency (allocative ability). In this case, consumers receive the highest combined benefit from the consumption of various goods and services, i.e. the volume and structure of the output is fully consistent with the volume and structure of the purchasing needs of consumers. From this point of view, the efficiency of the industry market formation can be seen as an increase in the aggregate surplus received by consumers. In fact, this means that the creation of new industry markets is feasible if the needs of buyers are better met at lower prices for the products offered (Efimenko, 2009).

In economics, when analysing the distribution efficiency, the concept of X-efficiency is often used. Unlike the classical concept, X-efficiency considers the conditions in which a given set of resources is used to produce products. It does not consider the option of making the best use of these resources in other areas of activity.

The second type of efficiency is the production efficiency. It consists in producing goods in such a way as to ensure that the price of the products sold is consistent with the minimum possible average cost of the production. If this condition is met across all economy sectors, then it ensures the efficient use of the limited resources available to the economy. From this point of view, the creation of new industry markets is useful if the average cost of production across the national economy is reduced.

It is believed that the types of efficiency under consideration are integral to the state of statics, i.e. the market equilibrium. However, funds are regularly invested in the development of the sector of the economy to implement innovations, develop and enhance production technology, which leads to the need to consider the dynamic efficiency. Organisational population ecology considers the competition as a process analogous to natural selection, providing for the survival of the fittest. Herewith, in a stable environment (in statics state), those firms that best meet its requirements are considered the most adapted, while in a dynamically developing environment the most adapted ones are those having the more universal skills. This means that firms that are efficient from the point of view of an equilibrium, stable state in the industry do not always turn out to be efficient in the context of the dynamic development of the industry market (Radaev, 2003).

Unlike allocative and production efficiency, the dynamic efficiency is not easy to measure. It is even more difficult to compare the relative magnitude of static inefficiency (allocative or production) with the magnitude of dynamic inefficiency. Therefore,

economists have always tended to pay more attention to static inefficiencies than to dynamic inefficiencies (Cabral, 2023).

When analysing the efficiency of an industry market, one should not forget about efficiency from the point of view of the firm operating in this market, and social-and-economic efficiency from the point of view of society, manifested in the implementation of the law of economy of time. An industry market is formed if the most economic production is achieved, economies of scale in production are achieved, and the products offered by the firm satisfy the market needs. Such a market may take the form of a monopoly or oligopoly, since there is a positive dependence of the number of sellers with the value of savings on the scale of production.

The industry structures emerging in practice are not always the ones that minimise costs; they are a fair, reasonable approximation of efficient structures. The influence of the market must necessarily make a highly inefficient market structure vulnerable to entry, displacement of established firms by foreign competitors, or some other destabilising impact (Baumol, 1982).

First, attention should be paid to the relative size of the organisation (firm) operating in the industry market. This is an important element of the market structure that influences firm policies and practices and the efficiency of the industry market. Firms of the same size in relation to the size of their markets may have different price and production policies in different market situations. Differences in price response to changes in costs or demand conditions can be explained by differences in the internal organisation of the firm and the structure of the market in which the firm sells its products. Consequently, the price depends both on differences in the organisation of the firm as such and the differences in the organisation of the industry market.

The industry market (using the example of road transport services) is construed as a system of institutional relations ensuring the interaction of the state, carriers, consignors and consignees. This system determines the behaviour of road transport organisations in such matters as pricing and investment policy, the degree of openness of agreements between organisations, as well as influences the formation of strategies for these organisations in various industry segments. The main activity of the state in this field is the creation of strategies for the development of certain types of activities and the service market. Herewith, these strategies should not be equated with direct state regulation of certain types of activities, because in general they do not imply state control over pricing and cash flows but are primarily aimed at setting development goals and areas of state support for industry players. The status of a segment of the motor transport services market is proposed to be assessed by the following criteria: the state and competitive environment within the industry, the level of supply and demand in the services market, geographical location, market dynamics, price, analysis of competitors, organisation of the transport process, the number of producers and consumers of products and services, name, type of cargo, etc. (Efimenko, 2009).

The main production element of the market economy is an enterprise (firm) that produces economic benefits to meet the needs of the individuals and society. A firm should optimise the size considering the ability to control its activities, employee motivation, cost effectiveness, facilitating the search for external partners, responding quickly and flexibly to changes in the industry market, and shape product and price policies in such a way as to maximise profits and ensure sustainable development. One of the main tasks of the company is to create harmonious relationships with the external environment, to ensure the coordinated evolution of the company and the environment in which it operates, to counteract the lag of internal changes from external changes. To achieve this task, it is necessary to combine the stability of the rules for making strategic decisions and the flexibility in making tactical decisions in an optimum manner.

When analysing the efficiency of an industry market, it should be considered that entry into an industry market is difficult if incumbent firms have sufficient power to make a firm that decides to enter this market unprofitable. These capacities may not be fully employed in the absence of attempts by new firms to enter the market, which may lead, for a given output, to higher than necessary production costs, and, as a result, to higher prices and a lower level of production, compared to various forms of restrictive pricing. Thus, production capacity and other investment instruments are effective means of preventing new players from entering the industry market because they are irreversible and represent certain obligations to the industry.

The efficiency of the industry market is influenced by the research and development activities and their results. The possibilities of small organisations (firms) are maximum in the early stages of the production cycle, when economies of scale are not very significant, market share is volatile, and there are many attempts to enter the industry market. At this stage, the success of entry largely depends on scientific and technological capabilities. At the stage when research is relatively complex and specialised, the high costs of ensuring the success of research and development form a barrier to entry into the industry market, contributing to the emergence of large scientific laboratories, that is, technological competition prevails, and large organisations (firms) have advantages. Initial success in research provides a foundation and opportunities for further success; successful organisations (firms) become leaders in the industry market. As technology reaches its full development, the scale and efficiency of production become more important, and the capabilities of small firms decrease. At the product maturity stage, major

patents expire, manufacturing methods are standardised, and barriers to entry into an industry market are based not on the difficulty of meeting research requirements, but on the scale of production and marketing. Price competition replaces the technological competition.

Herewith, studies of the American economists (Clodius & Mueller, 1961) on the correlation between the degree of monopolisation of the industry market (the size of the firm, the degree of ease of entry into the market) and innovative activity have shown that the possession of monopoly power is a necessary (but not sufficient) condition for the effective functioning of the market. Entrepreneurial leadership and competition are qualified as the necessary conditions.

When evaluating the effectiveness of industry markets, it should be considered that the market is a complex mechanism. Modern institutionalism considers the market as: the interaction of traditions, pursuant to which the parties get used to certain restrictions; agreements that are supported by social norms regarding the objects of sale, etc.; legislative acts regulating the process of competition and pricing; actions of other interested market participants.

All of this comprises the industry market and determines its effectiveness. While analysing the behaviour of industry economic agents, it should be borne in mind that enterprises do not always rely on the interest of cost recovery and maximum profits. They work with business partners on the principles of reciprocity and future benefits, not necessarily in equivalent form. Constant contacts in the industry market enable the industry market participants to exchange useful information, learn from each other, adopt technological and organisational innovations, exercise mutual control, form social capital in the form of trust and business reputation and, ultimately, stabilise the market and enhance its efficiency.

Contemporary institutionalism is closely linked to the organisation theory. From this point of view, the market is an institutionalised space. The major players in the market use stronger resources and specific social skills to stabilise or change the existing industry market institutions. The market structure can be destroyed and made more effective by the intervention of stronger actors that emerged both within and outside the industry market. It should be borne in mind that the market order or method of coordinating the behaviour of enterprises (firms) in the industry market may collide with other coordination mechanisms. There are methods of coordination associated with the interests and institutions of the industrial method of coordination (production technology, the effect of economies of scale in production, etc.); the interests of households based on traditional relationships, kinship, locality; interests of a civil society built on collective interests and adherence to the principles of democracy. As a result, striving for market efficiency may run into rejection of such an approach by other ways of coordinating the industrial market, which leads to a redistribution of resources between subjects and branches of the economy. From this point of view, participants are interested in stabilising the industrial market, forming an agreed order, which is a mechanism for deterrence of the short-term economic interests, a condition for maintaining a competitive environment and market efficiency.

Representatives of the theory of market organisation distinguish three categories of markets: the market of perfect competition with the maximum degree of competitive interactions; a monopoly market with a minimum degree of competition and an imperfect competition market (competition is present, but its effect is distorted by the behaviour of economic agents).

Competition is part of the market structure. On the other hand, the structural approach identifies the relationship between profit and concentration level in the industry. The aggregate industry profit (*P*) is calculated by the formula:

$$\Pi = \sum(P\text{-}C_i)q_i, \quad (1)$$

where P is the market price;
C_i is the average amount of expenses of a similar firm in the market;
q_i is the sales volume of the i^{th} firm.

The difference between the price and the average expenses of the i^{th} firm is expressed through the Lerner's index *(L):*

$$L = (P - Ci) + (siP) / e \quad (2)$$

where si is the market share of the i^{th} firm;
e is the price elasticity of demand.

By substituting the above expression to formula (1) and multiplying the entire expression by Q/Q, which is the industry volume of sales, we obtain:

$$\Pi = HHI\ P\ Q / e \quad (3)$$

where *HHI* is the Herfindahl-Hirschman index that characterises the industry concentration degree.

This expression can be presented in a different way:

$$\Pi / PQ = HHI / e \quad (4)$$

The right part of this expression shows the share of industry profits in total sales, and the left part shows the ratio of the Herfindahl-Hirschman index to the price elasticity of demand.

Consequently, the value of industry profits (as a percentage of sales) is directly proportional to the level of concentration in the industry (measured by the Herfindahl-Hirschman index) and is inversely proportional to the price elasticity of demand. Respectively, high concentration level in the industry results in high profitability and organisational (firm) profitability – and vice versa.

The global nature of competition leads to the situation where the leading role in the development of the company, along with competition, is played by the processes of cooperation and integration, which require continuous coordination of the behaviour of firms, ensuring the economic effect of joint activities. Cooperation is gradually becoming a strict business requirement as a mechanism for adapting to constant changes (Welborn & Kasten, 2004). In integration at the industrial stage of development of society, organisational forms of unions of enterprises (firms) with a hierarchical management structure prevailed.

With the transition to the post-industrial stage of development, this form of organisation has ceased to cope with the increased flows of information and innovation that lead to the permanent renewal of all aspects of the enterprise (firm) and of the economy. The hierarchical structures are therefore replaced by self-managed networks built on horizontal links and special, participatory interactions (Gnatiuk & Efimenko, 2017; Efimenko & Gnatyuk, 2023). Enterprises (firms) master a hybrid version of the organisation of production and management (employ the cluster network principle), which is more flexible compared to the hierarchical model and more integrated compared to the market model of economic organisation.

In the market economy, the interpretation and hierarchy of effectiveness criteria and their content have changed. Since the main objective of entrepreneurship is profit, then the criterion of economic efficiency is the maximisation of profit per unit of capital (resources) expenditures with a high level of labour quality and ensuring the competitiveness of products. In the application of resource-efficient technologies, the criterion of efficiency is the minimisation of costs and resources per unit of output. Under market conditions, the general criterion of efficiency is retained: maximisation of national income, gross domestic product per unit of expenditure and resources to enhance the standard of living of the population.

Conclusions

1. Currently, the functioning and formation of industry markets must be consistent with the essential
2. Principles of state sovereignty, as well as with the ability of various economies to integrate into the world economy. The concept of 'market' is close to the concept of 'industry'. If markets bring together sellers and buyers of goods that are close substitutes from the point of view of their buyers, the industries combine sellers (producers) of goods (services) that are close substitutes in production or 'on the supply side'. In a certain sense, the market is larger than the industry, as it includes not only the sellers of close (demand-driven) substitutes, but their buyers as well. However, the industry is generally larger than the market. The concept of 'industry market research' can be defined as the collection and analysis of data to make decisions on the independent development of a product (service) or the acquisition of appropriate technology.
3. When evaluating the economic efficiency of the formation of industry markets, it should be considered that modern markets are the imperfect competition markets, and therefore various factors (like regulatory frameworks, institutional influences, behavioural constraints on socio-economic efficiency) that restrict freedom of competition and to some extent regulate the activities of organisations in industry markets must be considered and introduced into the models. When analysing the efficiency of industrial markets, the achievements of modern institutionalism must be considered and the influence of market institutions on the behaviour of economic entities, which will affect the social-and-economic efficiency of the market, must be included in the analysis.
4. Most enterprises (firms) are forced to change their organisational form, enter into various agreements with other enterprises under the influence of the following factors: permanent changes in the external conditions for the functioning of the enterprise and the need to adapt to these changes; complication of production and commercial activities of enterprises in the context of globalisation and openness of the national economy; increasing the role of the time factor requiring prompt action, a new approach to production and management methods; expanding the market space of the enterprise in order to survive in a competitive environment.

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THE IMPACT SOCIO-ECONOMIC AND GEOPOLITICAL CHANGES ON RURAL TOURISM FLOW

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Abstract
Tourism is one of the most important economic sectors in the world. According to the Ministry of Economics of the Republic of Latvia, the tourism sector is very important for the Latvian economy. The industry's share has recovered after the pandemic, reaching 2.1% in 2023. In 2023, around 30,000 people worked in the industry. There are inequalities in the tourism sector in the regions of Latvia compared to the Riga region. The limited or completely stopped flow of tourism during Covid pandemics in the regions, has had long-term consequences for the tourism industry. It is very important, as tourism provides thousands of jobs and business opportunities for SMEs businesses who specialised in crafts and trades in the regions. Rural tourism can promote community development by providing economic opportunities, cultural preservation and environmental protection in rural regions. This article investigates the changes in rural tourism flows and the challenges faced by the tourism sector due to socio-economic and geopolitical events. The aim of the research is to analyse the changes in the tourism flows and challenges the tourism sector has faced due to socio-economic and geo-political factors. The methodology involved statistical data analysis and survey with tourists to understand tourist perception on Latvia as safe tourism destination. Research identifies political, economic and social factors that helps with further improvements aimed at enhancing Latvia's image due to geopolitical situation and can help in making policy decisions for the development of tourism in rural areas.
Keywords: rural areas, tourism industry, geopolitical risks, tourist flow.

Introduction

Tourism has been identified as a key driver of economic recovery and growth. A recent International Monetary Fund report outlines the positive impact of the sector's rapid recovery on certain economies worldwide. The global economy is forecast to grow by around 2.9% in 2024, according to the World Economic Outlook report, exceeding previous forecasts but still below the 3.5% growth rate recorded in 2022, citing the ongoing impact of the pandemic and the war in Ukraine, as well as the tourism crisis. Latest World Tourism Barometer indicates that a total of 1.4 billion international tourists travelled in 2024, representing an almost complete recovery from pre-pandemic levels (99%) (World Tourism Organization, 2025). Tourism has become one of the most important socio-economic phenomenon of modern times. It is among the largest economic sectors, providing income and jobs, and is a significant generator of foreign exchange at the national level (Melece & Rucins, 2012), stimulating a range of other related sectors through its multiplier effect. Tourism functions as a multifaceted economic activity, cutting across different sectors, including economic, social, cultural, and environmental dimensions. Tourism enables export, creates workplaces and additional income for regional development by influencing job creation, business growth, and infrastructure development. Even before current geopolitical situation, in 2020, due to Covid-19 virus the global tourism industry shrank by 72% increasing unemployment, bankrupting small companies, which was most evident in regions (Pole & Grizane, 2021).

Theoretical Findings

Rural Tourism: A Driver of Socio-Economic Development

Rural tourism remains a vital tool for socio-economic regeneration, offering authentic experiences that attract modern travellers. Integrated within local economies, cultures, and social structures, its development is shaped by various factors, including tourist motivations and market shifts rather than just economic or physical conditions (Streimikiene & Bilan, 2019). Tourism enhances rural vitality by generating employment, fostering business cooperation, and increasing regional attractiveness. Studies confirm its economic benefits, yet the evolving landscape necessitates continuous assessment of challenges and opportunities (Zaleckiene & Turcinskaite, 2019).

Rural Tourism and Its Economic, Social, and Environmental Impact

Tourism plays a crucial role in regional economies, with economic impact analyses highlighting its influence on public planning, marketing, and development decisions (Tokhirovich, 2021). Rural tourism combines the economic, social and environmental components of rural areas. It is closely linked to people, space and products and has unique effects on the environment and on economic growth. The development of tourism in villages can promote rapid economic growth, create more jobs and improve the quality of residents' life (Yang et al., 2021). The World Tourism Organization (WTO) (2013) emphasizes measuring tourism's socio-economic effects, including employment, infrastructure, and sustainability. In 2013, the United Nations agency of WTO developed the Guidelines for Socio-economic Measurement and Analysis of Regional Tourism. It integrates economic, social, and environmental factors, driving growth, job creation, and quality of life improvements (Yang et al., 2021). Activities range from eco-tourism to agritourism, offering both supplementary and primary income sources (Berzina & Lauberte, 2019). Rural regions in many countries continue to suffer from significant outmigration,

unemployment, and social isolation. The lack of social innovations is one of the primary factors which hinders population regeneration and promotes long term depopulation. Furthermore, wars, conflicts, terrorism, and violations expand the scope of geopolitical risk which adversely affects tourism for many countries encouraging tourist to travel less which results in reduced tourism in those countries (Papagianni et al., 2023).

Geopolitical impact on tourism

The latest global crises affecting political, economic, and community life worldwide – including those impacting tourism - are the ongoing SARS-related COVID-19 pandemic and the war waged by Russia against its sovereign neighbouring state, Ukraine. Even before Russian Ukrainian war, such political events like the US-led invasions of Iraq and Afghanistan fuelled conflicts in Western Asia, were impacting tourism. Besides that, natural disasters such as the tsunami in 2004 and the Eyjafjallajokull eruption in 2010 had immense impact on travel. Researchers have shown continuous interest in studying the effects of geopolitical risks since the 9-11 attacks, which influenced the global economy and many industries, particularly the tourism industry and travel demand worldwide (Gozgor et al., 2021). Geopolitical uncertainties, such as wars and terrorist threats, create economic instability and can exert notable effect on tourism arrivals, tourism imports, number of overnight stays and other indicators of tourism development and overall development (Akadiri et al., 2020). The WTO (2018) ranks tourism as the third-largest global industry but highlights its susceptibility to political and economic turmoil. Political shifts, regional integration, and transnational corporations are reshaping the global tourism framework (Webster & Ivanov, 2015). Events like elections and economic uncertainty influence tourism flows, yet the full impact of geopolitical risks remains understudied. Tourism inherently interacts with global politics, yet its geopolitical implications require deeper analysis. Topics like border security, military occupation, and nation-building have been explored, but everyday geopolitical encounters in tourism remain underexamined (Akadiri et al., 2020).

Rural Tourism in Latvia

Tourism contributes approximately €1 billion (4.3%) to Latvia's GDP. In 2019, the sector employed 77.000 people (9% of the workforce). The industry's share has a good recovery after the pandemic, reaching 2.1% in 2023. Sadly, many people working in tourism had to leave the industry during the Covid pandemic and retrain in other sectors. Around 30,000 people worked in the industry of all employed people in 2023 which is half of pre-pandemic level (LDDK, 2024). The number of visitors to Latvian tourism establishments has fluctuated significantly over the years. In 2019, Latvia had 2.85 million tourists. The number decreased by more than 70% during the COVID-19 pandemic. In the year 2023, the number of tourists in Riga for the first time since 2019 exceeded one million - the capital city was visited by 1.2 million guests. (Riga Investment and Tourism Agency, 2024). In comparison with Riga, in 2024, 2.7 million foreign and local guests were served in Latvian tourist accommodations, representing a 10.9% increase compared to 2023, according to data from the Central Statistical Bureau. Data shows that 50% of tourists mostly spend time in Riga not in regions. Before 2022, around 30% of Latvia's tourists came from Russia, Belarus, and Ukraine. Since the war, Latvia has shifted its focus to Western markets, increasing visitor numbers from Lithuania and Estonia. U.S. tourist arrivals increased by 45% in 2024 (CSB, 2024). The largest number of foreign visitors came from Lithuania, Estonia, Finland, the United Kingdom and other countries. This correlates with the survey results showing the influx of tourists from neighbouring countries. In 2024, foreign tourists were most often found in Riga – 71.5%, in Jurmala - 8.4%, Liepaja, Sigulda region and in Ventspils. Tourism development at the regional level has several meanings and, in addition to economic activity, it also helps to diversify business in rural areas, ensure a certain lifestyle of business, organize public infrastructure, improve the living environment for local communities, strengthen the identity of the place and, through quality hospitality services, indirectly promote the development of business in other sectors or the attractiveness of the place to live (Ministry of Economics of Latvia, 2024). Cultural events and heritage play a crucial role in attracting international visitors and businesses to Latvian regions. To implement regular management of a tourist destination, data is needed that regularly shows the development of tourism and related sectors. This is necessary both for monitoring development, as well as for the effectiveness of implemented activities and for predicting future actions.

Rural Tourism and Socio-Economic challenges

In recent years, Latvia's tourism sector in the regions of Kurzeme, Latgale, Riga, Vidzeme, and Zemgale encountered several challenges. Underuse of social capital has been recognized in Zemgale as an obstacle to the development of regions. Erosion of development policy effectiveness, public disconnection from democratic institutions, low participation of NGOs, emigration, and limited resources in local governments have created inequalities between territories. According to studies, local deputies' education levels correlate with higher social potential and socially active inclusion. It is recommended to enhance funding for NGOs to strengthen community initiatives and support long-term development (Jankova et al., 2017). Summer tourism in the Kurzeme region has contributed to a seasonal distribution of visitors throughout the year. In 2024, the Kurzeme Planning Region organized 2 informative seminars on the off-

season tourism, during which participants brainstormed ways to attract visitors outside of summer while ensuring that the tourism product remains sustainable and appealing (Ivanova, 2015). The development of Kurzeme has been characterized by a heterogeneity and difference in social and economic development of the municipalities that have inevitably affected tourism. In Latgale, the adoption of digital marketing strategies for tourism promotion has been limited. A study revealed that only 20% of tourism information providers actively engage with social media, often prioritizing traditional printed materials over digital content like videos. Moreover, regional tourism websites such as Visitlatgale.com and Latgale.travel lack comprehensive digital marketing features. Creating communication plans, leveraging EU opportunities for funding, and training the tourism information providers in digital marketing are the measures that are necessary to be put in place to advance the region's online presence (Karvele & Znotina, 2019). Pronounced problems have been observed for a long time in the Latgale region, where the unemployment rate remains almost twice as high as the national average and almost three times higher than in the Riga region (Economic Development Report of Latvia, 2024). A nationwide issue affecting regions like Vidzeme is the shortage of labor resources in the tourism industry. This problem is exacerbated by emigration and the migration of the workforce to the capital, Riga. Consequently, some tourism enterprises have considered recruiting workers from abroad, including countries like Ukraine, Belarus. Additionally, there is a significant portion of workers lacking experience in their employed sectors, highlighting the need for targeted personnel training and development programs (Lukjanova, 2019). In Vidzeme, challenges related to public services and infrastructure have impacted tourism. Issues such as inadequate intra-regional public transportation, insufficient mobility services, and poor road infrastructure have been identified. These limitations affect both residents and tourists, underscoring the necessity for improved transport services and infrastructure to enhance accessibility and regional attractiveness.

Materials and Methods

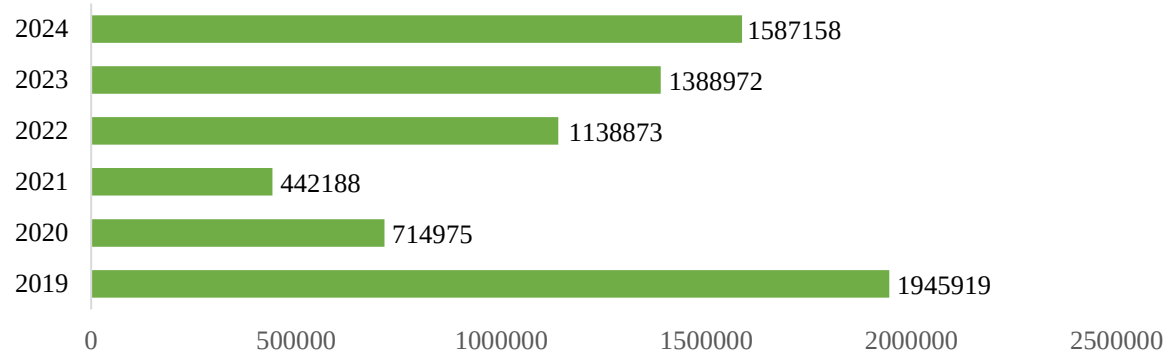
The research aim was to analyse the changes in the tourism flows and challenges the tourism sector has faced due to socio-economic and geo-political factors. The methodology of research involved statistical data analysis to understand differences in tourism flow in regions, and a survey of tourists to understand tourist perception of Latvia as a safe tourism destination.

Statistical analysis

The necessary statistical data on number of tourists visiting Latvia were acquired through statistical outlooks, databases and annual overviews by the Central Bureau of Statistics of Latvia (CSB). The study conducted a statistical data analysis to assess changes in tourist flows in Latvia and its regions within the framework of geopolitical events in recent years.

Figure 1

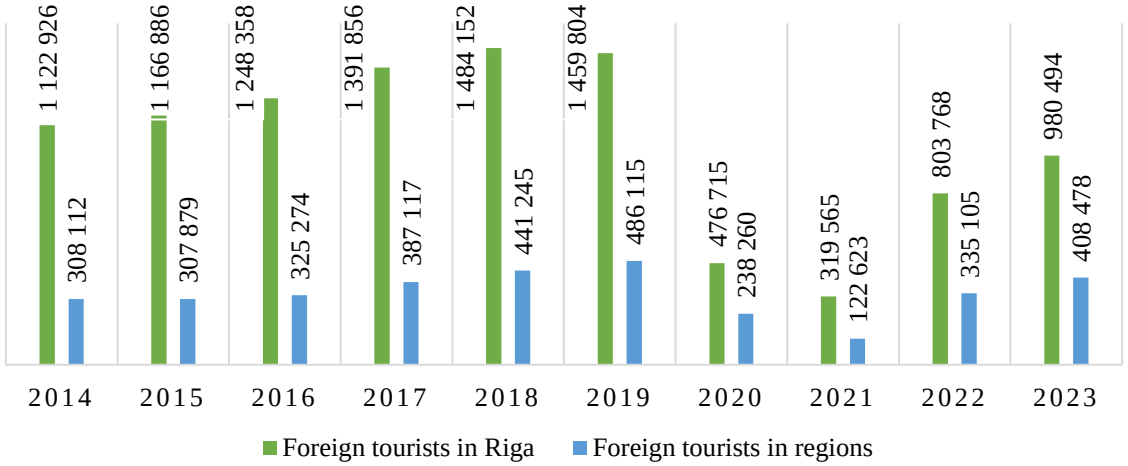
Foreign guests in hotels and other tourist accommodation in Latvia (thousands)



Source: author's construction based on the CSB data.

Tourism statistics all over the world must be divided in two parts – before and after Covid-19 pandemics. Figure 1 indicates that, compared to 2019, the tourism flow is recovering at an average speed. However, it is complicated to determine whether its slower growth is because of the geopolitical situation or still a consequence of Covid-19. Statistical analysis clearly shows large difference between tourist flow in the capital city and regions outside it, Figure 2. Before Covid the difference was three times bigger than it is now. In recent years, after the geopolitical conflicts started in the neighbourhood, the situation has levelled off, and the difference in tourist flow in Riga is now twice as big, not three times as big, as that of other regions. Despite the geopolitical situation, regional statistics have returned to their previous level compared to the pre-Covid period, which means that neither the consequences of Covid nor the current geopolitical situation have affected the overall tourism flow in the regions.

Figure 2
Differences in the number of foreign tourists in Riga and the regions (thousands)

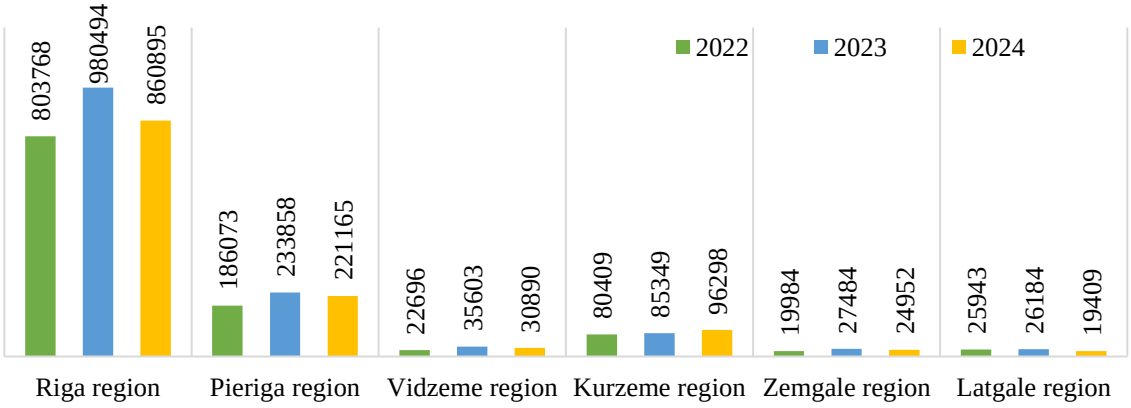


Source: author's construction based on CSB data.

The Riga region has unquestionably the most tourists, as seen by Figure 3, which shows a notable growth from 803.768 in 2022 to 980.494 in 2023. Over the last three years, the number of visitors visiting the Vidzeme Region has steadily increased. The decline in 2024 can be brought on by competition from other areas or outside variables that impact traveller demand.

The number of visitors to the Kurzeme Region has been rising gradually, which may indicate an increasing attractiveness of the region. The number of visitors to the Zemgale Region increased from 19.984 in 2022 to 27.484 in 2023, before declining slightly to 24.952 in 2024.

Figure 3
Foreign tourists by regions (thousands)



Source: author's construction based on CSB data.

Unlike Kurzeme, Latgale shows an increasing trend increasing from 25.943 in 2022 to 26.184 in 2023 and then dropping further to 19.409 in 2024. The Riga region remains the top tourist destination, reaffirming its prominence as a major travel centre. The number of tourists in Kurzeme is steadily increasing, indicating possibilities for tourism development. Pieriga, Vidzeme, Zemgale, and Latgale show diverse patterns, with Latgale indicating the most decrease.

Survey results

In research, a sample refers to a subset of the population that is selected for study purposes. In this research foreign tourists or potential tourists were selected as a sample for the pilot survey.

The pilot survey consists of three parts. The first part started with finding out the demographic information about tourists, specifically their country of residence, have they ever visited Latvia, for what purposes and how many times. The second part was developed to understand tourism perception of Latvia as a safe or unsafe tourism destination even if they haven't been in Latvia. The purpose of the third part was to show tourist experience while travelling to Latvia. The second and third part of the survey were compiled according to the Likert scale in a five -point system from '5-very safe' to '1-not safe'; '1-very poor' to '5-excellent'. The survey contained several questions for evaluation: whether any safety concerns influence a tourist decision to visit Latvia due to the geopolitical situation,

how safe they feel during the visit and whether there was enough information about safety during the visit.
The questionnaire was distributed in two ways. First, it was prepared electronically and filled online for those who haven't been in Latvia. Other method was a field survey by approaching tourists face to face during their travel, mainly Riga, to understand how safe they feel being here as tourists.

Results and Discussion

The survey was conducted during the period 1.03.2025 – 16.03.2025, during which 109 responses were collected. Responses correlate with data from Central Statistical Bureau showing that Latvia indeed has increasing visitor numbers from neighbourhood countries like Lithuania, Estonia and Northern countries, like Sweden, Finland and Norway.

Table 1

The profile of respondents

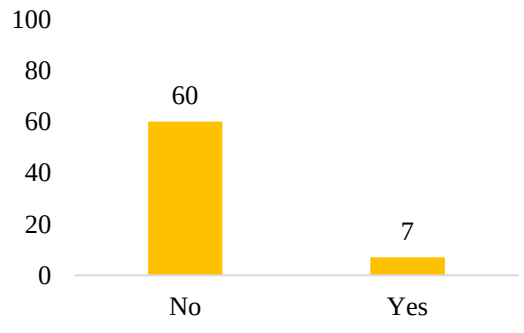
Category	Profile
Gender	female – 59.6%; male – 40.4%
Age	18-25 – 33.9%; 26-35 – 22%; 36-45 – 21.1%; 46-45 – 13.8%; 55-65 – 6.4%; 66 or above – 2.8%
Country of residence	**Lithuania**: 19.27%; **Estonia**: 12.84%; **Sweden**: 8.26%; **Finland**: 7.34%; **Norway**: 6.42%; Canada: 5.50%; Bangladesh: 4.59%; India: 4.59%; Belgium: 3.67%; Spain: 3.67%; Bulgaria: 3.67%; Poland: 2.75%; Australia: 1.83%; France: 1.83%; Pakistan: 1.83%; Russia, USA, Ukraine: 1.83% each; Azerbaijan, Kazakhstan, Botswana, Qatar, Philippines, Turkiye, Uzbekistan: 0.92% each

Source: author's calculations based on survey results.

Results show that 28.4% (31) of respondents have not been in Latvia, but 71.6% (78) have visited Latvia before. More often tourists stay less than 3 days (47.7%), 1 week stayed 19.3% and just 9.2% stayed more than a week. The primary purpose of visiting Latvia was leisure (58.7%) and business (19.3%), also visiting friends, scientific purposes and shopping (Table 1). Despite the theoretical analysis that shows – the geopolitical situation has impact on tourism, survey results in case of Latvia show otherwise. The tourist perception mostly has not been influenced by Russian- Ukrainian war, as 91.7% of respondents answered that the recent geopolitical situation has not influenced the perception of Latvia as a travel destination. The author received only 67 answers regarding safety concerns but results also show that tourists feel safe travelling to Latvia, and they don't have any safety concerns, Figure 4. Some received answers were that Latvia is specifically safe for students to study, and that Latvians do not like to speak Russian, so tourists from post-soviet countries are not welcome.

Figure 4

Safety concerns about Latvia as a travel destination

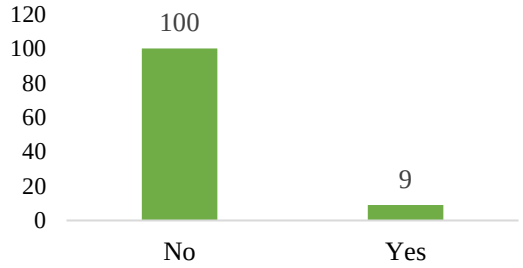


Source: author's calculations based on survey results.

Despite geopolitical concerns, most travellers feel safe in Latvia, and geopolitical events haven't changed the tourist perception of Latvia as a travel destination, as 100 respondents indicated no negative impact on their perception, Figure 5. However, external perceptions (without visiting) are slightly more cautious. According to the survey data, tourists see Latvia as a safe destination for a traveller.

Figure 5

Influence of geopolitical events on tourist perception on Latvia as a travel destination

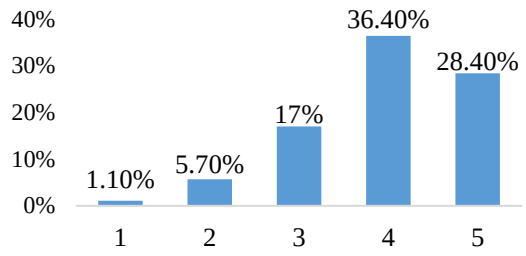


Source: author's calculations based on survey results.

Using Likert scale in a five-point system from '5-very safe' to '1-not safe', 76% (83 responses) see Latvia as a safe or very safe destination. Only 2.7% of respondents think that it is unsafe. Similar answers were received from tourists who have been in Latvia during the ongoing political situation, 86.6% rate their visit as safe or very safe in public spaces. Only 2.2% rated the country as unsafe.
Figure 6 shows friendliness and helpfulness of local authorities in ensuring tourist safety. The analysis shows that most of tourist experience was positive, but some improvements can be done, as 23.8% of tourist experience was bad to medium bad. Regarding the analysis of security concerns related to Latvia's

geographical location (e.g., proximity to Russia), 78% of respondents expressed no concerns, while 22% indicated that they did have some concerns. Despite the results showing Latvia as a safe tourism destination from the view of tourists, information about safety measures for a tourist visiting Latvia is limited. Results show that 46.1% of respondents rate availability of information on 3 of Likert scale showing not enough information in public spaces and media about safety.

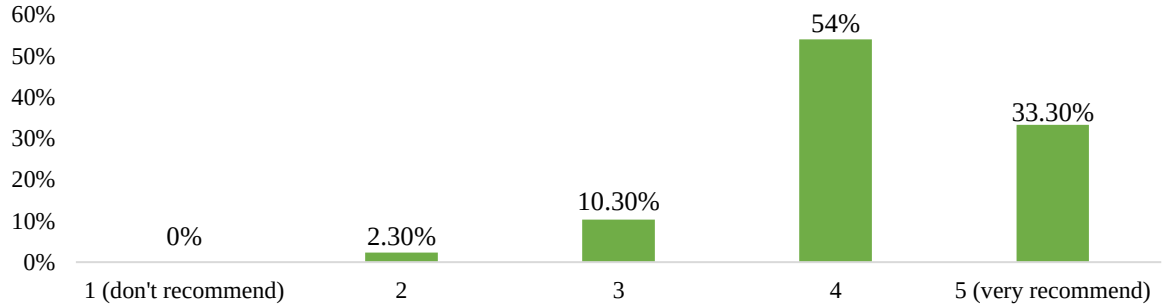
Figure 6
Analysis of helpfulness of local authorities



Source: author's calculations based on survey results.

Overall, based on tourist experience during travel, 87% of respondents would likely recommend Latvia as a safe travel destination, with only 10.3% (9 responses) being not sure about recommending Latvia, Figure 7.
Suggestions for safety improvements for Latvia's tourism sector were related not only to the geopolitical situation but also to the improvement of the tourist experience. Tourists suggested several ideas for safety and overall experience improvement: establishing a train connection between the airport and city; creating an app or other medium to provide tourists with updates on current events in Latvia, with content available not only in English but also visually for those who don't speak English well; ensuring English-speaking staff are available at police stations and hospitals in case of emergency; increasing police presence at tourist attractions; providing more information on statistics of other religions in Latvia that may concern tourists; informing tourists about current political situation, including guidelines for actions in the case of a real threat; improving traffic management and road conditions.

Figure 7
Analysis of tourist recommendation on Latvia as safe tourism destination for others



Source: author's calculations based on survey results.

Conclusions

1. The findings indicate that while tourism is recovering at a moderate pace compared to pre-COVID levels, it remains unclear whether slow growth is due to lingering pandemic effects or geopolitical instability.
2. The findings highlight regional disparities in tourism development, influenced by infrastructure, labour shortages, digital marketing gaps, and policy effectiveness. A significant shift in tourism distribution is observed, with the gap between Riga and regional tourism flows narrowing.
3. Despite geopolitical tensions, regional tourism has rebounded to pre-pandemic levels, suggesting resilience in the sector.
4. Riga remains the primary tourist centre, showing notable growth in 2023 before a decline in 2024. Kurzeme demonstrates a steady growth, indicating increasing attractiveness. Vidzeme and Zemgale show fluctuations, while Latgale faces the sharpest decline, possibly due to economic or competitive factors. Despite these challenges, tourism in Latvia is stabilizing, addressing labour migration, digital transformation, and regional infrastructure will be the key to enhancing tourism resilience and long-term growth.
5. To preserve the rural world and its economic, social, and cultural significance, rural tourism should be developed and promoted. An increase in public information, enhanced police presence addressing safety concerns related to the political situation, and digital tools can enhance Latvia's tourism appeal. Tourism can help sustain the viability and stability of rural communities, as young people leave for urban regions, abandoning family homes.
6. The study also finds that even a theoretical analysis shows that globally geopolitical risks negatively affect tourism. In case of Latvia findings of survey indicate that, tourists largely perceive Latvia as a safe destination. The majority (91.7%) reported that the Russia-Ukraine war did not affect their travel decisions, and 76% of respondents rated Latvia as 'safe' or 'very safe'.

7. Visitor numbers from neighbouring countries, such as Lithuania, Estonia, and the Nordic nations, are increasing. Most tourists visit Latvia for leisure (58.7%) or business (19.3%), with nearly half staying for up to three days. While tourists generally feel safe, some areas for improvement include better public information on safety, English-speaking assistance at key locations, improved transport connectivity, and infrastructure upgrades.
8. Overall, Latvia remains a stable and attractive travel destination, with 87% of visitors likely to recommend it. Enhancing safety communication and infrastructure could further strengthen its tourism sector.

Acknowledgements
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EVALUATION OF THE RETURN ON INVESTMENT SUPPORT IN AGRICULTURE USING THE CEM METHOD

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Abstract
The purpose of the study is the assessment of the effectiveness and efficiency of the investment measure M04 'Investments in physical assets' of the RDP (Rural Development Program) 2014-2020 (2022) in Latvia, regarding the economic performance of agricultural farms. To do this, the CEM (Coarsened Exact Matching) method is used. This method was chosen because it is well applicable to a small number of units and pre-support variables. The data panel includes FADN (Farm Accountancy Data Network) units that have received support only under the support measure 'Investments in physical assets', which are compared with the control group. The results obtained indicate a significant impact of support on the improvement of economic indicators of farms. The indicative impact of support is estimated at around 40% of the total labor productivity growth in the reporting period and 60% of the income increase. Compared to non-recipients of support, the largest positive impact is obtained in the group of small farms, as well as in grazing livestock specializations. The average deadweight on investments is 47%. The results of the study and the discussion show that the CEM method can be successfully used in assessing the impact of support, including for smaller groups, and the results obtained can be used in improving support policy.
Keywords: agriculture, support, investment, economics.

Introduction

Since Rural Development Program (RDP) is an essential part of Common Agricultural Policy (CAP) of the EU, RDP evaluation is an essential and necessary component of the Programme implementation to assess the achievement of objectives and the efficiency and effectiveness of the use of public funding. The measure 'Investments in physical assets' is the largest in terms of funding (38% of the total RDP 2014-2020 (2022) funding), as well as with a complex structure, different beneficiaries and investment in five focus areas of three priorities. Therefore, its detailed evaluation is particularly important.

The aim of the work is to assess the effectiveness and efficiency of the investment measure M04 'Investments in physical assets' implemented within the framework of the programme, considering the set objectives and achievable results. The structure of the work is created considering the purpose and format constraints.

In accordance with the aim, the following tasks were set for the work - to evaluate the results of the support of the investment measure; to evaluate the achieved objectives; to provide conclusions and recommendations for further support in achieving similar objectives.

According to the evaluation guidelines, the net value of the indicators must be assessed, i.e. the net impact of the support. Theoretically, it could be determined by subtracting from the actual results of the aid recipients the results that would have been achieved without the aid being evaluated. Since this is not possible in practice, a hypothetical or counterfactual analysis is performed. This is done by matching - the aid recipients are compared with enterprises (farms) that have not received the relevant aid, which are as similar as possible to the aid recipients according to various parameters. To match the aid recipients and non-recipients, the CEM or Coarsened Exact Matching method was chosen for the relevant task of the study (Iacus et al., 2011).

Materials and Methods

One of the most popular methods for causality in observational studies is the Propensity Score Matching (PSM) method developed by Rosenbaum and Rubin (Rosenbaum & Rubin, 1983). It recommends including as many pre-support covariates as possible in the calculation of the propensity score. In contrast, King and Nielsen argue that PSM often increases imbalance, inefficiency, and bias, depending on the model (King & Nielsen, 2019). The CEM was developed by Iacus, King, and Porro (Iacus et al., 2011). According to the authors, CEM generates appropriate solutions that are better balanced and have a smaller mean square error. At the same time, Black et al. points out that CEM can produce very different results from other methods, and the estimated full sample results may not be consistent with the results of subsamples (Black et al., 2020). Comparing the performance of PSM and CEM based on randomized clinical trials, the authors found that both methods produce greater balance of pre-aid covariates while preserving most of the original data. When there are few pre-aid variables, CEM produces satisfactory results (Guy et al., 2021). Since the available FADN data do not have large number of variables with all items having non-zero values, the CEM method was chosen for the purpose of the study. The difference-in-difference method was used to obtain matched recipients and non-recipients and determine the direct effect.

In the data panel, the support group includes FADN units that have received support only and exclusively in the corresponding measure, and the control group includes units that have not received support in any measure. Receiving support is considered a binary support variable, the value of which is 1 for recipients and 0 for non-recipients. Since participation in the

measure is not randomized, there are differences in the pre-support covariates in the support and control groups. To reduce the overall imbalance of covariates, the pre-support covariates are granulated into 'bins'. The user can either choose the bin sizes arbitrarily or use one of the recommended formulas. There are several methods for determining the bin sizes (Scott, 2010), but they are not used this time because the data panel is not that large. Bins are determined arbitrarily. In the data panel, the FADN units that have received support only and exclusively in the corresponding measure are included in the support group, and the control group - units that have not received support in any measure. Receiving support in the M04 measure is treated as a binary support variable, with the value 1 for recipients and 0 for non-recipients. Since participation in the measure is not randomized, there are differences in pre-support covariates between the support and control groups. To reduce overall covariate imbalance, pre-support covariates are granulated into strata.

The initial data panel includes 270 non-recipient and 337 beneficiary units. The group of beneficiaries includes those farms in the FADN cluster that have received support under sub-measures M04.1 or M04.3 by the end of 2020 (so that the support effect would have been manifested by 2022). In turn, the group of non-recipients includes those farms in the FADN cluster that have not received any investment support (including in other measures) during the entire period under analysis (2014-2022).

Since automated software is not used in the calculations, a simple distribution of covariates into three groups is chosen for granulating pre-support covariates in strata. The first group (crop growing) includes units specializing in field farming, vegetable growing, mixed crop growing, and growing permanent crops. The second group includes dairy farms. The third group (other livestock) includes farms specializing in grazing livestock, mixed cropping and livestock, mixed livestock, pig farming and poultry farming.

The size groups of farms are also created differently, with three strata including farms of two adjacent size groups. Under small farms we assume farms with Standard Output (SO) from 4,000 to 25,000 EUR, medium farms – SO from 25,000 to 100,000 EUR, and large farms – those with SO more than 100,000 EUR.

The calculations have been made using individual FADN data for the years 2014-2022. The initial data panel with 607 units is divided into 151 strata. After excluding the unsuitable strata from the granular data panel, 57 strata with 193 non-recipient units and 255 beneficiary units are retained for further calculations.

The analysis of the results of the beneficiaries and the control group has been carried out using the Austrian experience in the evaluation of the RDP 2007-2013 measure no. 121 (European Commission, 2014).

Farm characteristics used to compare the beneficiary group with the control group: Type of farming; farm size group; standard output; labour input; net turnover; output.

The main indicator used to measure the impact of the support is the increase in labour productivity (R2), which is calculated as the output of agricultural products per full-time employee (FTE). The increase in the farm's net income is used as an additional indicator. The increase in labour productivity for all supported farms is calculated using the characteristics of the entire beneficiary group according to the Rural Support Service (RSS) data - average agricultural product output and average labour consumption in full-time units (before the project, as well as the calculated increase). This corrects for the shift that would occur due to the fact, that the average size of farms in the FADN group is approximately 20% larger than in the entire beneficiary group according to the RSS data. The calculated total output of the supported farms both before and after the support is divided by the total labour force utilization in them, thus obtaining the average labour productivity in the beginning and end year in the group of supported farmers. By applying the previously calculated % ratio between the increase in labour productivity of the supported farmers and non-supported farmers to this, the impact of the support is calculated. The impact of the support at the national level is assessed by applying the impact at the level of the beneficiaries to the entire agricultural sector of the country in proportion to the number of employees.

The changes in net income in the entire set of supported farms are calculated using data on the total income of farmers in the country (from Economic Accounts for Agriculture – EAA), dividing it by the share of supported farms. Income in supported farms before the support is obtained by taking data on one average farm from the assimilated FADN set, applied to the entire number of beneficiaries, before making a correction proportional to the differences in the value of agricultural output in the RSS data and the FADN set (coefficient 0.77). Incomes in supported farms after support were obtained by applying a coefficient obtained from calculations, which shows by how much percentage the income of the beneficiaries of support grew faster than in all farms.

The effectiveness of the support is analysed by comparing the results obtained for the beneficiaries against the same indicators for the non-beneficiaries (%), which is equivalent to the increase in a certain result indicator for the group of beneficiaries compared to the increase in the same indicator for the control group. In addition, we analyse the percentage structure of the increase obtained (what % of the increase can be attributed to the support of the specific measure).

The efficiency of the support is calculated as the ratio between the achieved result indicator value and the corresponding amount of support paid. The support paid in this calculation is included until the end of 2020, because the assessment was made with 2022 data. It is done for assessing the impact of the support provided, although the time frame when it manifests itself may vary depending on the sector.

The second indicator used to assess the efficiency of

the support is the deadweight. This means what proportion of farms would have made similar investments if the support had not been granted. This indicator is also calculated by evaluating the matched groups of beneficiaries and non-beneficiaries and evaluating the amount of investment made in them before and after the support period.

Results and Discussion

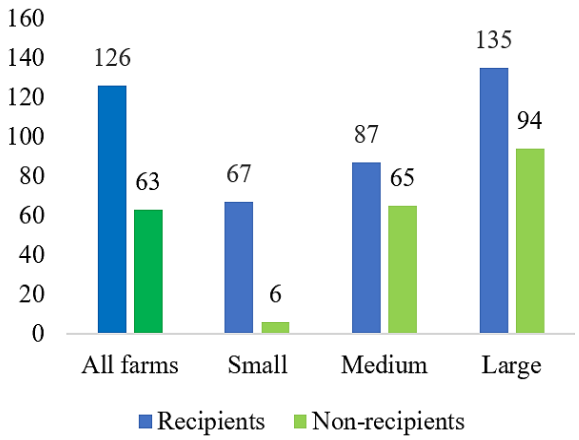
The percentage changes in labour productivity, comparing recipients and non-recipients of support, are summarized in Figure 1. Since the goal was to increase the competitiveness of especially small and medium-sized farms, the impact of support has also been assessed in farm groups.

Expressing the impact of support as a percentage of the results of farms that did not receive support, it can be concluded that the largest impact was in the small farm group, where the impact of support accounted for 91% of the total increase in labour productivity in the reporting period. In medium-sized farms, labour productivity has also increased significantly for those who did not receive support, therefore the importance of investment support in the medium-sized farm group is significantly lower – only 25%. In turn, large farms have the fastest growth in both groups, and it is precisely the growth in the large farm group that has contributed the most to the growth of the average indicators of all farms. It should be noted that the results in the farm groups can only be assessed indicatively, since there are few representatives in the small farm recipient group and the large farm non-recipient group, therefore their representativeness is limited.

The efficiency of the support at the farm level is calculated by applying the estimated increase in output for all beneficiaries (481 million EUR) to the total support paid out up to and including 2020 (354 million EUR). This means that 1 EUR of support has resulted in an increase in output of 1.36 EUR, while also slightly increasing employment. In turn, the increase in labour productivity per 1 EUR of support is 32 cents per FTE, i.e. the effectiveness is 32%.

Figure 1

Changes in agricultural output per work unit depending on the support of the M04 measure by farm size in Latvia (% increase in 2022 compared to 2014)



The relevant numerical indicators in farm size groups are summarized in Table 1. This table also shows the calculations for direct effect of support.

By size group, the efficiency of support in relation to the amount of support paid decreases as the size of farms increases: the highest impact is in the small farm group (1 EUR of support gives an increase of 41 cents), in the medium-sized farm group, it is 25 cents, but in the large group, it is only 15 cents per 1 EUR of support.

By applying the increase in labour productivity affected by the support to the agricultural sector of the entire country, we obtain that the total increase in labour productivity due to the support has increased by 8.3 thousand EUR per FTE, or 41% of the total increase.

Table 1

Increase in labour productivity due to investment support in Latvia on average FADN farm by size

Farm group	Output EUR/AWU			Average support, EUR
	2014	2022	Increase (2022-2014)	
	SO 4000 - 25 000 EUR			
Recipients	15114	25322	10208 (67%)	22326
Non-recipients	15410	16564	1155 (6%)	
Support effect %			**91%** (67-6)/67	**41%**
	SO 25 000 - 100 000 EUR			
Recipients	31212	58534	27322 (87%)	32241
Non-recipients	29115	48252	19137 (65%)	
Support effect %			**25%** (87-65)/87	**25%**
	SO over 100 000 EUR			
Recipients	55808	131586	75778 (135%)	158860
Non-recipients	46974	91581	44607 (94%)	
Support effect %			**30%** (135-94)/135	**15%**

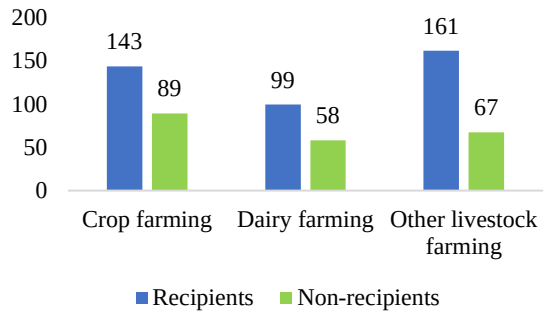
According to the calculation, on average, each 1 million EUR of support under this measure increases labour productivity in agriculture by 23.5 EUR per FTE. Since the indicator R2 (change in output per full-time employee) was introduced only in this programming period, there is a lack of correct comparisons, including with the RDPs of other countries. Indicatively, considering the contribution of this one measure to the total CAP support, the overall results of the measure in terms of the increase in the indicator R2 can be assessed positively.

Similarly, the relationship between the impact of support and farm specialization has been assessed, creating three main groups.

Calculations show that the impact of support, both in percentage and to compare with non-recipients, is higher in the livestock farming group, which includes grazing livestock, pig farming and poultry farming, as well as mixed farms. The impact of support assessed in this group is 58% of the total increase in labour productivity. In dairy farming it is 41%, while in the crop farming group it is 38%. This indicatively shows that it is economically efficient to set livestock farming as one of the investment support priorities. Farms in this group are on average smaller than in other groups. However, in general, the differences between the three analysed groups are not very significant. Due to the small number of representatives in the FADN sample, it is not possible to separate fruit and vegetable farms; therefore, in this classification, they are counted together with agricultural farms, Figure 2.

Figure 2

Changes in agricultural output per work unit depending on the support of the M04 measure by specialization in Latvia (% increase in 2022 compared to 2014)



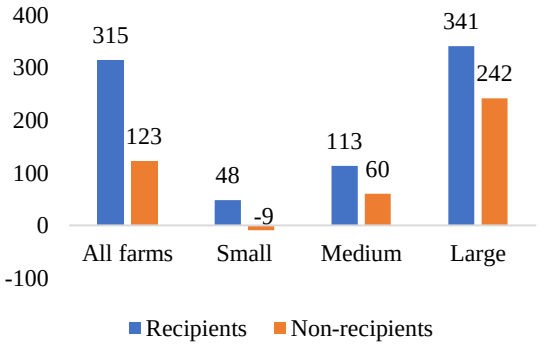
Since output alone does not provide a complete picture of the effectiveness of support, additional indicators have been selected. This assessment looks at changes in net income and the weight of long-term investments. Changes in net income of farms due to support are summarized in Figure 3. The calculation is for one average farm in the entire FADN sample total and within each group.

The results show that on average, the income of one support recipient has increased significantly faster than that of a non-recipient between 2014 and 2022.

It is estimated that 61% of the increase in income can be attributed to the impact of M04 support. When the results obtained are applied to all beneficiaries, we obtain that on average, income has increased by 78,7 thousand EUR in one farm due to support over the entire period, or by 9,834 EUR per year. When the achieved increase in income is attributed to public funding, we obtain that the effectiveness of the support is 78%, or 1 EUR of support has resulted in 0.78 EUR of increase in income in the net income of agricultural holdings. The results of the calculations, broken down by SO groups, show that the percentage of income increase attributable to support decreases rapidly as the size of the holdings increases. In the group of small farms, the impact of support is even more than 100% of the increase in income, because without support, income has decreased. In the group of large farms, however, only 29% of the increase in income can be explained by the impact of support. In contrast, total income growth becomes faster as farm size increases.

Figure 3

Changes in net income depending on the support of the M04 measure by farm size in Latvia (% increase in 2022 compared to 2014



This means that although investment support is a very important factor for income growth in small farms, the increase is still significantly smaller than in large farms even without support. The effectiveness of support in terms of income growth also increases with the size of the farms. According to the calculation, 1 EUR of support increased income by 21 cents in small farms, by 31 cents in medium farms, and by 56 cents in large farms. These results should be evaluated with caution due to the small sample, but they show that in terms of income growth, the return is greater with increasing farm size. Since the obtained trend is different from the increase in output, it is related to the ability of large farms to reduce costs more effectively, as well as to the distribution of subsidies. In turn, the results in the main specialization groups indicate that the percentage significance of support was greatest in other livestock farms, where support contributed to 87% of the total income increase. In turn, the fastest income growth is

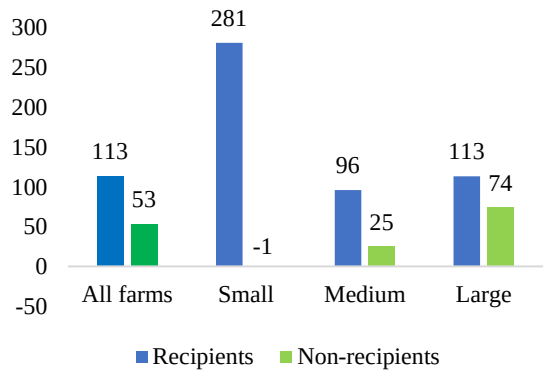
in crop farms, but this occurred for both recipients and non-recipients, so the support has contributed to only 34% of the total income growth. In dairy farms, this figure is 41%. Applying the obtained results to all recipients, we obtain that the impact of the M04 measure support can be assessed at 276 million EUR on farmers' income in 2022, which constitutes 29% of the total income value in this year and 57% of the income growth compared to 2014. It can be provisionally concluded that at the national level, M04 support has had a very significant positive impact on farmers' income, as it accounts for the majority of the entire increase in farm income.

An important indicator that shows the importance of support is the loss of deadweight. For this purpose, long-term changes in investments depending on the receipt of support are calculated. For the entire set of farms, the average deadweight (the proportion of investments that would have been made even without support) is calculated to be 47%. Such a loss of deadweight indicates that almost half of the investments would have been made even without support, or more than half of the investments would not have been made without support.

The division into three farm size groups in Figure 4 shows that the deadweight is significantly affected by the size of the farms.

Figure 4

Changes in long-term investments depending on the farm size and the M04 measure support in Latvia (% increase in 2022 compared to 2014)



The smaller the farms, the more important the role of support in promoting investments. The deadweight is calculated by dividing the indicators of farms operating without support in the relevant group by the indicators of supported farms.

In the group of small farms (size groups 1-2), the deadweight is 0, because the amount of capital investments has decreased for farms operating without support, so all additional investments were made with support. For medium-sized farms (size groups 3-4), the deadweight is estimated at 26%, which is also small, but in the group of large and very large farms – 65%. This means that in this group two-thirds of the investments would have been made even if the support had not been granted.

Thus, it is possible to conclude that agricultural output per FTE in supported farms has increased, and approximately half of this increase can be attributed to the support of the M04 measure. Although in absolute terms the output increase is faster in large farms, the importance of the possibility of receiving support for making investments for small farms is significantly higher. In the division by specialization, the specialization of grazing livestock can be distinguished as one in which support is required for investment. The presence of support for other specializations increases investment activity, however, they are partly carried out without investment support.

Compared to a similar study conducted in Latvia 10 years ago (Veveris, 2014), the economic return of large farms has improved; however, the context should be considered – differences in the changes in the general economic situation before and after receiving support, as well as differences in research methods. However, the trend that the return on support is higher in small and medium-sized farms persists.

In Slovakia, when assessing with the Conditional Difference in Differences (CDID) method, it was found that productivity of both beneficiaries and non-beneficiaries of the investment support slightly decreased over time. They found mixed evidence of investment support net effects on farm performance indicators. The authors suggest that investment support in Slovakia should be redesigned to target smaller farms with low capital endowment (Bartova & Hurnakova, 2016).

An example of the application of quasi-experimental methods for the assessment of Polish investment support is in the work of the Institute of Agricultural and Food Economics (Pawlowska et al., 2018). For matching, the different variables are used – economic size, type of farming, education and age of farmer, etc. The PSM method is used. The results show an increase in labour productivity under the support in terms of GVA per FTE by 44,000 PLN per FTE (about 10,000 EUR per FTE. Although no direct percentage effect has been calculated, this is still a significant effect.

A Czech study (Medonos et al., 2012) points out the importance of support in the economic development of farms, while noting possible significant deadweight. However, the situation in the Czech Republic is different from Latvia, as only a small part of the total investment volume is financed from European funds.

Since those studies were conducted for the previous period, the analysed indicators also differ. Previously, the main indicator was Gross Value Added (GVA), and productivity was measured as GVA per FTE. Since the indicators were changed in the currently evaluated program, the results are not directly comparable.

Conclusions

1. The effectiveness of the support on the competitiveness of the entire agricultural sector is significant. The support has contributed to approximately half of the total income and labour productivity growth in the RDP 2014-2020 (2022) period in Latvia.
2. The increase in labour productivity (R2) due to the support is estimated at 61% in medium-sized farms, 25% in medium-sized farms, and 41% in large farms. There is almost no growth for small farms operating without support, but there is an increase for medium-sized and especially large farms also among those not receiving support.
3. As a result of measure M04, the volume of long-term investments in agricultural farms has grown more than twice, compared to the hypothetical situation if this type of support had not been granted.
4. The efficiency of the support for investments in agricultural farms is assessed as high. 1 EUR of support has resulted in an average increase in production output of 1.36 EUR in supported farms in 2022, as well as an increase in net income of 0.78 EUR.
5. Labor productivity (output per full-time employee) in supported farms has increased by 0.32 EUR per 1 EUR of support. Of these, the highest increase is in small farms - 0.41 EUR.
6. The average loss of self-weight (% of investments that would have been made even without support) is 47%. Including in farms with SI up to 100 thousand EUR it is 21%, which means that 4/5 of investments would not have been made without support.
7. Support for investments is particularly important in the specialization of grazing livestock, both in attracting investments and in promoting income. However, it also plays an important role in other specializations.
8. Studies conducted in other countries generally confirm the positive impact of investment support on the economic performance of farms, however, due to different indicators, the results of different programs are difficult to compare. There is a lack of results on the impact of support on different farm groups.

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TRENDS IN PPP IMPLEMENTATION IN THE EUROPEAN REGION FROM 2007 TO 2022

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Abstract
The study analyses the development and implementation trends of public-private partnerships (PPP) projects in the European region between 2007 and 2022. The study aims to assess the dynamics of PPP projects in the European region over the period 2007 – 2022, looking at the implementation pathways, investment attraction and the most active implementers in the process. Using a quantitative research approach, secondary data analysis, time series analysis and comparative statistical analysis, data on the number of PPP projects, investment volumes and sectoral distribution in the Member States are collected. The main results show significant differences in PPP activity between countries, with France, Italy and Greece leading the way. Between 2007 and 2016, the number of infrastructure PPP projects varied between 50 and 125 per year, while the average investment per project increased from 150 to 300 million of euros. In 2016, France led the way with a total investment volume of 2.3 billion of euros, and in 2022, France retains the lead with 21 contracts worth more than 4.2 billions of euros. Institutional investors, in particular pension funds and insurance companies, are playing an increasingly important role in financing, mainly in Western Europe. The 2022 sector analysis points to a focus on energy efficiency, transport, water and social infrastructure. The study examines the take-up of PPP projects in the European region and their distribution by sector and investment size. The results of study can serve as a basis for decision – making and further research by policy makers.
Keywords: public-private partnership, Europe, region, projects.

Introduction

As societies in different regions of the world create demand for quality and modern public services, there is a need for the public sector to invest in modernising service delivery and infrastructure. The introduction of modern standards and the modernisation of existing processes, in a context of limited public sector budgetary capacity, requires the leveraging of private sector financial investment in various forms of project implementation. One of the most popular is the Public Private Partnership (PPP), which provides an opportunity to combine the experience, expertise and technical and financial capacity of several sectors to implement solutions that meet public demand. Akintoye (2016) in his publication describes Public Private Partnership as a contractual arrangement between the private sector and a public agency for joint ownership in which benefits, risks and resources are shared and pooled to achieve efficiency in the production of private and public services or goods. With reference to the definition in the United Nations Secretary-General's report, Clark L., in his 2014 study, describes public-private partnerships as a joint and voluntary relationship in which a non-state actor and the state agree to work together to perform a specific task, achieve a common goal and share responsibilities, risks and rewards. Publications available in scientific databases include Wang & Ma (2020), Wang et al. (2017), Osei-Kyei & Chan (2015), Zou et al. (2016), there is no single definition of PPP, but it is possible to find common characteristics of this legal form: 1. PPP projects are often infrastructure; 2. The private sector participates in the project design, implementation and subsequent maintenance; 3. It is a long-term partnership of up to 30 years; 4. Up to several hundreds of millions of euros or dollars are invested in project implementation; 5. The parties involved share costs, resources, risks as well as profits; 6. The private partner provides financial and knowledge support to the public sector; 7. The private partner's investment yields a long-term return. The public- private partnership model has been increasingly used in recent decades as a strategic solution for the development of public infrastructure, especially in context where the public sector lacks sufficient resources for long-term investment. Despite the European Union's efforts to promote PPP projects, this approach has developed at different speeds in different European countries. The urgency of the problem lies in the need to assess the extent to which the PPP mechanism can effectively deliver infrastructure development, identify regional differences, and determine key success factors in the delivery of PPP projects at the European level. In Latvia, Public Private Partnerships have been described and defined by the Ministry of Finance of the Republic of Latvia, which oversees the implementation of these projects, and the Public Private Partnership Law of 2009 - PPP is a long-term cooperation between the two sectors with the aim of providing public works or a service for the public needs. The study involves quantitative data analysis using secondary statistics to look at the PPP projects in the field of infrastructure development. Particular attention is paid to the geographical concentration of PPP projects, the structure of investments and the cooperation between public and private parties. **Hypothesis**: PPP projects have become an important instrument for infrastructure development in the European region between 2007 and 2022, but their implementation and the level of investment vary considerably from region to region, depending on national institutional capacity, EU support and the level of private sector involvement. **The aim of the**

study is to assess the dynamics of PPP projects in the European region over the period 2007 – 2022, looking at the implementation pathways, investment attraction and the most active implementers in the process. To achieve this objective, the study sets out to: 1) analyse the number of PPP projects, investment volumes and priority sectors in different European countries based on statistical data collected between 2007 and 2022; 2) identify the leading European region countries in terms of the intensity of PPP projects.

Materials and Methods

The study is based on a compilation of publications available in scientific databases and analysis of industry statistics. Monographic and descriptive methods, as well as analysis, synthesis and graphical methods were applied to present and interpret the data in structured way. The information considered was based on scientific publications supplemented by data from publicly available documents, databases, articles by private investment firms, the European Investment Bank annual market reports as well as data provided by the Central Financial and Contract Agency. All data in the study are presented as actual year-end data. The data analysis covers the period from 2007 to 2022. The paper will gather information on a group of economic indicators that measure the impact of infrastructure investment and will compare the European region without distinguishing between EU Member States.

Results and Discussion

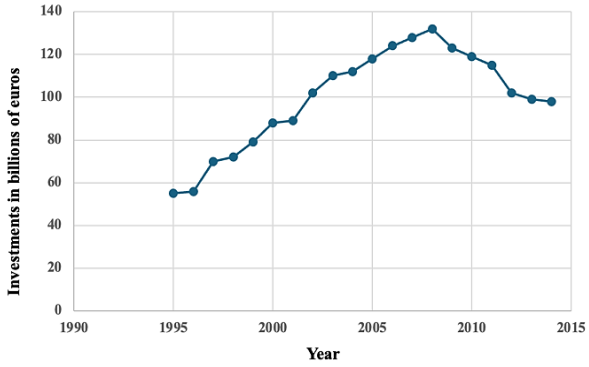
The public sector is under pressure to find sustainable solutions to meet society's growing demand for quality infrastructure. PPPs have the potential to deliver the highest public benefits, but there is a need to gather indicators of the impact of PPP projects. These include economic indicators (EIB, 2024) – investment volume, cost effectiveness, budget savings; social indicators (OECD, 2023) – infrastructure governance to ensure public satisfaction, access to infrastructure; institutional indicators (EPEC, 2021) – to project governance, transparency, partnership sustainability; environmental indicators (WB, 2024) – climate change aspects, CO2 emission reductions, energy efficiency improvements in projects. While these indicators provide important insights, it would be useful for future studies to include structural and institution indicators that were not analysed in depth in this study. For example, the quality of public governance, based on sources such as the World Bank's Governance Indicators (WB, 2022), can help to understand how the effectiveness and transparency of governance affects the delivery of PPP projects. It is also important to assess the role of EU financial instruments (EC, 2014), including European Investment Bank loans and EU founds, on the financing models of PPP projects. It is also worth paying additional attention to the investment climate's reliability ratings which influence private investors decisions in the context of long-term commitments. Taken together, these economic and institutional indicators could provide not only a quantitative and dynamic assessment of evolution of PPP projects but also a deeper understanding of conditions that determine the effectiveness and spread of PPP projects in different European regions (ECA, 2018a).

Public-private partnerships in the European region

Stephane Saussier and Elisabetta Iossa 2018 publication on PPPs in Europe *(Public private partnerships in Europe for building and managing public infrastructures: an economic perspective (2018))* analyses the provision of construction and public services with private sector support in a period of severe budget constraints. The authors analyse OECD data and conclude that emerging and developing economies need to increase the level of investment in infrastructure modernisation to ensure economic growth and meet environmental targets. OECD data show that to meet the 3.5% of GDP required for total infrastructure investment between 2007 and 2030, at least USD 71 trillion need to be invested in transport logistics, electricity generation and transmission, water supply modernisation and telecommunications by 2030. And in a paper published in 2015 Perqin (Perqin, 2015) a private investment data company based in London, points out that alongside infrastructure modernisation, additional investment is need in social services – hospitals, schools, prisons and community housing, which in Europe generates between 10 billion and 18 billion euros of investment each year. Public funding is commonly used to secure such investments, but PPPs with private sectors input are an option in a context of constrained public sector budgets. OECD data from 2013 shows that 15% of annual government capital investment in Europe is delivered through the PPP project management model.

Figure 1

Infrastructure investment in Europe 1995-2014, million euros



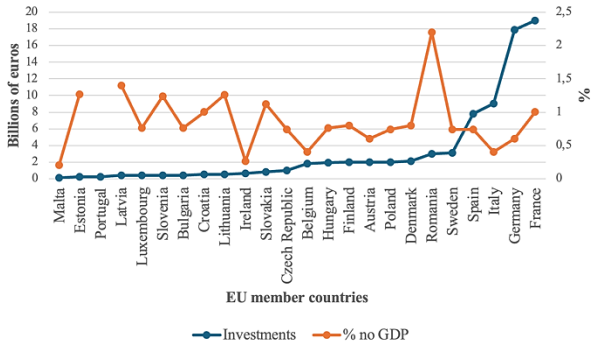
Source: made by the author from (*Public Private Partnerships in the EU*, 2018).

Figure 1 shows how investment in infrastructure modernisation in Europe, has exceeded 100 million euros annually since 2003, reaching a peak in 2007,

followed by a 25% drop until 2014 due to the economic crisis and other circumstances.

Figure 2

Infrastructure investment by countries in the European region (billions of euros) and share of GDP (%) in 2014

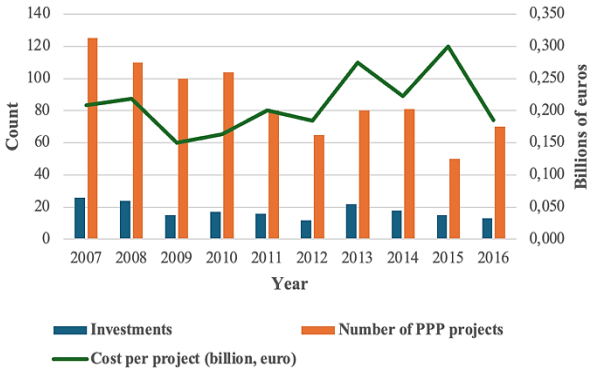


Source: made by the author from (*Public Private Partnerships in the EU*, 2018).

From the data in 'Figure 2', it is possible to conclude that there is some variation in the level of investment in each European region country, with Romania investing 2% of its GDP and Ireland investing only 0.2%. In 2014, Latvia contributed 1.4% of its annual GDP, or 400 millions of euros, more than average of 0.86% of GDP for the countries listed, in infrastructure modernisation. The OECD calls for more efficient use of public funding, with more private partner financing for infrastructure development through concessions or accessibility agreements. This type of contractual arrangement was first used in the UK in the 1990s for urban and social infrastructure modernisation projects.

Figure 3

Investment volumes and timetable of infrastructure PPP projects in European region 2007 - 2016

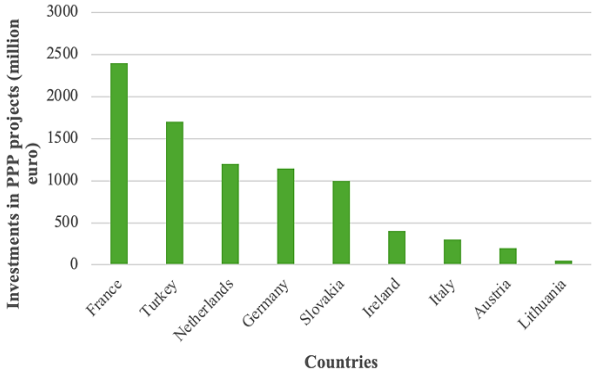


Source: made by the author from (*Public Private Partnerships in the EU*, 2018).

From the data in 'Figure 3', it is possible to conclude that the number of PPP projects implemented between 2007 and 2015 ranges from 125 to a low point 2015, with only 50 projects completed. The amount of investment has varied from € 150 million per PPP project in 2009 to € 300 million per project in 2015. This demonstrates a trend of increasing average project costs alongside a reduction in the number of projects. This could indicate the influence of external factors such as economic development and stakeholder assests on the dynamics of PPP implementation.

Figure 4

Top 10 most financially intensive infrastructure PPP countries in the European region in 2016, millions of euros



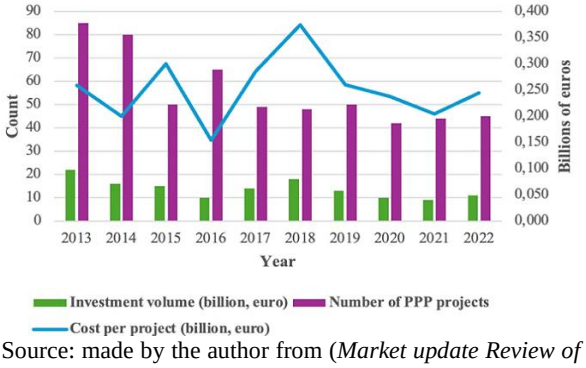
Source: made by the author from (*Public Private Partnerships in the EU*, 2018).

From the data in 'Figure 4', it is possible to conclude that France leads the way with € 2.3 billion invested in PPPs in 2016, the Netherlands, Germany and Slovakia invest over one billion, while Austria and Lithuania show much lower investment figures. The analysis points to significant differences in the financing of PPP projects, leading to different regional experience of project implementation.

Already in March 2023, the European Investment Bank's Market Update Review (EPEC, 2023) of the European public-private partnership market in 2022 shows that 45 PPP deals worth € 9.8 billion have been signed in Europe in 2022, representing a 17% increase compared to 2021 (€ 8.4 billion). 15 countries have signed at least one PPP contract, with France being the most active implementing country. Transport logistics is seen as the most numerically popular and financially intensive sector, accounting for 70% of total deals.

Figure 5

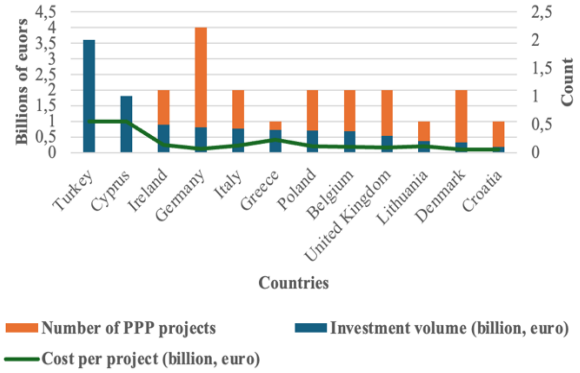
PPP project investments and number of investments in the European region 2013 - 2022



Source: made by the author from (*Market update Review of the public-private partnership market in 2022*, 2022).

From the data in 'Figure 5', it is possible to conclude that the number of PPP projects has remained relatively constant over the last three years since 2022, while the average transaction volume per PPP project has increased by around 14.2% from € 190 million in 2021 to € 217 million in 2022. The recovery of PPP market after the turmoil caused by the COVID-19 pandemic has not been significantly affected by the rise in inflation or the increase in construction costs. The three largest deals – the redevelopment of the port of Larnaca in Cyprus (1 billion of euros), the construction of the French military accommodation point CEGELOG (€ 1.4 billion) and the Turkish Antalya airport concession (€ 1.8 billion) – account for 44% of the total PPP market in 2022, with Turkey raising € 2 billion in PPPs overall.

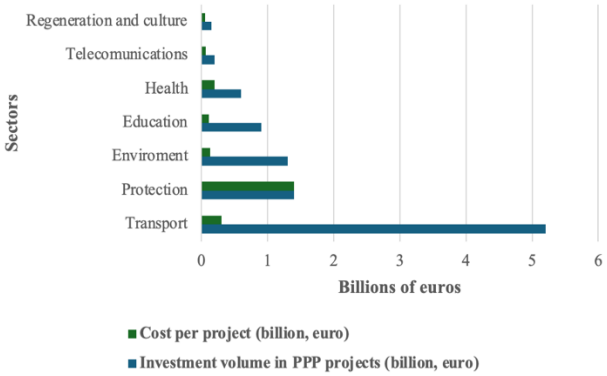
Figure 6
Countries in the European region value of number of PPPs in 2022



Source: made by the author from (*Market update Review of the public-private partnership market in 2022*, 2022).

From the data in 'Figure 6', it is possible to conclude that in 2022, nine countries, including Cyprus and Turkey, have at least two PPP deals and fifteen countries in the European region have at least one deal. Turkey stands out as the country with the highest investment in PPP projects, with a total investment of more that € 3.5 billion in infrastructure modernisation. France signed 21 deals worth more than € 4.2 billion in 2022, a significant increase on the 18 PPP deals worth € 1.6 billion signed in 2021. These figures show the interest of investors in the implementation and development of the PPP model of financing infrastructure projects.
From the data in 'Figure 7' it is possible to conclude that transport reached € 5.2 billion in 2022, down 14% on the previous year, with 17 PPP projects, four of which modernised ports and four build roads. The € 1.3 billion has enabled ten environmental PPP projects to be implemented, five of which are French district heating solution.
In the UK, Germany and Belgium, eight schools and their infrastructure have been modernised, and half a billion euros worth of Danish and Turkish healthcare projects have enabled the construction of hospitals. In the Europe region, PPP projects are not only financed by the financial capacity of private investors (ECA, 2018b).

Figure 7
Breakdown of PPP projects by sector and investment volume in the European region in 2022



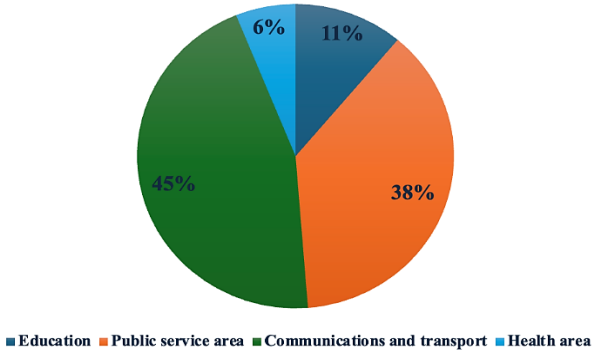
Source: made by the author from (*Market update Review of the public-private partnership market in 2022*, 2022).

In 2022, 17 out of 45 deals involved insurance companies or pension funds, which have become very popular in Western Europe. While local authorities, national governments and the European Union play a relatively small role in financing PPP projects, the European Investment Bank supported four PPP projects with a total value of one billion of euros. In addition, a new PPP structure, the NeuConnect Interconnector (EUAC, 2023), was launched in 2022, financing projects worth more than 3.3. billions of euros. The data shows that France with fifty projects, Italy with thirty projects and Greece with twenty-eight projects are the leading countries in the implementation of PPP projects. Greece has been particularly active in PPP projects over the last three years, ensuring a transparent procurement process and efficient mobilisation of EU funding. Around half of its PPP projects focus on upgrading pipelines and water infrastructure, as well as building student hostels and schools. Lithuania has also seen its position in the European PPP market strengthened. According to the Lithuanian PPP Competence Centre, by December 2022, 68 PPP contracts had been signed in the country, attracting private partner investment of € 213 million for the development of recreational, cultural and sports projects. Lithuanian regional authorities are focusing on improving energy efficiency in public infrastructure, street lighting and parking, as well as improving safety, including seven sports infrastructure projects.
The Law on Public-Private Partnership in Latvia entered into force on 1 October 2009, but the first references to PPPs in the Latvian economy appeared as early as 1999, when the importance of PPPs for the development of the innovation economy was analysed in the bulletins published by the Latvian Academy of Sciences. In 2010, the Baltic Institute of Social Sciences (BISS, 2010) published a study analysing the development of PPP policy in Latvia. The study t noted

that while PPP was one of the components of the National Development Plan (2007-2013), its implementation was slow until 2009. Furthermore, the global financial crisis (2007-2010) led to the suspension of project implementation in accordance with an agreement between the Latvian government and the International Monetary Fund.

Figure 8

Structure of PPP projects implemented in Latvia in 2011, % by sector



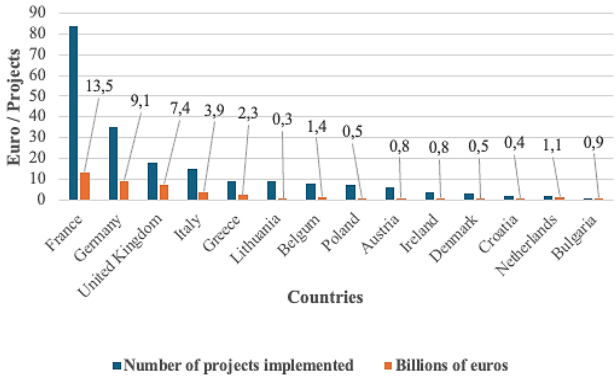
Source: made by the author from (*Impact of the 'Promoting PPP in Latvia' programme on the quality and availability of public services at national and regional level, 2022*).

A 2011 Ernst & Young Baltic study, see 'Figure 8', concluded that until 2009, PPP development in Latvia was coordinated by the Latvian Investment and Development Agency (EPPA, 2011). While the agency had launched five project initiatives, only one the modernisation of the Ogre Art School, was ultimately implemented. Overall, by March 2011, in Latvia, 70 PPP contracts worth € 56.9 million were signed, most of them for long-term service provision and construction. In the end, ten public service projects were implemented – waste management in Sigulda, heating in Incukalns and Ventspils – which were later suspended due to lack of private funding. Construction of pre-school educational institution in Kekava, Marupe, Tukums and Ogre, forty-eight transport and communications projects, and a development project for the Jelgava District Hospital. These contracts were often concluded for a 20-year term, with the private partner's profit margin ranging from 4% to 12%m depending on the size of the company. In 2021, The Ministry of Transport of the Republic of Latvia and State Enterprise 'Latvian State Roads' launched a new 'Kekava bypass' PPP project to modernise the public service. This project is the first in the Baltics in which a private partner takes part and is responsible for design, construction, financing and maintenance for 23 years, ensuring the initial quality of the project until 2048. The 'Kekava bypass' project provides an alternative to the Bauska highway from Kekava to Riga, where traffic volumes can reach up to 25 000 cars per day. At the end of the construction phase of the project and upon its commissioning in 2022, the Cabinet Order No 951 of 2022 clarified the reverse value added tax for the private partner of the project, adjusting it to the construction volumes and setting the Gross Availability Payment for design, civil works and royalties, and the remainder for maintenance, fundraising fees and replacement of the asphalt pavement.

The August 2024 publication of the Bank of Latvia states that since the Covid-19 pandemic, PPP implementation has focused on health projects, while the geopolitical situation in 2023 led to more active PPP development in South America and Asia, with an emphasis on the transport sector, where 73 % of new projects have been implemented.

Figure 9

Number of PPP projects implemented in the European region 2019 -2023, number of list / billions of euro



Source: made by the author from (*PPPs - global experience and Latvian practice*, 2024).

From the data in Figure 9, it is possible to conclude that Germany and France are currently the leading PPP countries in the European region, whereas in the past this title was held by the UK, where projects in health and education sectors were often implemented, as well as local projects coordinated by a municipality to manage waste or develop a lighting system. The European region is planning to increase the intensity of PPPs in the coming years, with almost 200 new projects aimed at meeting the climate targets. In France, almost 50% of the new projects focus on the modernisation of waste management and heating as well as the development of transport logistics, thus contributing to climate neutrality (FM, 2020). Other countries in the European region can follow suit, and Latvia has the potential to implement emission-reducing projects in the coming years, such as –the development of transport and logistics solutions and public service provision in energy-efficient facilities. The Bank of Latvia's experts see low-cost rental housing management and a construction programme for which the State Joint Stock Company 'State Real Estate' plans to invest between 100 and 125 millions of euros in 17 regional municipalities as a potentional PPP breakthrough. This form of the project management would help to promote the quality of the public service and ensure its sustainable development.

Conclusions

1. The dynamics of Public-Private partnership infrastructure project development in Europe between 2007 and 2022 show a structural shift from quantity to quality. Data analysis shows that while the total number of projects has remained relatively stable between 2021 and 2022, the average investment per project has increased from € 190 million in 2021 to € 217 million in 2022, an increase of around 14.2%, in 2015 the average investment reached more than € 300 million. This indicates an increasing trend for countries to focus on larger, strategically important infrastructure projects. This finding confirms the growing importance of PPPs as a tool for diversifying public funding and delivering large capital projects of public interest.

2. France, Italy, Germany and Greece have consolidated their position as the main PPP leaders in the European region, regularly implementing a large number of projects with a significant total investment volume. For example, France alone signed 21 contracts worth more than € 4.2 billion in 2022. These results clearly demonstrate the strong link between institutional frameworks, political support and long-term strategic vision. This concentration in Western Europe reveals territorial asymmetries and opens the way for more detailed policy analysis aimed at activating the potential of PPPs in other EU regions.

3. PPP projects in Europe are mainly concentrated in areas of public interest – transport, health, education and the environment account for the bulk of all investment in this area. This sectoral structure has remained stable over the period analysed and reflects the essence of PPPs: providing critically needed services with private sectors participation, while keeping the public interest at the forefront. This suggests that PPPs are not only an investment instrument, but also function as a component of public development policy, especially in constrained public budget contexts.

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FISH FEED AS A FACTOR AFFECTING AQUACULTURE IN LATVIA

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Abstract
Aquaculture in Latvia represents a minor economic sector, characterised by a limited number of enterprises, employees and overall turnover. However, recent years have seen growth in both production areas and output levels, indicating a promising potential for development in this field. Fish feed constitutes a significant portion of aquaculture expenses, accounting for 60-80% of total costs, making it a crucial factor influencing the industry. The purpose of the study is to determine the impact of fish feed in fish farms in Latvia. The study was carried out in different regions of Latvia, depending on the location of the aquaculture establishment. The data was collected through a partially structured interview using a questionnaire. The log-linear regression model was used to determine the relationship between all independent variables. The results showed that more than 90% of aquaculture farms were small farms and only 30% of the surveyed fish farmers use fish feed produced in Latvia on their farms. The study concluded that fish growers in Latvia face problems from the aspect of fish feed, which is influenced by the high feed price, co-operation opportunities among growers, feed logistics, as well as awareness of local fish feed from their producers. Alternative feed could become a possible solution to reduce the price of feed and buy it from local feed producers. Exploring alternative feed options may provide a feasible solution to lower feed prices while supporting local producers. Identifying issues related to aquaculture feed is essential for achieving efficient production and economic viability.
Keywords: aquaculture, fish feed, Latvia.

Introduction

Aquaculture in Latvia represents a minor economic sector, characterised by a limited number of enterprises, employees and overall turnover. However, recent years have seen growth in both production areas and output levels, indicating a promising potential for development in this field.

The impact of fish feed on aquaculture is a critical area of concern, largely due to the economic, environmental, and nutritional implications associated with various feed components. The overarching challenge is to develop sustainable feed alternatives that maintain or improve fish health and growth performance while minimising ecological footprints.

The dependency of aquaculture on traditional fishmeal and fish oil has become increasingly unsustainable. Aquaculture is recognised as the largest global consumer of these marine resources, accounting for approximately 70% of fishmeal and 73% of fish oil utilised (Lozano-Muñoz et al., 2022). This heavy reliance on wild-caught fish threatens both marine ecosystems and the future viability of aquaculture as a food source.

The increasing demand for fish is projected to rise from 50% currently to 62% by 2030, thus exacerbating this issue (Han et al., 2016). Sustainable solutions must therefore address these economic pressures and ecological concerns.

Various alternatives to conventional fish feed have emerged, including the use of plant proteins and insect meals. Studies show that diets incorporating alternative plant proteins, such as bioconverted vegetable waste, have resulted in improved growth rates and feed utilisation efficiency in aquaculture species (Azad & Lal, 2018; Arru et al., 2019). This shift towards plant-based feeds is viewed as a viable solution to meet the nutritional requirements of fish while alleviating pressure on fishmeal and fish oil markets.

Furthermore, the inclusion of insect meal has shown promise in improving economic sustainability within aquaculture, providing a low-cost, high-protein alternative (Arru et al., 2019). The introduction of these alternatives could help reduce feeding costs (Garg & Meena, 2023).

The nutritional quality of fish feed also plays a vital role in mitigating health issues and enhancing growth efficiency. The incorporation of biologically active substances and additives has been demonstrated to improve feed digestibility and fish immunity, potentially correcting nutritional deficiencies that can compromise fish health (Ponomarev et al., 2022; Syanya et al., 2023).

Moreover, understanding the impact of feeds on fish metabolism, particularly concerning the balance of essential amino acids, emphasises the need for tailored feeding strategies that align with the specific nutritional profiles of different fish species for optimal growth and health (Snellgrove & Alexander, 2011; Pratiwi & Zidni, 2023).

Additionally, recent studies suggest that utilising ingredients such as microalgae and fermented plant materials can yield highly nutritious feed options that support rapid fish growth while addressing sustainability concerns (MacLeod et al., 2020; Sarker et al., 2020). For instance, the application of microalgae-blend feeds has been noted to eliminate the need for fishmeal while improving growth outcomes in tilapia, showcasing both ecological and economic benefits (Sarker et al., 2020). In light of these findings, it is pivotal for the aquaculture sector to innovate and adopt sustainable feeding practices that support fish health and productivity while mitigating environmental impacts. Addressing the prevalent reliance on wild-caught marine resources through the integration of alternative protein sources and the optimisation of feed formulations can drive the aquaculture industry towards a more sustainable future.

Aquaculture is constrained by a number of challenges, including high feed costs, which account for 60–80%

of fish farming costs (Ragasa et al., 2018). In addition to high feed costs, other challenges include limited feed availability and poor feed and management practices, especially among smallholder farmers (Ragasa, 2018; Obwanga et al., 2018).

Fish require a high quality and balanced diet to grow as quickly as possible. Although imported feed is becoming more accessible, some countries are boosting investment in local feed production to capitalise on more affordable, locally sourced raw materials and improved access for fish farmers.

Research in aquaculture is essential for evaluating locally available feed ingredients, and expanding cost-effective local fish feed production is vital for the growth and sustainability of the industry. Quality feed at an affordable price will make fish farming more profitable for small entrepreneurs. Producing high quality and cost effective feed is a complex process that requires an understanding of the nutrient levels that optimise fish growth, survival and profitability.

Materials and Methods

The study was conducted from January to March 2025, with 40 fish farmers selected from various regions of Latvia. The regions represented included Kurzeme (15 farms), Zemgale (ten farms), Latgale (eight farms), Vidzeme (five farms), and Riga (two farms).

A semi-structured interview format with a questionnaire was used to collect data from Latvian fish farmers. The questionnaire includes some questions about fish culture, farm size, activity type, culture type, culture system, feed costs, used feed type, availability of feed, alternative feed types, place of origin of the feed, membership in a co-operative group, market information, the marketing channels and some economical parameters.

Data were analysed using SAS statistical software. The log-linear regression model was used to determine and quantify the relations between all the independent variables (fish growing experience years, the marketing channels, market information, membership in a co-operative group, fish farm size, culture type, activity type, culture system, labour cost, used feed type, availability of feed, alternative feed types, place of origin of the feed, transportation cost, total cost and feed cost (the dependent variable).

The log-linear regression model was formulated to assume a linear relationship between the log-dependent variable and log-explanatory variables, allowing for traditional estimation procedures (Gujarati, 2003).

The regression model in Equation 1 takes the following form:

$$InYi=\alpha+\beta 1InX1+\beta 2InX2+\beta 3InX3+\beta 4InX4+\beta 5InX5+\beta 6InX6+\beta 7InX7+\beta 8InX8+\beta 9InX9+\beta 10InX10+\beta 11InX11+\beta 12InX12+\beta 13InX13+\beta 14InX14+\beta 15InX15+\varepsilon \quad (1)$$

where:

α= intercept term, Y= value of feed cost, X1= experience (years), X2= marketing channels, X3= market information, X4= membership in a co-operative group, X5= farm size, X6= culture type, X7= activity type, X8= culture system, X9= labour cost, X10= fry price, X11= used feed type, X12= availability of feed, X13= alternative feed types, X14= place of origin of the feed, X15= transportation cost, βi= the explanatory variables coefficients, In= the natural logarithm and ε= error term (normally distributed with a mean of zero and constant variance).

Results and Discussion

Table 1 illustrates that over 75% of fish farmers have 21 years or more of experience in fish breeding, with 90% of fish farms categorised as small. Most popular fish farm growing method is freshwater ponds (80%). However, only 12% of the respondents produced fish in recirculation systems. The development of recirculation systems is important for the Latvian aquaculture industry, as recirculation systems cause less pollution to the environment and water.

Table 1

Distribution of the respondents based on socio-economic characteristics

Variable	***Category***	***N***	***%***
Experience (years)	Low (≤5)	3	7.50
	Medium (6-20)	6	15.0
	High (≥21)	31	77.5
Farm ownership	Owned	31	77.50
	Owned, rented	5	12.50
	Rented	4	10.00
Membership in co-operative group	Yes	20	50.00
	No	20	50.00
Access to market information	Yes	7	17.50
	No	33	82.50
Origin of fish feed	Latvia	12	30.00
	Other country	28	70.00
Co-operation in the procurement of feed	Yes	12	30.00
	No	28	70.00

Variable	*Category*	*N*	*%*
Farm size	Small	37	92.50
	Medium	2	5.00
	Large	1	2.50
Farm type	Freshwater ponds	32	80.00
	Recirculation system	5	12.50
	Basins	3	7.50
Feed type	Grains	25	62.50
	Extruded	4	10.00
	Combined	11	27.50
Business activity type	Aquaculture only	4	10.00
	Aquaculture, agriculture	31	77.50
	Other	5	12.50
Alternative protein source	Yes	20	50.00
	No	20	50.00
Culture system	Extensive	24	60.00
	Semi-intensive	6	15.00
	Intensive	10	25.00

About 77% of the respondents own their fish farm. About 91% of the respondents reported employing 10-15 workers on their farms. While 17% of the respondents lacked access to training and credit, only 83% reported limited access to market information. Half of the fish farmers were members of a cooperative group, and 74% sold their fish production directly from the farm. The predominant culture type among respondents was polyculture (76%), while 24% engaged solely in aquaculture activities. The extensive culture system was the most common production method, utilised by 60% of respondents. More than 60% of the fish farmers fed their fish with grains, while only 10% of the fish farmers used extruded feed. This also reflects the small number of recirculating farms using only this type of fish feed. Aquaculture is the only source of income for only 10% of the respondents, while 77% of the respondents engage in additional agricultural activities on their farms – cereal farming, beekeeping, forestry, etc. When asked whether fish farmers would be willing to use fish feed that has been produced in Latvia and offers higher protein content and lower price on their farms, only 50% said yes. This implies that fish farmers either rely on trusted feed producers or lack confidence in the quality and effectiveness of locally produced feed. 70% of the respondents would not be willing to participate in the purchase of fish feed in cooperation with other fish farmers, which shows that there are problems of cooperation in the aquaculture sector in Latvia. Half of the respondents were members of a Latvian aquaculture NGO, which shows that fish farmers are involved in policy making in the aquaculture sector.

Table 2

Fish feed related problems facing the fish culture farmers in Latvia

Problem	*Problem Severity**				*PFI***	*Score*
	FS	*FM*	*FL*	*FN*		
High feed price	105	5	0	0	325	1
Low protein content	99	7	4	0	315	2
High feed impact on environment	99	5	6	0	313	3
Lack of feed quality	45	15	21	29	186	4
High feed transportation cost	33	27	17	33	170	5
Lack of feed storage knowledge	25	20	28	37	143	6
Long feed delivery	26	7	7	70	99	7
Lack of Latvian feed marketing information	15	6	10	79	67	8
Incomplete Latvian fish feed	15	6	10	79	67	9
Underdeveloped cooperation in feed procurement	15	6	10	79	67	10

Note:* FS: numbers of fish farmers facing a severe problem, FM: numbers of fish farmers facing a moderate problem, FL: numbers of fish farmers facing a little problem, and FN: numbers of fish farmers facing no problem.

** PFI (Problem Facing Index) = 3 × FS + 2 × FM + 1 × FL + 0 × FN.

According to Table 2, the fish culture farmers identified 20 significant challenges. A total of 105 out of 110 farmers regarded high feed prices as a critical issue. The rise in feed costs is attributed to ingredient imports and fluctuations in foreign currency exchange rates. Problems faced by the fish culture farmers were categorised based on severity: severe, moderate, little, and none, assigned scores of 3, 2, 1, and 0, respectively. The Problem Facing Index (PFI) was calculated using the formula:

$$\text{Problem Facing Index (PFI)} = 3 \times FS + 2 \times FM + 1 \times FL + 0 \times FN \quad (2)$$

where:
FS = quantity of fish farmers facing a severe problem,
FM = quantity of fish farmers facing a moderate problem,
FL = quantity of fish farmers facing a little problem,
FN = quantity of fish farmers facing no problem.
As shown in Table 2, the most important problems in the Latvian aquaculture sector are the high price of fish feed, the low protein content of fish feed, and the environmental impact of the feed. The opportunities for cooperation in fish feed procurement and the insufficiency of locally produced fish feed in Latvia for meeting consumption needs were identified as less significant issues. Since only 30% of the respondents purchase fish feed in Latvia, this suggests that the quality of the feed is insufficient to attract the interest of other fish farmers.

Conclusions

1. Aquaculture serves as a vital source of fish, providing an alternative to the diminishing natural ecosystems. It also plays a crucial role in enhancing the social and economic status of fish farmers, thereby alleviating poverty and improving their living conditions. It is therefore necessary to promote the development of aquaculture.
2. The cost of fish feed in Latvian fish farms accounts for 60–80% of the total expenses of the enterprise. This indicates the need to explore economically viable alternatives that utilise food industry by-products to reduce fish feed costs, replace protein in fish feed, and support the circular economy.
3. Only 30% of fish farmers surveyed use fish feed produced in Latvia on their farms. Latvian fish feed producers need to stimulate the interest of local fish farmers in Latvian production and identify the needs of potential customers.
4. The study concludes that fish farmers in Latvia encounter challenges related to fish feed, driven by high feed prices, low protein content, opportunities for farmer cooperation, feed logistics, and awareness of locally produced fish feed.
5. Identifying feed problems in aquaculture is necessary for efficient production and economic returns, and is essential for the development of sustainable aquaculture.

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BIOREGION DEVELOPMENT AND STRATEGIC SPECIALIZATION: INSIGHTS FOR LATVIAN REGIONAL PLANNING

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Abstract
Bioregions offer a means of reconciling ecological conservation with economic growth by emphasising the unique natural and cultural values of each territory. Latvia, with its diverse ecosystems and distinct cultural heritage, is well positioned to adopt bioregional strategies to enhance resilience, foster sustainable development, and increase regional competitiveness. This study examines the theoretical foundations of bioregionalism, tracing its origins and evolution as a planning tool within both European and global contexts. It highlights how bioregional structures have facilitated sustainable economic specialisation in other regions by attracting localised resources, fostering innovation in green technologies, and promoting cultural tourism. The study focuses on the Latvian context, analysing the challenges and opportunities associated with adopting bioregionalism as a complement to the country's existing administrative framework. Particular attention is given to the potential influence of bioregions on Latvia's Smart Specialisation Strategy and their role in supporting sustainable economic growth within knowledge-intensive bioeconomy sectors. A review of the existing literature identifies the key factors influencing the specialisation of rural areas, including the availability of natural resources, demographic dynamics, infrastructure development, and institutional support. The literature underscores the importance of aligning local resources with innovation-driven strategies to enhance rural competitiveness while ensuring sustainability. This alignment is particularly pertinent to bioregional planning, which integrates ecological and socio-economic dimensions to support context-specific development strategies.
Keywords: bioregion, smart specialization, rural development, regional planning.

Introduction

The concept of bioregions has emerged as a transformative approach to regional planning, integrating the ecological, cultural, and economic dimensions of development (Stefanovic et al., 2023). At its core, bioregionalism promotes the idea that human activity should be harmonised with the natural environment, utilising the unique characteristics of a region's landscape, ecosystems, and cultural heritage as guiding principles for sustainable development (Dias et al., 2021). This approach not only emphasises ecological conservation (Di Veroli et al., 2024) but also seeks to foster local economic resilience, innovation, and specialisation (Bravaglieri et al., 2025) by leveraging the distinctive resources and values of each bioregion.

In recent years, bioregionalism has gained increasing attention as a framework that can offer both ecological and socio-economic benefits, particularly in the context of rural and peripheral areas (Bakker et al., 2023). These regions often face significant challenges (Casini et al., 2019), such as population decline, demographic ageing (Mattas et al., 2024), economic stagnation, and environmental degradation. Bioregional strategies provide a potential solution by promoting localised, resource-based economic activities (Olmo-García et al., 2023) while maintaining environmental integrity. By tailoring development strategies to the ecological and cultural context of a specific region, bioregionalism helps foster a deeper sense of place and identity, encouraging sustainable and balanced growth (Mazzocchi et al., 2021).

Latvia, with its rich natural resources, diverse ecosystems, and strong cultural heritage, stands at the threshold of significant transformations in regional economic planning. The country's landscape is characterised by extensive forests, fertile agricultural land, wetlands, and coastal areas, all of which present unique opportunities for the adoption of bioregional principles. Furthermore, Latvia's historical connection to its natural environment has fostered a strong sense of environmental stewardship, which could serve as a foundation for the broader adoption of bioregional strategies.

At the same time, Latvia's transition to a knowledge-based economy, as outlined in its Smart Specialisation Strategy (Research and Innovation Strategy for Smart Specialisation - RIS3), presents both challenges and opportunities for regional planning (Smart Specialisation Strategy…). The S3 aims to enhance Latvia's economic competitiveness by focusing on knowledge-intensive sectors such as the bioeconomy, information and communication technologies (ICT), and green technologies. While these sectors hold promise for economic growth, careful consideration must be given to how local resources—both human and natural—can be effectively mobilised to foster innovation and specialisation. This is where bioregionalism emerges as a complementary approach to Latvia's S3, integrating the ecological and socio-economic dimensions of regional development.

This study explores the potential of bioregionalism as a strategic tool for sustainable rural development in Latvia. It examines how bioregional structures could be implemented within the Smart Specialisation Strategy, focusing on localised, environmentally sustainable economic sectors. The paper also discusses the broader theoretical foundations of bioregionalism, drawing on global examples to illustrate how such strategies have been applied in other parts of Europe. Finally, the study evaluates the practical implications of bioregionalism within the framework of Latvian regional planning, highlighting the challenges, opportunities, and potential benefits of integrating

bioregional principles into Latvia's development agenda.

The analysis of bioregional development is linked to the existing administrative structure of Latvia and the context of Latvia's sustainable development goals (Muska et al., 2022). This study aims to contribute to the pressing issue of sustainable regional planning in Latvia's economic development. Specifically, it seeks to deepen the understanding of how bioregionalism can serve as a framework for reconciling economic growth with environmental conservation. By doing so, the study aims to support Latvia in fostering a more resilient and sustainable future for its rural communities.

Materials and Methods

The primary materials used in this study include academic journal articles, books related to bioregionalism, sustainable development, and regional planning. These sources provide the theoretical foundation for bioregional planning and its impact on regional economic specialisation. The methodology involved a review of literature from Europe and other regions of the world where bioregional strategies (Simon-Rojo et al., 2023) have been implemented. Additionally, data related to Latvia's Smart Specialisation Strategy, ecological resources, and demographic trends were analysed to assess the feasibility of implementing bioregional strategies in the country.

Results and Discussion

The findings of this study reveal a range of insights regarding the potential application of the bioregional approach within the framework of regional planning in Latvia. By examining the theoretical foundations and conducting practical case studies, several key trends, challenges (Coquil et al., 2018), and opportunities influencing the implementation of bioregional strategies in Latvia have been identified. These findings not only highlight the ecological and economic potential of bioregionalism but also indicate specific factors that may affect its successful integration into Latvia's broader regional development and Smart Specialisation Strategy.

Latvia's natural conditions, characterized by extensive forests, diverse wetlands, fertile soils, and coastal ecosystems, are the basis for bioregional strategies. The potential for sustainable rural development lies in harnessing these resources in a manner that respects and enhances Latvia's ecological systems while simultaneously promoting local economic specialisation. A key aspect of this process is the recognition of the interdependence between natural capital and cultural heritage. In particular, rural areas in Latvia are closely connected to their natural surroundings, with local communities often relying on traditional sectors such as agriculture, forestry, and fisheries.

Sustainable forest management, combined with innovations in the bioeconomy, such as wood-based bioproducts, could not only contribute to environmental conservation but also stimulate the local economy through green technologies. Similarly, Latvia's abundant water resources could serve as a foundation for the expansion of ecotourism, focusing on the conservation of biodiversity and the promotion of sustainable practices that benefit both local communities and the environment.

Furthermore, Latvia's cultural heritage, particularly in rural areas, plays a crucial role in shaping its bioregions. Traditional knowledge related to land use, local crafts, and rural customs offers unique opportunities for cultural tourism. This is in line with the broader trend of using bioregionalism to promote sustainable tourism, encouraging visitors to explore and appreciate the natural and cultural features of a region, while supporting its economic viability (Balčūne, 2022).

By incorporating these cultural elements into the bioregional planning process, Latvia can contribute to the revitalisation of its rural communities and generate new opportunities for economic growth that respect local traditions.

Latvia's Smart Specialisation Strategy (RIS3), which focuses on knowledge-intensive sectors such as the bioeconomy, digitalisation, and green technologies, aligns well with the principles of bioregionalism. Research data on projects that have received support specifically aimed at innovation indicate a strong interest among rural entrepreneurs and the successful implementation of projects. These findings provide a solid basis for optimism regarding the future transformation of rural enterprises towards green industrialisation (Veveris, 2022). By concentrating on localised resources and innovation-driven strategies, bioregions could significantly contribute to the success of Latvia's RIS3 by fostering regional specialisation in sectors that leverage both the country's natural and human resources.

One promising area for integration is the bioeconomy, a central pillar of Latvia's RIS3. The country's extensive forests, agricultural land, and natural resources create an ideal environment for biological sectors such as renewable energy, sustainable forestry, organic farming (Altieri et al., 2017), and fisheries (Eizenberga et al., 2022). Bioregionalism could help structure these industries according to the specific needs and opportunities of different ecological regions, fostering innovation in green technologies and sustainable practices. For example, local knowledge in sustainable agriculture could be utilised to develop new green technologies for organic farming, while Latvia's timber industry could focus on creating sustainable, value-added products.

Moreover, the establishment and development of bioregions could support the growth of local innovation and start-up ecosystems that reinforce these industries (Jungsberg et al., 2020). Regional business clusters, research institutions, and local authorities could collaborate to develop new technologies, products, and

services tailored to the unique ecological characteristics of each region. These regional clusters would benefit from the synergies created by localised knowledge and shared resources, promoting sustainable development and economic resilience.

Table 1
Common objectives of RIS3 and bioregions

RIS3 Objectives	***Bioregion-specific objectives***
Innovation and research	Bioinnovations, organic food, green tourism
Specialization and competitiveness	Organic production, crafts, cultural economy
Sustainability and resource efficiency	Organic agriculture, green industrialization, sustainable tourism
Human capital and skills development	Bioeconomy, agricultural, tourism and cultural competences
International cooperation and export	Export of bioproducts, bioinnovations and cultural tourism

The study identifies potential innovative and sustainable concepts for local rural communities including organic production as an important element in the development of food systems.

Rural Innovation Ecosystem – a network of diverse entities—including businesses, research institutions, business support intermediaries, and individuals such as entrepreneurs, investors, policymakers, researchers, and students—engaged in collaboration and knowledge exchange. This ecosystem fosters sustainability, skill development, and economic balance while leveraging anchor institutions (Marshall & Murphy, 2021).

Smart Village – the smart village concept focuses on enhancing the potential of rural areas and their communities through the strategic and effective use of new technologies, including digital innovations. It emphasises the role of institutions, service networks, local resources, social innovation, and entrepreneurship while fostering a sustainable relationship with the surrounding environment (Bokun & Nazarko, 2023).

Startup Village – a startup village refers to a rural area—or a network of smaller settlements—that embraces innovation and entrepreneurial ambition to drive local development. It creates an enabling environment for dynamic business ecosystems, integrating innovation, market access, and external knowledge to support sustainable rural growth (Goodwin-Hawkins et al., 2023).

Rural Heritage Hub is a physical or community-based space where local stakeholders engage in knowledge exchange and collaborative initiatives. These hubs serve as focal points for community coordination, engagement, and the development of shared strategies (De Luca et al., 2021).

Living Lab – is a user-driven, open innovation environment that integrates research and innovation within real-world settings. Through co-creation and community involvement, living labs facilitate technological development and sector-specific advancements (Bacco et al., 2020).

Sustainable Communities – is a community defined by either geographical or political boundaries—united by a shared commitment to environmental stewardship and quality of life. These communities collaborate to protect natural resources and ensure long-term sustainability (Ravazzoli & Valero, 2020).

Organic farming practices promote sustainable resource use, soil fertility conservation and biodiversity protection, thus creating an ecologically balanced food production model (Guccione, 2024).

However, the potential inclusion of bioregionalism in Latvia's RIS3 presents certain challenges. A key issue is the need for a robust institutional framework that ensures collaboration between different levels of government, local stakeholders, and businesses. While Latvia has made progress in developing its RIS3, further coordination between national and regional authorities is necessary to ensure the effective utilisation of regional resources for economic development. The first bioregion established in Gauja National Park is a successful example of how local governments and community stakeholders can work together to promote sustainable development. In this process, special attention was paid to ensuring that bioregional strategies meet the unique needs of rural communities, combining nature conservation with local business and tourism development (International forum…, 2023).

This study has identified several challenges that may hinder the effective implementation of bioregional strategies in Latvia. One of the primary obstacles is the existing administrative structure, which is largely based on political rather than ecological boundaries. The current regional division in Latvia does not always correspond to natural ecosystems, which may complicate the process of establishing bioregions. Additionally, the separation of urban and rural governance structures does not facilitate the transition towards sustainable regional development. Potential bioregions may transcend political boundaries, making it difficult to implement policies that address environmental issues at the appropriate scale.

Another challenge is the demographic shift occurring in Latvia's rural areas. The country is experiencing significant rural depopulation, with many younger people relocating to urban centres in search of education and employment opportunities. This migration has led to an ageing population in rural regions, posing a challenge to the long-term sustainability of bioregional strategies. To counter this trend, bioregionalism must not only promote sustainable economic activities but also enhance the quality of life in rural areas (Vindevoghel, 2024), creating new economic opportunities and improving infrastructure. The success of bioregionalism in

Latvia's rural areas will depend on its ability to attract and retain young people by offering viable career prospects in green technologies, the bioeconomy, and ecotourism.

Finally, bioregionalism requires strong institutional support and active participation from local communities in planning and decision-making processes. While the Latvian government has demonstrated a commitment to fostering sustainable development, further capacity-building at the local level remains necessary. Local governments, businesses, and civil society organisations must be equipped with the tools and knowledge required to effectively design and implement bioregional strategies. This may involve providing training on sustainable resource management, fostering cross-sector collaboration, and creating incentives for businesses to adopt environmentally sustainable practices.

Although the findings of this study suggest that bioregionalism could significantly benefit Latvia's rural development, further research is needed to refine and test these concepts in practice. Future studies could focus on specific case studies of bioregional planning in Latvia, examining pilot projects that integrate ecological and economic strategies. Additionally, research could explore the potential of bioregions to foster innovation and entrepreneurship, particularly in rural areas that have traditionally been economically marginalised.

Moreover, closer collaboration between academia, policymakers, and economic sectors (Gava et al., 2025) is required to develop the frameworks necessary for the success of bioregions. Bioregional principles should be incorporated into policy-making at both national and regional levels, and long-term strategies should be developed to promote innovation while preserving natural resources. The use of data analytics and geographic information systems (GIS) plays a major role in identifying the most promising areas for bioregional development, ensuring the integration of ecological factors into regional planning decisions.

Conclusions

1. Bioregional strategies can effectively complement the Latvian Smart Specialisation Strategy (RIS3).
2. Bioregionalism offers strategic advantages for improving rural resilience, promoting innovation and incorporating ecological and cultural values into regional economic planning.
3. The strongest synergy between bioregionalism and knowledge-based rural development in Latvia is visible in the bioeconomy sector, sustainably using natural resources, green technologies, promoting innovation and low-carbon solutions, cultural tourism, and using heritage and identity for local community development.
4. In order to fully realise the potential of bioregionalism, institutional fragmentation, demographic decline in rural areas, structural constraints in policy coordination and resource allocation will need to be overcome.

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DETERMINING THE PRIORITY RESEARCH AREAS IN FOOD SECURITY AND BIOECONOMY OF UKRAINE BY EXPERT SURVEY

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Abstract
The research uses the Delphi method to identify the priority research areas for Ukraine's scientific and technological (S&T) development. Conducted in three stages from July to December 2024, the research engages 543 experts across nine thematic blocks, including 'Food security, sustainable agricultural development and related technologies, bioeconomy'. The study aims to update the priority research areas established in 2021, identify potential priority research areas of Ukrainian agriculture in 2024 considering the influence of the Russian military invasion, and explore innovative approaches to Ukrainian S&T policy. Experts evaluate the potential research areas based on relevance, personnel, equipment, achievements, and international cooperation of the research area. The study shows the significant gaps in Ukraine's current science policy framework. Key outcomes include refining priority research areas, confirmed by over 50% of experts, and developing recommendations for strengthening Ukrainian S&T policy. The research identifies new high-priority research areas in Ukraine (percentage of highest relevance ratings among responses) under the thematic block 'Food security, sustainable agricultural development and related technologies, bioeconomy': 'Nanotechnology, biotechnology for efficient processing of agricultural raw materials into food and technical products, green energy' (82%), 'Energy and resource-saving technologies and technical means of agro-industrial production' (68%), 'Institutional support for national security and sustainable development through the development of comprehensive programs for the development of the national economy, defence capability and the well-being of the population' (66%).
Keywords: food security, bioeconomy, sustainable agriculture, S&T policy, technological foresight.

Introduction

Food security and bioeconomy play a crucial role in resilient supply chain stability, providing the UN SDGs 2030 Agenda in an ongoing full-scale war. Ensuring food security in Ukraine faces unstable household incomes, food prices, logistics disruption, and rising inflation (Berndt et al., 2022; Kuzoma, 2024). During the past two years, the state of the food supply, its availability for the population, and the self-sufficiency of domestic production have been declining (Hafurova et al., 2024; Meijl et al., 2022). Ukraine's main internal problems, such as irrational use of land, labour migration, destructive chemicalization of products and losses of land reproduction, increased their influence (Podsokha, 2023). An essential contribution to this field of study was made by Shvets et al. (2023) who identified directions in the innovative development of bioeconomy, food security based on smart specialisation strategies by Central and Eastern European countries (Shvets et al., 2023). There are works dedicated to specific aspects of food security, such as food shortfall influenced by environmental pollution and the population rising and its overcoming by the development of the agro-industrial complex (Olshanska et al., 2022). Other authors provided a three-round survey and proved the urgency for modelling a national strategy for bio-economic transformation and its harmonisation of EU policies (Vostriakova, 2024). There are papers devoted to solving strategic planning problems, promoting methods for pre-foresight research (Deineko & Sheludko, 2021), determining the priorities of innovative development of the economy based on official statistical information and the Scopus database (Koretskyi, 2017), and identifying priorities for S&T like the green economy, digital transformation, zero hunger, and healthcare (Pysarenko et al., 2020). At the same time, there has been no in-depth research on defining the scientific priorities in the conditions of full-scale war concerning the negative tendencies in agricultural infrastructure, the formation of multifaceted S&T policy recommendations, determining the biggest problems at the stages of implementing a new scientific discovery, measures to restore human resources, etc. Hence, this paper aims to fill this gap. The study aims to determine whether the areas of scientific development that experts recognised as priorities in 2021 remain relevant, as well as to identify new challenges that have gained significance in modern conditions and require the concentration of efforts of domestic scientists, in particular for the post-war restoration of the agrarian sector of Ukraine, to identify new ideas regarding the mechanisms for implementing the state's S&T policy, emphasising non-standard ideas and alternative approaches to its development.

Materials and Methods

To ensure the organisation of the survey, nine methodological groups worked for each of the nine thematic areas (Popovych et al., 2024). The general methodological group coordinated the activities of these groups, a total of twenty five researchers. For each of the nine thematic areas, the methodological group prepared a single type of Google questionnaire. It was proposed to evaluate specific studies recognised as a priority in 2021 by experts of the relevant thematic area in the form of closed questions when assessing the relevance, personnel and material support, scientific achievements and the level of international cooperation, as well as in the form of open questions when formulating new ideas and

proposals. Afterwards, the methodological groups of the relevant thematic areas sent links to Google questionnaires and collected responses, monitored the completion time, and communicated directly with experts if necessary. Members of the thematic groups also directly participated in the initial interpretation and comprehension of the received materials. In addition, in the form of open questions, they were asked to name those problems and areas of research that, in their opinion, were relevant today but were not named in 2021 (Popovych, 2022).

The survey was conducted in three stages using the Delphi method and the latest methodological recommendations of the RAND Corporation (Khodyakov et al., 2023), considering the experience of previous forecasting and analytical studies carried out by the Dobrov Institute. The basis for assessing the relevance of research areas and their potential was the results of a study conducted in 2021 using the Delphi method. This expert assessment and forecasting approach is based on a phased survey of experts to reach an agreement on specific issues. The study includes three stages with clearly defined tasks. The first round carries out an initial assessment of the relevance of research areas and generates new ideas for priorities and policies. The second round aims to refine the assessments of the significance of research areas based on previous results and a preliminary evaluation of the ideas put forward. The third round finalises new ideas, identifies priority areas for research and policies, and achieves a coordinated vision of key recommendations. In the survey, 543 experts assessed nine thematic research blocks. Fifty-eight experts worked in the thematic area of 'Food security, sustainable development of agriculture and related technologies, bioeconomy'.

Results and Discussion

In the context of active hostilities and counteraction, the issue of reviewing scientific and technical priorities and identifying new areas of scientific research is becoming more relevant. It is essential to focus on those scientific innovations that will have practical significance and strengthen their S&T potential. In the second round of the survey, experts were asked to review the pre-research areas identified as priorities in the 2021 survey (Table 1).

Table 1

Research directions within the research block: 'Food security, sustainable agricultural development and related technologies, bioeconomy' 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	Nanotechnology, biotechnology for efficient processing of agricultural raw materials into food and technical products, 'green energy'	82%	4.55	3.62	3.16	3.30	3.43
2	Energy- and resource-saving technologies and technical means of agro-industrial production	68%	4.32	3.70	3.22	3.24	3.30
3	Institutional support for national security and sustainable development through comprehensive national economic, defense and welfare programs	66%	4.37	3.63	3.43	3.26	3.54
4	Genetic foundations for increasing the productivity of cereal grains with enhanced adaptive potential to adverse environmental factors	64%	4.28	3.79	3.28	3.49	3.28
5	Development of methods for targeted manipulation of plant heredity. Genetic improvement of plants using molecular genetics and marker-assisted selection with enhanced adaptive potential to adverse environmental conditions	59%	4.11	3.39	2.97	3.17	3.28
6	Information-resource screening of soil conditions in Ukraine for their natural and artificial restoration	57%	4.14	3.59	3.19	3.27	3.43
7	Biofortification of grains (increasing the content of essential phytonutrients in grains)	53%	4.08	3.42	3.06	3.28	3.08

Source: authors' calculations based on the results of the experts' survey.

The shown results demonstrate that the highest level of relevance (82%) took the direction 'Nanotechnology, biotechnology for efficient processing of agricultural raw materials into food and technical products, 'green energy'. Also, high priority was given to the directions 'Energy-and resource-saving technologies and technical means of agro-industrial production' (68%), 'Institutional support for national security and sustainable development through comprehensive national economic, defence and welfare programs' (66%) and 'Genetic foundations for increasing the productivity of cereal grains with enhanced adaptive potential to adverse environmental factors' (64%).

The lowest relevance was given to the research directions 'Formation of a valuable genotypic base of new high-protein crops as an alternative source of animal-origin products for sustainable food security' (39%) and 'Building a qualitatively new paradigm of eco-socio-economic growth based on inclusivity' (46%). These positions may be due to the lack of high-tech laboratories and modern equipment and the long duration of obtaining practical results. The worst situation of all indicators is 'Genomic selection in animal husbandry' (37%). Most experts do not believe that it deserves priority support. Almost a third note is that the equipment is currently insufficient for conducting research or is simply absent. Another third considers the current equipment to be outdated and ineffective. Only 6.8% believe that the equipment is sufficient. Assessments of human resources, achievements and international cooperation indicate that the development of this direction is possible only through participation in the work of foreign scientific centres. We consider those three directions mentioned before as those that lost their high priority for Ukrainian science in the mid and long term.

In the third round, experts had the opportunity to evaluate new proposals for research areas supported by most experts in the second round. Table 2 provides a generalized assessment of experts' most supported new ideas to supplement the list of promising areas for the thematic block.

Table 2

New ideas for research directions within the research block: 'Food security, sustainable agricultural development and related technologies, bioeconomy'

	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 post-war restoration methods for agrophytocenoses, including agricultural lands, cleaning of soils and water resources contaminated as a result of the large-scale invasion of the Russian Federation into the territory of Ukraine	74%	4.62	3.72	3.10	3.36	3.36
2	Enhancing drought resistance of crops. Searching for new approaches to increase crop yields	65%	4.40	3.73	3.23	3.55	3.15
3	Development of national breeding, national seed production, intellectual property in seed production. Creation and implementation of high-quality grain crops as the basis for food and economic security of the state	63%	4.35	3.93	3.30	3.83	3.20
4	Creation and transfer of the first grain crop varieties in Ukraine with unique grain characteristics intended for the production of healthy food products	55%	4.28	3.55	3.20	3.40	3.18
5	Development of technologies and technical means for ensuring the country's sustainable agricultural production and food security. Circular economy	51%	4.22	3.38	3.03	3.05	3.22
6	Environmental protection, restoration of the country's ecological security. Integration of fundamental agroecology principles into agricultural development. Sustainable natural resource management	51%	4.31	3.51	3.10	3.34	3.08

Source: authors' calculations based on the results of the experts' survey.

The shown results demonstrate that the highest level of relevance (74%) took the direction 'Development of post-war restoration methods for agrophytocenoses, including agricultural lands, cleaning of soils and

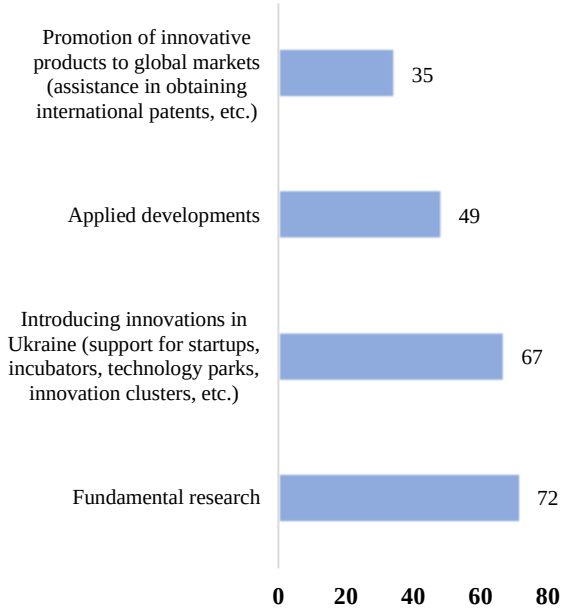
water resources contaminated as a result of the large-scale invasion of the Russian Federation into the territory of Ukraine'. Besides that, a high priority was given to the directions 'Enhancing drought resistance of crops'. Searching for new approaches to increase crop yields (65%), 'Development of national breeding, national seed production, and intellectual property in seed production'. 'Creation and implementation of high-quality grain crops as the basis for food and economic security of the state' (63%) and 'Creation and transfer of the first-grain crop varieties in Ukraine with unique grain characteristics intended for the production of healthy food products' (55%). Experts decided that the above-mentioned research directions are the most relevant scientific priorities for Ukrainian bioeconomics and food security. Cleaning soils and water contamination from explosive materials will be appropriate for the next decades.

The research directions, judging from the experts' opinions, can't be assessed as priorities for Ukrainian S&T: 'Development of technologies for producing ethanol biodiesel fuel based on renewable raw materials' (49%), 'Biotechnologies for accelerated reproduction of agricultural animals, ensuring veterinary and sanitary well-being'. 'Development of serums and vaccines for agricultural animals' (44%), 'Genetic engineering of plants and animals; transgenic organisms'. Research on the impact of genetically modified products on the human body (44%), 'Development of unmanned (remote) monitoring systems for agricultural lands based on artificial intelligence' (43%). Judging from the experts' opinions, the less relevant research directions are 'Phytosanitary condition of agrocenoses'. Formation of a genetic bank of domestic varieties of fruit and ornamental crops. 'Development of plant protection systems and tools based on NBIC technologies' (39%), 'Development of new environmentally safe plant growth regulators based on azagheterocycle derivatives to increase productivity and stress resistance of crops' (26%) and 'Creation and implementation of systems for efficient resource use (nitrogen/nutrients, crop protection agents, etc.) to reduce greenhouse gas emissions and increase the profitability of crop production' (24%). The experts' opinion in Ukraine can explain such a tendency because there are not enough qualified staff, the availability of high-tech equipment, research background and the necessary level of scientific international cooperation for solving scientific problems mentioned before.

In the second round of the survey, experts voted for the directions of S&T policy in Ukraine that should be focused on as a priority. Figure 1 shows the highest priority of S&T policy for providing 'Fundamental research' (72%). Such a direction of science allows for the creation of new scientific knowledge and the preparation of technological breakthroughs in the future. The direction 'Introducing innovations in Ukraine' (67%) received a high assessment from the experts, indicating the desire to transform scientific developments into actual commercial products within the country, which can be used for post-war economic recovery and strengthening the technological sector. The less actual directions for Ukrainian S&T are 'Applied development' and 'Promotion of innovative products to global markets (assistance in obtaining international patents)' with 49% and 35% of all responses, respectively. These results explain that promoting innovative products is necessary but not the first task for implementing and focusing on the S&T policy.

Figure 1

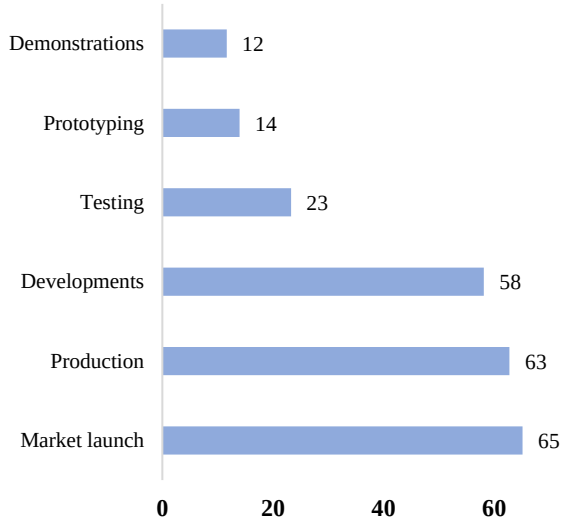
The state's S&T policy should be focused on directions (the percentage of experts' responses)



Source: authors' calculations based on the results of the experts' survey.

'Market launch' (65%), 'Production' (63%) and 'Developments' (58%) are the stages of implementing a new scientific discovery where the most significant problems arise from the experts' opinions, Figure 2. Fewer problems occur in the early stages of implementing a new scientific discovery, such as 'Demonstrations' (12%), 'Prototyping' (14%) and 'Testing' (23%). A clear tendency lies in that the later and final stages of creating a new scientific discovery require much higher human, material, and financial resources. Only leading scientific institutions can afford to bring their discovery to the market. That's why cooperation with businesses and international partners plays a significant role in gaining success. This emphasises the importance of international collaboration to advance scientific discoveries. It is defined that a much bigger problem is not implementing scientific discovery into the industry but scaling it up.

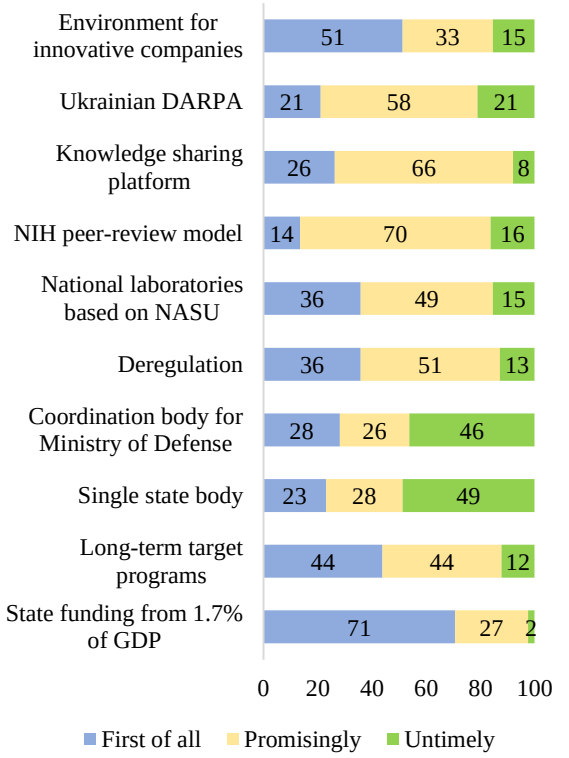
Figure 2
The most significant problems arise at the stage of implementing scientific discovery (the percentage of experts' responses)



Source: authors' calculations based on the results of the experts' survey.

In the third round of the survey, experts were asked to assess the priority of the state's S&T policy measures, Figure 3. The experts identified the following S&T policy measures as a top priority for fulfilment:
1. 'State funding from 1.7% of GDP' (71%) by increasing government spending for science, approximately to $3.04 billion per year;
2. 'Environment for innovative companies' (51%) by creating a favourable environment for startups and innovative companies (reducing bureaucracy, access to venture capital, supporting incubators and accelerators, developing technology parks and innovation clusters; 3. 'Long-term target programs' (44%) are formed by providing long-term target programs with appropriate guaranteed funding in clearly defined priority areas. Also, experts think that deregulation and reduction of bureaucratic procedures in organizing and financing research (36%) and development of a model similar to the US National Laboratories based on the institutes of the National Academy of Sciences of Ukraine are also necessary S&T policy measures and must be implemented as a priority. On the other hand, there are quite a lot of experts who think that creating a 'Single state body' (49%) by making a single state authority responsible for innovation policy, eliminating the dispersion of responsibility between different ministries) and 'Coordination body for Ministry of Defence of Ukraine' (46%) by creating a coordination body between research institutions, defence industry enterprises and the Ministry of Defense to ensure effective interaction, ensuring full state financing of the entire cycle of defence-oriented developments are the untimely policy measures for fulfilment.

Figure 3
Assessment of the state's scientific priorities and S&T policy measures (the percentage of experts' responses)

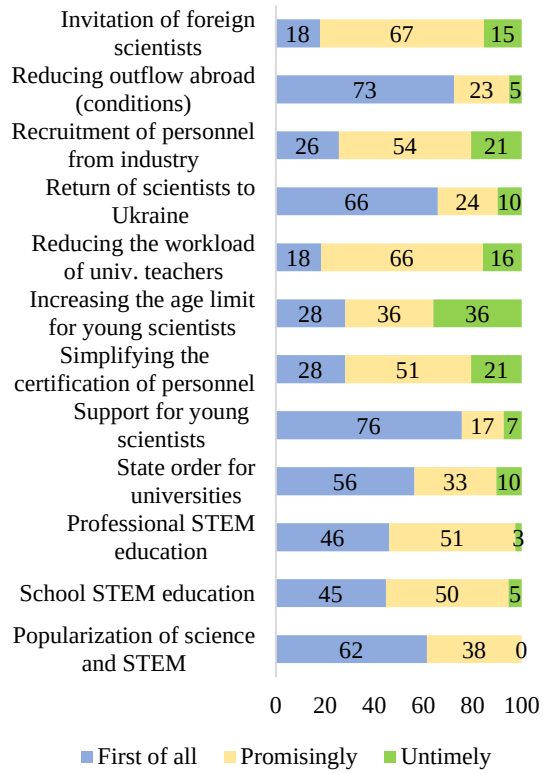


Source: authors' calculations based on the results of the experts' survey.

As we see, first, S&T policy needs to enlarge the base funding of science, provide long-term target programs with guaranteed financing, and reduce the influence of controlling state bodies at all stages of the innovation cycle. In the third round of the survey, experts assessed the priority measures to restore human resources as an essential target of the state's S&T policy, Figure 4. The experts identified the following S&T as a priority guidelines for the implementation: 1. 'Support of young scientists' (76%), 2. 'Reducing outflow abroad (ensuring proper working conditions and wages)' (73%); 3. 'Return of scientists to Ukraine' (66%), and 'State order for universities' (56%). Experts assessed 'Invitation of foreign scientists' (67%) and 'Reducing the workload of university teachers' (66%), 'Recruitment of personnel from industry' (54%) and 'Simplifying the certification of personnel' (51%) as those that are promising measures to restore the human resources. Still, they are not as efficient as mentioned before, as first of all, for fulfilment. Judging the gained results, we define that supporting young scientists and making proper conditions for their career development are vital S&T policy measures for stimulating the restoration of scientific staff. Experts noted the importance of supporting the middle generation of experienced scientists who can transfer their knowledge to the younger, rising generation.

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.

Conclusions

1. The study defines the highest relevance priority research directions that have not lost their high actuality in Ukraine despite the influence of full-scale war (percentage of relevance responses): 'Nanotechnology, biotechnology for efficient processing of agricultural raw materials into food and technical products, 'green energy' (82%), 'Energy-and resource-saving technologies and technical means of agro-industrial production' (68%) and 'Institutional support for national security and sustainable development through comprehensive national economic, defence and welfare programs' (66%).
2. The study defines the highest relevance priority research directions for the development of Ukrainian S&T for a mid- and -long term: 'Development of post-war restoration methods for agrophytocenoses, including agricultural lands, cleaning of soils and water resources contaminated as a result of the large-scale invasion of the Russian Federation into the territory of Ukraine' (74%), 'Enhancing drought resistance of crops'. Searching for new approaches to increase crop yields (65%) and 'Development of national breeding, national seed production, intellectual property in seed production'. 'Creation and implementation of high-quality grain crops as the basis for food and economic security of the state' (63%).
3. The state's S&T policy must be focused chiefly on 'Fundamental research' (72%) and 'Introducing innovations in Ukraine (support for startups, incubators, technology parks, innovation clusters, etc.)' (67%) as essential cornerstones of progressive science.
4. 'Market launch' (65%), 'Production' (63%) and 'Developments' (58%) are the most challenging stages of implementing a new scientific discovery. Only leading scientific institutions can afford to bring their discovery to the market and scale it up.
5. S&T state policy needs to enlarge the base funding of science, provide long-term target programs with guaranteed financing, and reduce the influence of controlling state bodies at all stages of the innovation cycle.
6. Experts noted that supporting young professionals is the most efficient S&T policy measure to restore scientific staff.

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SUSTAINABLE ALGAL BIOMASS HARVESTING STRATEGIES FOR BIOSTIMULANTS IN THE BALTIC SEA REGION

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Abstract
The research evaluates and optimizes algae cultivation and harvesting methods for the production of biostimulants in the Baltic Sea region, covering Scandinavia, the Baltic States, and Germany. Current practices in seven countries are investigated, focusing on initial investment, operational efficiency, environmental impact, and seasonality mitigation. The methodology combines a literature review, regional data collection, and the application of the Analytical Hierarchy Process (AHP). The results show that initial investment is the most important factor (weight 0.52), followed by operational efficiency and environmental impact (0.20). Of the methods evaluated, seaweed farming by mechanical harvesting is optimal (weight 0.89), outperforming coastal farming by manual harvesting (0.68) and wild harvesting by mechanical methods (0.47). This approach provides a better balance between economic viability and environmental sustainability, improving nutrient use and reducing ecological impacts while providing more biomass. Sensitivity analysis confirms the robustness of the results and demonstrates their adaptability to different regional conditions. The research provides valuable insights for stakeholders in the algae bio-economy and forms the basis for further research into innovative technologies, species selection, and integrated aquaculture systems to promote sustainable algal biomass production, support bio-economy growth, and protect the environment. Future work should focus on pilot projects to validate results, explore new technologies, and assess the long-term impacts of large-scale seaweed farming in this unique marine environment.
Keywords: marine aquaculture, methods for decision making, environmental management, bio-economy.

Introduction

Scientific discourse on bioeconomy strategy papers and their objectives has become increasingly important in recent years, highlighting the role of the bioeconomy in promoting sustainable development (Stegmann et al., 2020). Strategies at the European Union and national level emphasize the need for interdisciplinary approaches and cross-sectoral collaboration to promote sustainable biomass use and the circular economy (Campbell et al., 2019). In this context, algal biomass has emerged as a strategically important resource in the global bioeconomy with a wide range of applications in different sectors, including food, agriculture, pharmaceuticals, and energy (Weinberger et al., 2019, Skapste et al., 2025). The Baltic Sea region, with its unique ecological characteristics, offers significant potential for algae cultivation and processing, but low salinity, seasonal temperature fluctuations and limited nutrient availability pose challenges for efficient biomass extraction (Pechsiri et al., 2016). Overcoming these challenges and identifying optimal methods for algae cultivation and harvesting has become a critical need in the context of sustainable development in the region (Visch et al., 2020).

The use of algal biomass for biostimulant production is a particularly promising area that can contribute significantly to agricultural sustainability and productivity (Meichßner et al., 2021). Algae-derived biostimulants can improve crop tolerance to environmental stresses, enhance nutrient uptake and increase yields while reducing the need for chemical fertilisers (Sharma et al., 2014).

The aim of this research is to evaluate and optimise algal cultivation and harvesting methods for biostimulant production in the Baltic Sea region using the Analytical Hierarchy Process (AHP). The AHP method allows for the integration of both quantitative and qualitative factors in the decision-making process, which is particularly important given the multidisciplinary nature of the bio-economy (Ren et al., 2020).

The research hypothesis is that marine cultivation methods combined with mechanical harvesting will provide more efficient and sustainable extraction of algal biomass for biostimulant production in the Baltic Sea region compared to other methods. In order to test this hypothesis and to achieve the aim of the study, the following objectives were set: (1) to analyse the existing methods of cultivation and harvesting of algae in seven countries in the Baltic Sea region; (2) to develop and apply the AHP methodology for evaluating methods of cultivation and harvesting of algae based on four criteria; (3) to carry out a comparative analysis between three main combinations of methods: marine cultivation with mechanical harvesting, land-based cultivation with manual harvesting and wild harvesting with mechanical harvesting.

By providing a systematic and scientifically sound approach to assessing sustainable algal biomass production methods in the Baltic Sea region, this study makes an important contribution. The results can serve as a basis for industry development guidelines, contributing to the growth of the bio-economy in the region and the achievement of the UN Sustainable Development Goals. At the same time, the results can be used for policy making in business planning to engage in algal biomass production and processing. Such an approach can contribute to sustainable resource use and economic development in the region, while addressing environmental issues and optimising algae cultivation and harvesting processes.

Materials and Methods

The study used a mixed methodological approach, combining qualitative and quantitative methods to provide a comprehensive analysis of algae cultivation and harvesting practices in the Baltic Sea region.

A systematic analysis of the scientific literature was carried out using databases such as Scopus, Web of Science, and ScienceDirect. The search terms used were 'algae cultivation', 'Baltic Sea', 'biostimulants', 'seaweed harvesting' and 'sustainable aquaculture'. The analysis included studies published in the last 10 years (2013-2023) to ensure up-to-date information. Data were collected on seaweed cultivation and harvesting practices in seven Baltic Sea countries.

AHP was used as the main decision-making method to evaluate and compare different algae farming and harvesting methods. The AHP method allows the integration of both quantitative and qualitative factors in the decision-making process, which is particularly important given the multidisciplinary nature of the bio-economy (Ren et al., 2020; Visch et al., 2020). The AHP process involved the following steps: (1) definition of criteria - Initial Investment (SI), Operational Efficiency (OE), Environmental Impact (VI) and Seasonality Mitigation (SM) (Sánchez Navarro et al., 2020; Sarjono et al., 2020); (2) development of a pairwise comparison matrix - criteria were compared using a scale (1-9) (Sarjono et al., 2020; Chai et al., 2023); (3) calculation of priority vectors - the geometric mean method was used to calculate priority vectors for each criterion; (4) consistency check - consistency ratios (CR) were calculated to check the reliability of the ratings. A CR value below 0.1 was considered acceptable (Sarjono et al., 2020; Salomon et al., 2024); (5) evaluation of alternatives - the three main combinations of methods (JM - marine cultivation + mechanical harvesting, KM - coastal cultivation + manual harvesting, SM - wild harvesting + mechanical harvesting) were evaluated for each criterion (Saaty, 2008; Sarjono et al., 2020); (6) calculation of the overall score - a weighted score was calculated for each alternative using formula (1).

$$V_i = \sum^{n}_{j} 1 w_j v_{ij} \quad (1)$$

where:

V_i is the total score of alternative i, w_j is the weight of criterion j, and v_{ij} is the score of alternative i relative to criterion j (Sánchez Navarro et al., 2020; Sarjono et al., 2020).

Robustness check

Sensitivity analyses were performed by varying the criterion weights within ±10% and observing changes in the overall scores (Leskinen et al., 2019; Chai et al., 2023; Sarjono et al., 2020).

This methodology allowed an objective assessment of different algal cultivation and harvesting methods, taking into account both quantitative and qualitative factors, and provided a scientifically sound approach to identifying optimal strategies in the Baltic Sea region.

Results and Discussion

The countries in the Baltic Sea region have different approaches to algae cultivation and harvesting. This diversity reflects not only different geographical and climatic conditions but also different approaches to developing sustainable aquaculture. To better understand these differences, Table 1 provides an overview of the methods used in each country.

Table 1

Algae cultivation and harvesting methods in the Baltic Sea region

Country	***Cultivation methods***	***Harvesting methods***
Denmark	Multitrophic kelp *Saccharina latissima* long-line floating systems	Manual and mechanical harvesting
Sweden	Multitrophic kelp *Saccharina latissima* aquaculture long-line floating systems	Mechanical harvesting
Finland	Coastal aquaculture systems, experimental low salinity culture	Experimental harvesting techniques
Latvia	Macroalgal cultivation experimental projects	Manual harvesting in natural populations
Estonia	Cultivation of *Furcellaria lumbricalis*, both free-floating and attached	Mechanical and manual harvesting in natural populations
Lithuania	Shore tanks, floating islands	Experimental harvesting technology
Germany	Long line floating systems for seaweed (*Saccharina latissima*), microalgae production	Mechanical harvesting

Source: Created by the author from (Ciervo, 2024; Weinberger et al., 2020; Wimmerova, 2019; Skapste et al., 2024; Froehlich et al., 2017; Gonzalez-Esquer et al., 2019).

Table 1 provides an overview of the cultivation and harvesting methods used in the Baltic Sea region. The information gathered shows a considerable diversity of algal cultivation methods in the region. Denmark and Sweden use advanced methods such as floating long-

line systems and multitrophic systems, which is in line with the findings of Yu et al. (2017) on the potential of algae farming in the marine environment. The Finnish approach with experimental low salinity cultivation and coastal aquaculture systems reflects efforts to adapt to the specific conditions of the Baltic Sea, as highlighted in the study by Armoškaitė et al. (2021).

The variety of harvesting methods, from manual to mechanical and experimental techniques, is illustrated by the work of Hu et al. (2023), which highlights the need for further research into innovative harvesting methods. The use of manual harvesting and beach harvesting in Latvia and Estonia may be due to lower production volumes or specific local conditions. The Estonian focus on cultivation of Furcellaria lumbricalis for both free-floating and attached forms shows adaptation to local species and conditions (Weinberger et al., 2020).

Germany's focus on microalgae production and macroalgae cultivation, as well as Lithuania's experimental macroalgae cultivation projects, indicate innovative efforts to adapt to local conditions and optimise production. The different approaches taken by the countries reflect the efforts to balance economic and environmental aspects, as highlighted by Monari et al. (2015).

The information gathered also illustrates the potential for further development and research in the field of algae cultivation and harvesting in the Baltic Sea region. The experimental methods used in Finland and Lithuania indicate a continuous process of innovation, which is in line with the conclusions of Pastare et al. (2014) on the need for further research to optimise the use of algae. Furthermore, as pointed out in the GRASS project (Ciervo, 2024), there is a need to develop clear guidelines and regulations for the cultivation and harvesting of algae in the Baltic Sea, taking into account environmental impacts and sustainability aspects.

This analysis shows that the countries in the Baltic Sea Region are actively seeking optimal methods for algae cultivation and harvesting, adapting to local conditions and striving to achieve the goals of sustainable aquaculture.

The AHP was used to assess the methods of algae cultivation and harvesting in the Baltic Sea region. This method allowed an objective comparison of different approaches, taking into account several criteria.

Within the AHP, a pairwise comparison matrix was developed to assess the importance of different criteria for the selection of algae farming and harvesting methods in the Baltic Sea region. The selection of criteria is based on previous studies.

1) Initial Investment (SI)

Recent studies have shown that the evaluation of initial investment has become particularly important as it determines the long-term viability of a project. Studies show that a properly assessed initial investment can reduce the total cost of a project by 15-30% in the long term (Buschmann et al., 2017).

2) Operational efficiency (OE)

The importance of operational efficiency is supported by recent studies showing a direct correlation between high operational efficiency and the ability of companies to implement environmental management practices (Gao & Wan, 2022). The integration of digital technologies and improved supply chain management have been identified as key factors in improving operational efficiency (Zhang, 2023).

3) Environmental impact (VI)

The relevance of the environmental impact criterion is reinforced by research on the challenges of climate change. 2023 research shows that integrating environmental considerations into decision making has become critical for business sustainability (Zanghelini et al., 2017). In particular, it highlights the need for a comprehensive approach to environmental impact assessment, including the analysis of both direct and indirect impacts.

4) Seasonal Mitigation (SM)

The importance of seasonality mitigation is supported by recent studies on the business impacts of climate change. Studies show that the impact of seasonal variations on business performance is becoming more pronounced, especially in the Baltic Sea region (Meier et al., 2022). Developing strategies to mitigate the effects of seasonality has become an important factor in ensuring the competitiveness of businesses.

Recent studies highlight the need for an integrated approach to sustainable development. The selected criteria form a complex assessment framework covering economic, environmental and operational aspects (Yang et al., 2023). This approach is in line with recent trends in sustainable development assessment.

Each of the defined criteria was assigned a weight of importance based on scientific discourse.

• Initial investment (SI = 0.52)

Initial investment is given the highest priority as it is crucial to the viability of a project. Studies show that a properly planned initial investment can have a significant impact on the long-term success of a project. For example, Troell et al. (2017) suggest that in aquaculture projects, initial investment can account for 40-60% of total project costs, and that effective planning can reduce total costs by 15-25% in the long term.

• Operational efficiency (OE = 0.20)

The weighting for operational efficiency is based on studies that show a direct correlation between high operational efficiency and the ability of companies to adopt sustainable environmental management practices. A study by Collins et al. (2020) concludes that companies with high operational efficiency are 30% more likely to adopt innovative environmental management practices.

• Environmental Impact (VI = 0.20)

The weight of the environmental impact criterion

reflects the increasing focus on environmental issues in decision-making processes. Guyondet et al. (2018) show that integrating environmental considerations into decision-making can reduce negative environmental impacts by 40-50%, while improving the long-term viability of a company.

• Seasonality mitigation (SM = 0.08)

The lowest, but still significant, weight is given to seasonality impacts. A study by Chan et al. (2019) on the impact of climate change on aquaculture in the Baltic Sea region shows that the impact of seasonal variations on business performance has increased by 15-20% over the last decade, highlighting the need for adaptation strategies.

The matrix in Table 2 provides an objective comparison of the relative importance of the criteria.

Table 2

Pairwise comparison matrix for algae cultivation and harvesting evaluation

Criteria	SI	OE	VI	SM
SI	1	3	3	5
OE	1/3	1	1	3
VI	1/3	1	1	3
SM	1/5	1/3	1/3	1

Source: Created by the author from (Dodevska et al., 2023).

The geometric mean for SI is 2.59, for OE and VI it is 1.00, and for SM it is 0.39.

Normalising these results, the following priority vectors were obtained: SI = 0.52, OE = 0.20, VI = 0.20, and SM = 0.08. The results indicate two important conclusions: (1) the SI criterion has the highest priority vector of 0.52, indicating its dominance in the overall evaluation; (2) OE and VI have the same priority vector of 0.20, ranking them second in terms of importance.

These results reflect the relative importance of the criteria in the decision-making process, with initial investment considered the most important factor, followed by operational efficiency and environmental impact on par. A consistency check (2) was carried out to check the consistency of the scores.

$$\lambda_max = 4.05 \quad (2)$$

$$CI = (\lambda_max - n) / (n - 1) = (4.05 - 4) / (4 - 1) = 0.02$$

$$CR = CI / RI = 0.02 / 0.9 = 0.02$$

where:

n is the number of criteria (4), and

RI is the random index (0.9 for four criteria).

In this case λ_max = 4.05 indicates that the matrix is close to perfect consistency (ideally λ_max would be equal to the matrix size, in this case (4)). This value is also used to calculate the consistency index (CI) and the consistency ratio (CR), which allow the reliability of pairwise comparisons to be assessed. A CR value of less than 0.1 confirms the consistency of the ratings.

At this stage, three main combinations of methods were evaluated by assigning weight coefficients based on the literature data. The analysis was based on the criteria defined above: SI, OE, VI and seasonality SM. In addition, codes were introduced for the method combinations.

1. The JM method offers several advantages in terms of nutrient use and environmental protection. Algae efficiently absorb nitrogen and phosphorus compounds from the water, reducing the risk of eutrophication (Duarte et al., 2017; Pechsiri et al., 2016). This process not only improves water quality, but also contributes to sustainable nutrient cycling in the marine ecosystem. Studies have shown that algae farming can significantly reduce nutrient pollution in coastal waters, absorbing up to 30% of total nitrogen and 33% of total phosphorus entering the ocean (World Bank, 2017). Mechanical harvesting allows precise control of the harvesting process, minimising the impact on the seabed and surrounding ecosystems (Stévant et al., 2017). This approach ensures more efficient use of resources while minimising potential damage to the marine environment. Furthermore, compared to other harvesting methods, mechanical harvesting can be particularly efficient in large-scale operations, which is essential given the increasing demand for algal biomass (Davis et al., 2016). Cultivation of algae offshore reduces competition with other marine resources in the coastal zone, reducing the overall ecological impact on fragile coastal ecosystems (Visch et al., 2020). This approach not only helps to protect coastal zones, but also opens up new opportunities for the use of marine space, potentially reducing pressure on congested coastal areas. In addition, offshore algae farming can create new habitat types for marine organisms, potentially increasing biodiversity (Hasselström et al., 2018).

2. The KM process improves nutrient utilisation as the algae are grown in a controlled environment close to shore, allowing the nitrogen and phosphorus compounds in the water to be absorbed efficiently. Manual harvesting ensures a precise and selective approach, minimising the impact on the environment. Hasselström et al. (2018) point out that this method is particularly suitable for smaller projects and can ensure a high quality end product. In addition, growing the algae close to shore provides better control over the growing conditions and reduces the impact on marine ecosystems. Kotta et al. (2022) emphasise that this approach provides better control over seasonal variations, which is an important factor in the changing climatic conditions of the Baltic Sea region.

3. The SM approach uses natural algal resources already growing in the sea, thus reducing the need for initial investment in cultivation infrastructure. Mechanical harvesting allows efficient harvesting of large amounts of biomass, as highlighted by Stévant et al. (2017).

However, as pointed out by Duarte et al. (2017), this method can have potentially negative impacts on marine ecosystems, as it can disrupt natural processes and biodiversity. In terms of nutrient use, this method can help reduce excess nutrients in the water, but it does not provide the same control over nutrient uptake as cultivation methods. Bleyl et al. (2013) highlight that this approach provides the least control over seasonal variations, which can affect the quality and quantity of biomass extracted depending on the season.

Each combination of methods was weighted according to each criterion on a 10-point scale (0-1, in steps of 0.1).

• Marine cultivation + mechanical harvesting (JM)

SI_JM (0.8): Visch et al. (2020) point to the high potential of marine cultivation in the Baltic Sea. Ren et al. (2020) highlight that larger scale systems reduce unit costs.

OE_JM (0.9): Stévant et al. (2017) highlight the advantages of mechanical harvesting in large-scale operations. Davis et al. (2016) suggest that larger systems improve operational efficiency.

VI_JM (0.85): A new study by Pechsiri et al. (2016) shows the positive impact of seaweed farming on reducing nutrient surpluses in the Baltic Sea.

SM_JM (0.7): Bleyl et al. (2013) show the effect of seasonal temperature variations on algal growth in the Baltic Sea.

• Coastal cultivation + manual harvesting (KM)

SI_KM (0.6): Campbell et al. (2019) point out that smaller systems require less initial investment.

OE_KM (0.7): Hasselström et al. (2018) highlight the suitability of this approach for smaller projects.

VI_KM (0.75): Weinberger et al. (2020) points out that there is a better control over environmental conditions near the coast.

SM_KM (0.8): Kotta et al. (2022) point out that there is a better control over seasonal variations near the coast.

• Wild harvesting + mechanical harvesting (SM)

SI_SM (0.5): Sharma et al. (2014) point out that this method requires less initial investment but provides less control.

OE_SM (0.6): Stévant et al. (2017) highlight the efficiency of mechanical harvesting.

VI_SM (0.65): Duarte et al. (2017) warns of potential negative impacts on marine ecosystems.

SM_SM (0.5): Bleyl et al. (2013) indicate that this method provides the least control over seasonal variations.

Using the pre-calculated criteria priorities and weighting factors, weighted scores were calculated for each combination of methods. This was done by multiplying the priority of each criterion by the weighting factor for that method and summing the results.

The weighted scores for the combinations of methods are as follows: JM received the highest score of 0.82, KM received a score of 0.72 and SM received the lowest score of 0.62.

Table 4

Impact on method combination scores of changes in criteria weights

Scenario	SI	OE	VI	SM	JM	KM	SM
Base scenario	0.52	0.20	0.20	0.08	0.82	0.72	0.62
Scenario 1: SI +10%, OE -10%	0.57	0.18	0.20	0.08	0.81	0.71	0.61
Scenario 2: VI +10%, SM +10%	0.52	0.20	0.22	0.09	0.83	0.73	0.62
Scenario 3: SI -10%, OE +10%	0.47	0.22	0.20	0.08	0.83	0.73	0.63

Source: author's calculations.

The results indicate that JM is the most effective method for the Baltic Sea region, providing an optimal balance between all the criteria assessed. It offers the best compromise between initial investment, operational efficiency, positive environmental impact and adaptability to seasonal changes. KM ranks second, while SM is the least efficient of the methods analysed. KM is the second best choice, especially in situations where mitigating seasonality is important. SM was the least effective method and could only be used in specific circumstances or as a complementary method to other approaches. The results are in line with the findings of Stévant et al. (2017) on the advantages of mechanical harvesting in large-scale operations. However, as in Duarte et al. (2017), potential ecological impacts need to be taken into account, especially for marine ecosystems.

In order to ensure the reliability and robustness of the results of the analysis, a sensitivity analysis was carried out. The aim of this analysis is to assess how changes in the weights of the criteria affect the overall scores for each combination of methods. This allows the sensitivity of the results to possible variations in the weights to be identified and provides additional confidence in the validity of the decisions taken.

Table 4 below summarises the results of the sensitivity analysis, showing the changes in the weights of the criteria and their impact on the scores of the combinations of methods in the different scenarios.

Based on the results of the sensitivity analysis presented in Table 4, the following qualitative conclusions can be drawn: (1) In all scenarios, the ranking of the method combinations remains unchanged, with JM as the best, KM as the second best and SM as the third best option. This stability reflects the robustness of the analysis results and increases the confidence in the initial assessment; (2) the changes in the rankings in all scenarios are relatively small (±0.02 points), indicating a low sensitivity to changes in the criteria weights within 10%. This confirms the reliability and robustness of the analysis results; (3) changes in SI and OE weights (scenarios 1 and 3) have a greater impact on the ratings than changes in VI and (SM) (scenario 2). This underlines the importance of SI and OE in the decision-making process; (4) JM shows the least variation across all scenarios, demonstrating the robustness of this methodology to changes in criteria weights. This provides additional confidence in the advantages of the JM method; (5) the robustness of the results gives decision makers confidence in the advantages of the JM method, even in the presence of small changes in priorities or weightings. This facilitates the development of long-term strategies and investment planning for the cultivation and harvesting of macroalgae in the Baltic Sea region.

Overall, the sensitivity analysis confirms the initial conclusions on the superiority of marine cultivation with mechanical harvesting (JM) and provides additional confidence in the reliability and applicability of the results for practical decision making.

Conclusions

1. The methods used in the Baltic Sea countries for growing and harvesting algae show considerable diversity, reflecting both geographical and climatic conditions and different approaches to the development of sustainable aquaculture. Denmark and Sweden use advanced techniques such as floating platforms and multitrophic systems, while Finland focuses on land-based tanks and experimental low salinity cultivation. In Latvia and Estonia, beach collection and manual harvesting dominate, while Germany and Lithuania are introducing innovative approaches such as micro-algae production and floating systems. These differences highlight the need for tailor-made strategies for each country to maximise the potential of the region.
2. The developed AHP methodology allowed an objective assessment of algae cultivation and harvesting methods based on four main criteria: initial investment, operational efficiency, environmental impact and seasonality mitigation. The results showed that initial investment was the most important criterion (0.52), followed by operational efficiency and environmental impact (0.20 each), while seasonality mitigation was the least important (0.08). This approach ensures a systematic and scientifically sound comparison of methods.
3. When comparing the three main combinations of methods, marine cultivation with mechanical harvesting (MC) was the most efficient method with a weighted score of 0.82, providing an optimal balance between economic and environmental factors. Coastal cultivation with manual harvesting (SC) ranked second with a score of 0.72, while wild harvesting with mechanical harvesting (WMU) was the least effective method with a score of 0.62. These results confirm the hypothesis of the study on the superiority of the JM method for the Baltic Sea region.
4. A sensitivity analysis confirmed the stability of the results, showing that even with ±10% variation in the weighting of the criteria, the JM method retains its superiority with the highest score. This analysis increases the reliability of the results and their applicability for practical decision making in the Baltic Sea region.

Future research could focus on analysing the long-term environmental impacts of large-scale projects, developing innovative technologies to improve operational efficiency and reduce environmental impacts, and developing strategies tailored to regional differences. Such research would contribute to the sustainable development of the bio-economy in the region and help address global environmental challenges.

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MILITARY TOURISM AS A MECHANISM FOR REVITALIZING DEOCCUPIED RURAL TERRITORIES OF UKRAINE

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Abstract
The article analyzes the current state, transformational processes, and development prospects of military tourism in Ukraine amid the full-scale war. Particular attention is paid to changes in the tourism industry in frontline regions that have suffered significant destruction due to hostilities and temporary occupation. Military tourism is considered a form of memorialization, a tool of public diplomacy, and a mechanism for local development. The study aims to identify the factors influencing the growth of military tourism, assess the readiness of local communities to host tourist groups, and examine the practices of tourism companies operating in de-occupied territories. Qualitative and quantitative research methods were applied: semi-structured interviews, regional sample observation, content analysis of open-ended responses, and statistical data analysis using IBM SPSS Statistics 21. The survey results of two respondent groups (local population and tourism business representatives) indicate the multifaceted perception of military tourism. On the one hand, it is associated with the opportunity to preserve the memory of wartime events, promote patriotic education, and stimulate economic revitalization. On the other hand, it raises concerns about the ethical boundaries of such activities, safety issues, and the privacy of those affected. The article also incorporates international experience and demonstrates how war-related tours shape a new interaction model between memory, business, and communities. Thus, military tourism in Ukraine is acquiring the features of an integrated socio-cultural practice that combines knowledge, empathy, commemoration, and economic support for affected communities.
Keywords: military tourism, revitalization, de-occupied territories, combat zone, post-war recovery.

Introduction

Russia's full-scale aggression against Ukraine has posed new challenges for the tourism industry, related to its recovery and functioning on qualitatively different foundations. The most significant transformations in the tourism sector have occurred in frontline regions that have suffered severe destruction due to hostilities and occupation. In this context, the study of international experience in restoring tourism potential, the analysis of views from representatives of the tourism industry in war-affected local communities, and the development of scientifically grounded and practically oriented recommendations for sustainable tourism development in these areas become especially relevant.

In their research, Umut Uzar and Mucahid Samet Yılmaz emphasize tourism's importance in global economic recovery. The study's results highlight the key role of political stability in a country and the spread of democracy and freedom of speech in increasing tourist numbers, particularly in low-income countries (Uzar & Yılmaz, 2025).

Adam Weaver argues that market forces determine how the military-industrial complex in the United States increasingly shapes the tourism industry. The business-oriented military structure, which has created a massive destructive potential, has significantly influenced the provision and nature of tourism. Examination of certain aspects of the tourism sector reveals, at times, a paradoxical yet ultimately profitable combination of pleasure-oriented consumption and the byproducts of the military economy (Weaver, 2011).

The article by K. Tomej, I. Bilynets, and O. Koval provides a brief overview of the resilience of the tourism business during wartime in Ukraine (Tomej et al., 2023).

An exciting approach to analyzing the present through the lens of the past is found in the publication by Alena Pfoser and Guzel Yusupova. Combining perspectives from memory studies and the geopolitics of tourism, the article highlights how memory is employed by the Russian Federation in constructing geopolitical relations, shaping its behavior toward both neighboring and distant countries (Pfoser & Yusupova, 2022).

Kristof Tomej and Iana Bilynets explore the complex changes in Ukraine's tourism system during the first year of Russia's full-scale military invasion. The study's results demonstrate how the Ukrainian tourism system transformed to survive, altering its structure and functions. New functions beyond recreation include humanitarian efforts, rehabilitation, community, and nation-building, thus establishing tourism's significant and unique contribution to the country's socio-ecological system (Tomej & Bilynets, 2024).

Military tourism draws foreign visitors to Ukraine at the height of the conflict. While some view it as a way to raise global awareness and build a profitable business that indirectly supports Ukraine's resistance, others criticize it as a form of morbid voyeurism that capitalizes on the suffering of Ukrainians (War Tourism in Ukraine, 2025).

The goal of this research is to explore the current state, transformational processes, and development

prospects of military tourism in Ukraine during the full-scale war, taking into account the impact of hostilities on the tourism sector in frontline regions, the perspectives of local communities, and the practices of tourism industry representatives. The study also builds on analyzing international experiences in shaping memory policies and restoring tourism in post-conflict zones.

This objective determines the following tasks:

1. Conduct a retrospective analysis of the development of military tourism in Ukraine before February 24, 2022, considering historical, patriotic, and regional tourism initiatives.
2. Evaluate the structural changes in the tourism industry of Ukraine's frontline areas following Russia's full-scale aggression, including new tourism functions, such as humanitarian, memorial, and rehabilitative roles.
3. Examine the attitudes of residents in affected regions toward the idea of organizing military tourism, their willingness to engage with tourist groups, and the moral-ethical boundaries of such activities.
4. Study the practical experience and vision of tourism business representatives specializing in military tours, including types of tours, target audiences, logistical and legal barriers, and marketing approaches.

Materials and Methods

As part of a comprehensive study examining the state and prospects of military tourism development in Ukraine, the research team employed a system of interrelated scientific methods that ensured an in-depth analysis of both quantitative and qualitative characteristics of this socio-cultural and economic phenomenon.

The assessment of the state of military tourism before 2022, as well as its evolution following the onset of Russia's full-scale invasion of Ukraine, was carried out using methods of analysis and synthesis through an analytical generalization of previous studies, reports, and empirical data. This approach enabled a retrospective analysis and tracked the transformational changes in this activity area.

Semi-structured interviews were used to survey respondents, combining closed and open-ended questions. This allowed for the collection of statistical data and captured the emotional and motivational components of respondents' answers, which are critically important.

The study sample was based on a purposive observation method (using a geographical-regional approach), which ensured the geographical relevance of the research and enabled generalizations that consider the territorial context.

Open-ended responses from respondents, particularly representatives of the tourism business, were processed using the qualitative content analysis method. This enabled the identification of core values, perceptions, concerns, and expectations related to the development of military tourism and the detection of emerging thought trends within the professional community.

The research team also investigated the activities of tourism companies organizing military tours and the prospects for military tourism development in Ukraine. Additionally, the study examined the opinions of local populations in settlements under occupation and/or active combat zones, which have become destinations for military tours.

- The study gathered opinions from two groups of respondents: residents living in Ukrainian settlements located in zones of active hostilities and/or under occupation, currently attracting the attention of tourism companies organizing military tours. The first group included 180 respondents from six regions of Ukraine: Kyiv region – 52 people (28.9%); Kharkiv region – 42 people (23.3%); Sumy region – 30 people (16.7%); Chernihiv region – 23 people (12.8%); Mykolaiv region – 18 people (10.0%); Kherson region – 15 people (8.3%).
- Owners, managers of tourism businesses, and representatives of civil society organizations involved in military-patriotic activities and operated in Ukraine's frontline regions. The second group consisted of 35 respondents from six regions of Ukraine: Kyiv region – 9 people (25.7%); Kharkiv region – 6 people (17.1%); Mykolaiv region – 4 people (11.4%); Kherson region – 2 people (5.7%); Zaporizhzhia region – 3 people (8.6%); Dnipropetrovsk region – 6 people (17.1%); Chernihiv region – 3 people (8.6%); Sumy region – 2 people (5.7%).
- Data collection was conducted from June 2024 to December 2024. The survey was conducted using the interview method, and the collected data were processed using IBM SPSS Statistics 21.

Results and Discussion

Before Russia's full-scale invasion, military tourism in Ukraine was at an early stage of development and lacked a systemic or mass character. The term 'military tourism' was rarely used officially – more common were terms such as 'military-historical tourism', 'patriotic tourism', and 'museum tourism'. The absence of a national policy, a register of relevant sites, safety regulations, or ethical standards hindered the development of this sector. It evolved as a niche, primarily regional tourism, targeting historical, patriotic, or educational audiences (Hladkyi & Hashimov). The main participants in such tours were schoolchildren, students, veterans of the Anti-Terrorist Operation (ATO), their families, military reenactors, and history enthusiasts. Foreign interest in military tours in Ukraine was limited but gradually grew among journalists, researchers, and members of the Ukrainian diaspora.

Between 1991 and 2022, the main sites of military tourism in Ukraine were places associated with World War II, the UPA (Ukrainian Insurgent Army) liberation struggle, and the Ukrainian Revolution of 1917–1921. Military equipment museums,

fortifications, battlefields, memorials, and mass graves were among the most visited locations. Examples include the National Museum of the History of Ukraine in the Second World War (Kyiv), the ʻSaur-Mohylaʼ Memorial, and defense lines in Volyn and the Carpathians (Tkachenko & Klymova, 2021).

Following the war in Donbas and the annexation of Crimea in 2014, a new subtype emerged – modern military-patriotic tourism. Travel companies began offering informational tours to frontline areas, including Mariupol, Avdiivka, Sloviansk, and meetings with ATO/JFO veterans. Some volunteer initiatives and organizations also arranged tours for foreigners to the contact line.

Given the extensive destruction and war crimes committed by the Russian armed forces in many Ukrainian cities, the development of any form of tourism must be considered through the lens of residents' willingness to host tourist groups. Not everyone wants their life and trauma turned into a tourist attraction. On abandoned homes, signs have appeared warning visitors not to enter or take photographs.

At the same time, the world must witness the crimes against humanity, the torture, and the atrocities committed by Russians on Ukrainian soil. Therefore, it is essential to show such sites to international visitors and compare such excursions to visits to Auschwitz.

Considering this aspect, we conducted a study with the first group of respondents, focusing on the attitudes of residents in Ukrainian territories affected by combat or occupation toward providing tourism services in settlements that have become symbolically significant for the Ukrainian people. The results of this study are presented in Table 1 and Figures 1 and 2.

Table 1

Attitudes of residents toward the idea of Military Tourism in Ukrainian settlements that were in zones of active hostilities and/or under occupation

Question	***Yes, %***	***No, %***
Do you support the idea of developing military tourism in your locality?	74	26
Are the residents of your locality ready to receive tourist groups in places where fighting or occupation occurred?	66	34
Do you consider it appropriate to compare visits to destroyed and affected cities with visits to Holocaust museums such as Auschwitz?	81	19
Are there places in your city/village that you would personally recommend for inclusion in a military tourism route?	96	4
Do you consider it morally acceptable for tourists to photograph and publish images of destroyed objects in your city/village?	63	37
Do you believe that tourist interest in war-affected cities and villages can help preserve the memory of the tragedies that occurred?	78	22
Should the state take into account the opinion of local residents when deciding to open tourist routes in affected communities?	95	5
Are you personally willing to share your story of living under occupation (or in a combat zone)?	69	31

Source: developed by the authors.

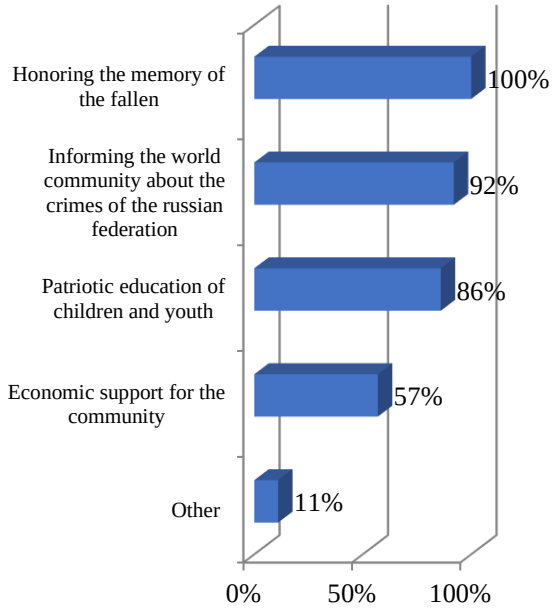
In response to the question ʻWhat, in your opinion, should be the purpose of military tourism in your region?' – to which multiple answers could be selected –the respondents' answers were distributed as follows: Honoring the memory of the fallen – 100 responses informing the international community about Russia's crimes – 92%; patriotic education of children and youth – 86%; economic support for the community – 57%; other – 11%, Figure 1.

Respondents were also allowed to select multiple options in response to the question ʻWhat conditions, in your opinion, must be strictly observed when organizing military tourism?', Figure 2.

As a result of the large-scale destruction caused by military operations, many rural communities in Ukraine are now facing the need not only for physical reconstruction but also for socio-economic renewal. In this context, military tourism is emerging as an effective mechanism of revitalization – a process of reinvigorating life in rural areas that experience occupation or were located in combat zones.

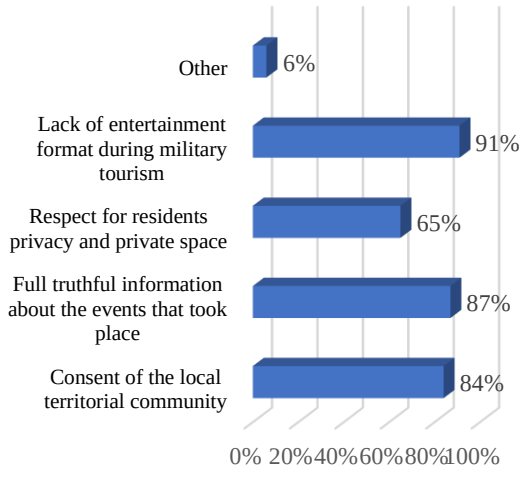
In practice, military tourism is already positively impacting local communities. By creating routes passing through war-affected villages and settlements, tourism traffic is increasing, demand for local services (such as food, lodging, guiding, and handicrafts) is rising, and investments are being attracted to restore infrastructure. For example, in communities across the Mykolaiv, Chernihiv, and Kherson regions, early cases have already been recorded where sites of tragedy are being transformed into centers of military tourism, which is combined with restoring the social environment.

Figure 1
The purpose of military tourism in Ukrainian settlements that were located in zones of active hostilities and /or occupation



Source: compiled by the authors.

Figure 2
Conditions required for organizing activities in residential areas that were located in zones of active hostilities and/or under occupation



Source: compiled by the authors.

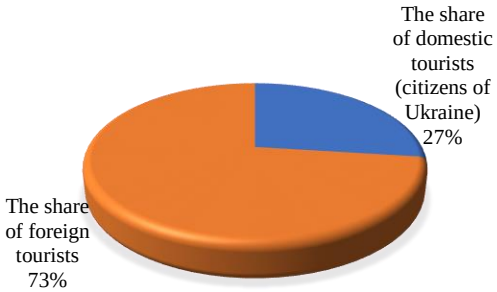
Beyond the economic impact, a crucial aspect is the psychological and social rehabilitation of the population through engagement in tourism activities. Residents increasingly act as guides, guesthouse hosts, consultants, or volunteers. In this way, a new local identity is formed, where people transition from being perceived as 'victims of war' to active agents of revitalization. These fosters restoring socialites, inner resilience, and motivation for further development.

Alongside the sociological survey of the first group of respondents (i.e., the population of areas affected by active hostilities or occupation), a study was also conducted among the second group of respondents representing the tourism industry and public authorities. They were asked eight questions, and the results are summarized below.

In response to the question 'What formats of military tourism does your tourism company implement or support?' (multiple answers allowed), the respondents answered as follows: excursions to sites of battles and occupation – 63%; visits to memorials and museums – 24%; guided expeditions with veterans – 72%; educational and patriotic tours – 32%; volunteer-tourism projects – 18%; other – 13%.

Regarding the question 'Which categories of tourists are most interested in military tourism in your experience?', it was found that domestic tourists (Ukrainian citizens) made up 27% of the total volume of military tourism. In comparison, the share of foreign tourists was significantly higher – 73%, Figure 3.

Figure 3
Categories of tourists interested in Military Tourism in Ukraine



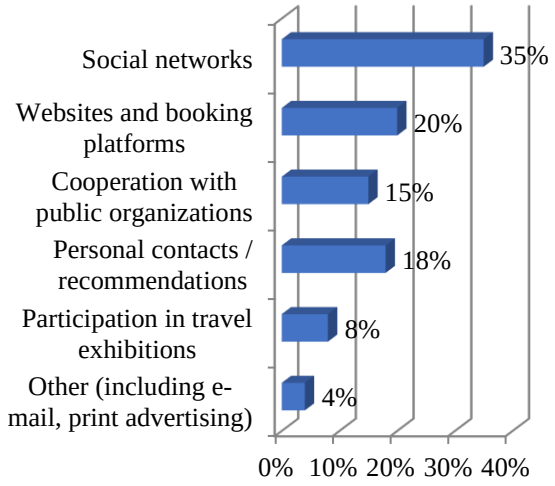
Source: compiled by the authors.

Domestic tourists included ordinary citizens, researchers, journalists, academics, veterans, family members, students, and schoolchildren. The foreign clientele of military tourism tours primarily consisted of politicians, journalists, researchers, military tourists, volunteers, civil society activists, and other interested individuals.

Tour prices start at $120 and typically range to $350, part of which tourism companies usually donate to support the Ukrainian army. The most expensive are 'Donor Tours' – their price reaches $2,000. This project combines traditional tourism with a humanitarian mission, organized with a local guide in southern Ukraine (Mykolaiv region). Participants are first given a tour of the city of Mykolaiv, followed by medical training sessions in the afternoon. The next day, local guides take them to the deoccupied territories of the region, where they distribute aid to medical facilities or children's centers, help animal shelters, or provide heating equipment and building

materials. The tour program is customized based on the preferences of the client.
This format is considered too radical for most military tourists, with only one or two monthly bookings. However, the company offers these tour (Visit Ukraine, 2025) plans to enhance its marketing efforts and collaborates with international organizations to attract more tourists and thereby contributes to the recovery of de-occupied territories. Figure 4 presents the list of marketing tools used by Ukrainian tourism companies in organizing military tours.

Figure 4
Marketing tools used by tourism companies to promote Military Tours (multiple answers allowed)



Source: compiled by the authors.

Table 2 lists the main challenges tourism companies face when organizing military tours.

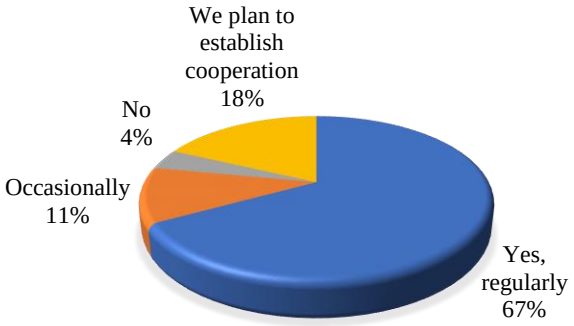
Table 2
Main challenges experienced by tourism companies in organizing Military Tours (multiple answers allowed)

Issue	Share of total responses, %
Security restrictions	100
Psychological sensitivity of the topic	96
Negative attitude from local residents	62
Legal or administrative barriers	49
Lack of infrastructure	71
Other	13

Source: compiled by the authors.

The authors also attempted to determine the widespread collaboration between tourism companies and military unit leadership, local self-government bodies, and regional military administrations. The results are shown in Figure 5.

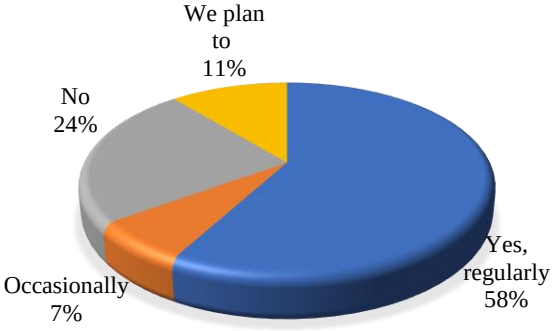
Figure 5
The level of cooperation between tourism companies and government bodies or military structures in organizing military tours



Source: compiled by the authors.

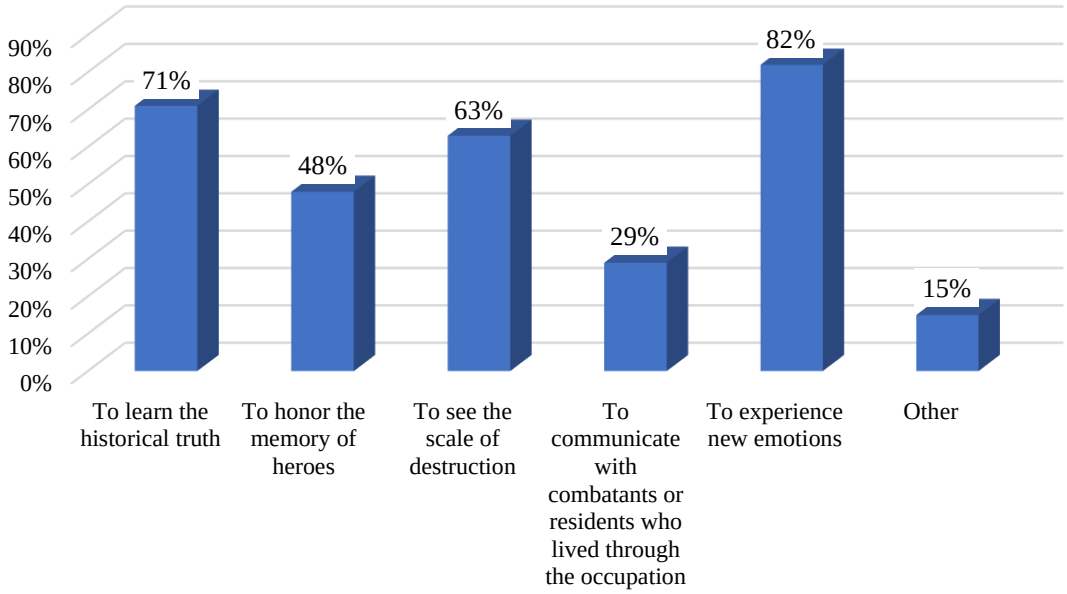
During the study, the research team found that Ukrainian tourism companies are working on developing new routes related to military tourism and are actively engaged in the search and training of guides for such tours. In this process, preference is given to veterans of the Russo-Ukrainian war, Figure 6.

Figure 6
Implementation of guide training activities for military tours by tourism companies



The final question concerned the purpose of purchasing a military tour and the quests or interests expressed by potential military tourists when contacting tourism companies (multiple answers allowed), Figure 7.
The data indicate a multifactorial motivation among tourists interested in military tours to Ukraine. Since respondents were allowed to select multiple answers, the results reflect not a single dominant motive but a broad spectrum of expectations shaping demand for military tourism.

Figure 7
Main expectations of tourists regarding military tours



Source: compiled by the authors.

The main drivers of interest in military tours include emotional engagement, the pursuit of knowledge, and the visual experience of war, which places a significant ethical responsibility on tourism companies. Military tourism is characterized by diverse motivations, ranging from humanitarian and memorial aspects to consumer-driven emotional experiences.

Organizers should consider the low level of readiness for direct interaction with victims, which requires a delicate approach to including elements of live communication in the tour program. The data confirm the relevance of developing educational, ethical, and interactive components within military tourism.

Conclusions

Russia's full-scale invasion of Ukraine is the largest continental war since World War II. The global community seeks to understand how a war of this nature could unfold in the 21st century. And, of course, they want to pay tribute to those who died and those who defended Ukraine. Military tourism in Ukraine serves as a form of shock therapy for those who may have forgotten that the war in Ukraine is still ongoing.

1. Military tourism in Ukraine remains a niche segment, primarily appealing to those interested in military history and those working in related fields, such as historians, ethnographers, and tour guides.

2. Before the full-scale war in 2022, military tourism in Ukraine was not institutionalized; lacked a systemic niche within the broader tourism industry, operated mainly through historical and volunteer initiatives, had no official status, methodology, or state regulation. However, recent events laid the foundation for a new model of tourism activity, emerging after 2022, and shaped by the experience of modern warfare, the patriotic demand of Ukrainian society, and growing international attention.

3. Given the increasing role of military tourism as a driver of local development, it is advisable to implement specialized national and regional support programs for tourism initiatives in de-occupied rural areas. Such support could include simplifying legal procedures, providing grants for tourism infrastructure development, training guides from among veterans and residents, and creating branded routes that integrate local histories into the national narrative of remembrance.

4. Thus, military tourism in Ukraine is gradually transforming from a tool of memorialization into a multi-purpose mechanism for sustainable development and revitalization of territories that experienced occupation and/or active hostilities. It is capable of harmonious combination of economic, social, and humanitarian objectives.

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THE IMPACT OF THE WAR ON FOREIGN TRADE IN UKRAINIAN AGRICULTURAL PRODUCTS WITH THE EU

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Abstract
Under modern conditions, studying the impact of the war on foreign economic operations is essential for understanding current challenges, adapting the agrarian sector to new realities and developing effective strategies to ensure the country's food security. In addition, the establishment of trade relations with EU plays a key role in ensuring the sustainable development of the industry and the integration of Ukraine into the global economy. The purpose of the study is to assess the impact of the war on the foreign trade of Ukrainian agricultural products and to determine the strategic guidelines for the development of trade relations with the EU. The article reveals the general state and changes in the dynamics of export-import operations of agricultural products under martial law. Based on the calculated forecast of the value of exported and imported products for the period until 2030, it is projected that there will be general economic growth and expansion of Ukraine's foreign economic activity, and the balance will remain positive, which is evidence of the excess of exports over imports and indicates an increase in the competitiveness of national goods on the international market. Strategic directions for the development of trade relations between Ukraine and the EU and the prospects for the import of agricultural products are considered, the volumes of which will largely depend on the domestic production and trade policy of Ukraine, which is influenced by factors of indirect action of the external environment.
Keywords: export, import, agricultural products, trade, impact of war.

Introduction

The war in Ukraine radically changed the structure and dynamics of international trade, especially in the agricultural sector. Ukraine is one of the world's largest exporters of cereals, oilseeds and other agricultural products, and the European Union is its key trading partner.

Export restrictions from Ukraine

Ukraine plays an important role in providing food to many countries of the world, and the war has threatened the stability of global markets. Restrictions on exports from Ukraine caused an increase in food prices, which was particularly felt by the countries of Africa, the Middle East and Asia.

The European Union has not only simplified the import of Ukrainian products, but also supports Ukrainian agricultural producers, which is of strategic importance for economic recovery.

Due to the blockade of Ukrainian ports on the Black Sea, trade has shifted to alternative routes: through Poland, Romania, Hungary and other EU countries. The 'Solidarity Roads' and the Danube Grain Corridor, which ensure the export of agricultural products, became important.

The EU provides Ukraine with duty-free access to its market, which is part of broader political support in war conditions, at the same time internal conflicts arise in the EU (for example, temporary bans on the import of Ukrainian grain by individual countries), which requires the search for compromise solutions.

Nechyporuk A., Kotova M. and Kochubei D. studied exports under martial law, in particular, considered alternative routes for the export of agricultural products from Ukraine via the Black Sea routes (through the revival of the Black Sea Grain Initiative and the creation of new routes with security guarantees for partner countries, including Turkey), land transport routes (due to the abolition of the ban on imports by Eastern European countries, the increase in the capacity of rail transport, the operation of dry ports on the border with Poland and Romania), ports of the Danube region (due to the increase in the capacity of Danube ports through investments in infrastructure and the creation of new logical routes to Croatian ports) (Nechyporuk et al., 2023).

Motorniuk I. U. and Yaremchuk T. S. considered the issue of restoring Ukrainian exports under martial law through the introduction of new effective mechanisms to encourage export promotion, harmonization of certification with EU standards, development of logistics infrastructure, expansion of export services and attraction of investments (Motorniuk & Yaremchuk, 2022).

Scientists Rose A., Zhenhua C. and Dan W. studied the macroeconomic consequences caused by disruptions in grain exports as a result of the Russian-Ukrainian war. Using the multi-regional model of CGE GTAP, the authors state that this event creates significant cascading economic consequences in both sectors and regions of the world (Rose et al., 2023).

Ay H. M. and Söylemez A., for his part, emphasizes that Turkey's balanced foreign policy since the first days of the war and the emphasis that it can take on the mission of mediator between the parties has brought success in the grain corridor (Ay & Söylemez, 2023).

So, after analysing scientific works, it can be argued that foreign trade is one of the main factors of the country's economic development.

Export achievements of Ukraine and forecast of the rules of the game on the EU market

In 2024, Ukraine demonstrated an increase in exports and imports of agri-food products, but it is already necessary to take all measures to maintain preferential trade conditions after June 5, 2025.

The share of agricultural products in the country's total exports was 60%, which, although slightly less than

the record figure of 2023 (62%), is still the second-best result in the history of independent Ukraine.

One of the key features of 2024 was the simultaneous growth of exports and imports of agricultural products. According to the State Customs Service of Ukraine, the total volume of foreign trade in agricultural products in 2024 amounted to 32.66 billion dollars USA, which is 11.5% more than in 2023.

Exports increased by 12.1%, reaching 24.84 billion USA. Imports increased by 9.7% and amounted to 7.82 billion USA. For the first time during the full-scale war, Ukraine managed to increase the volume of agricultural exports, largely due to the stable operation of the controlled sea corridor, through which about 60 million tons of agricultural goods were shipped.

However, in 2025, difficulties in foreign trade are expected due to possible changes in the terms of preferential trade with the EU.

Technical negotiations are ongoing in the European Union on new trading conditions for Ukraine, as the European Commission does not plan to extend the current preferential regime after June 5, 2025.

One of the options is to deepen cooperation within the Deep and Comprehensive Free Trade Area (DCFTA), which may provide for the establishment of quotas for certain categories of agricultural products and additional regulatory mechanisms. This will contribute to the gradual integration of Ukraine into the EU single market. European Commissioner for Agriculture Christophe Hansen noted that most agriculture ministers in EU countries support a more stable agreement within the DCFTA, which will provide for new volumes of exports and imports, instead of extending the current preferential regime.

The products of the agro-industrial complex are the basis of Ukrainian exports, so in conditions of instability associated with martial law, blockade of the sea, suspension of the Black Sea Grain Initiative, it is important to search for alternative ways of export implementation, using all possible types of transport and logistics supply chains.

The study of the impact of the war on export-import operations between Ukraine and the EU is extremely important for assessing the economic, political and social consequences, as well as for developing effective strategies for supporting and restoring Ukraine's agricultural sector.

The purpose of the study is to assess the impact of the war on the export and import of agricultural products and to determine strategic guidelines for the development of trade relations with EU countries.

The objectives of the study are:

1. To disclose the general state and changes in the dynamics of export-import operations of agricultural products, as well as to determine the impact of the war on the export and import of agricultural products with EU countries.
2. To forecast the cost of exported and imported agricultural products by Ukraine for the period up to 2030.
3. To determine the directions of support for exporters of agricultural products for their development in the future, as well as the prospects for importing products, considering the volume of production of such products in Ukraine.

Materials and Methods

The information base of the study is data from the European Commission, the Ministry of Agrarian Policy and Food of Ukraine (Minagro, 2025), State Statistics Service of Ukraine (State Statistics Service of Ukraine, 2025), and the Office for Entrepreneurship and Export Development.

To understand the problems and prospects for the development of export-import operations with the EU countries, a forecast of the value of exported and imported agricultural products by Ukraine for the period up to 2030 was made using MS Excel.

Before the forecasting procedure, the time series data for 2021-2024 were evaluated for structural integrity, volatility, and fulness. A seasonality analysis performed using the Excel auto-detection tool confirmed the presence of an annual additional seasonality typical of agricultural trade cycles. The missing values were populated using linear interpolation. The ETS (AAA) algorithm was chosen because of its suitability for short, variable data sets, especially in post-war economic conditions. The forecast was developed in MS Excel on the basis of official statistics of the State Statistics Service of Ukraine, as well as data from the European Commission, the Ministry of Agrarian Policy and Food of Ukraine, and the Office of Entrepreneurship and Export Development. The FORECAST.ETS function was used to predict the value of exports and imports of agricultural products from the EU until 2030. This method uses exponential smoothing with automatic determination of seasonality, a 95% confidence interval, and averaging for repeating values. The results reflect the most likely scenario of development, indicating a constant increase in trade volumes and indicating the economic recovery and expansion of Ukraine's foreign economic activity.

Results and Discussion

The factors that significantly influenced the volumes and directions of international trade in Ukraine during the war include the introduction of unilateral trade preferences by the EU in 2022, as well as the signing of a grain agreement and the creation of a Ukrainian maritime corridor after its termination.

In 2014, Ukraine and the European Union signed an Association Agreement, which led to the creation of a Complete and Comprehensive Free Trade Area, which contributed to the strengthening of trade ties between Ukraine and the EU (Center for Economic Strategy, 2024).

However, until June 2022, tariff quotas for agricultural products continued to apply. In June 2022, the EU implemented an unprecedented decision – temporarily

lifting restrictions on Ukrainian goods to support Ukraine's economy during the war. This made it possible to significantly increase the export of Ukrainian goods, mainly agricultural products, to the EU. In the process of European integration, Ukraine is actively adapting its legislation to the norms and standards of the European Union, which is an important step towards EU membership. Particular attention is paid to the agricultural sector, regulation of product quality, protection of producers' rights and improvement of state control in the field of food safety (Table 1).

Table 1
Legislative steps adopted in Ukraine in 2022 related to EU integration in the agricultural sector

Months of 2022	Characteristic
September	The Law of Ukraine dated 06.09.2022 was published. No. 2572-IX 'On the peculiarities of the legal protection of geographical indications for agricultural products and food products, the protection of rights and the application of quality schemes, including traditional guaranteed features for agricultural products and food products'
October	The draft law 'On the Association of Agricultural Producers' was registered (No. 8149 dated 24.10.2022)
November	The Law of Ukraine 'On Materials and Items Intended for Contact with Food Products' (No. 2718-IX dated 03.11.2022) was signed and published; The Law of Ukraine 'On Amendments to Certain Legislative Acts of Ukraine Regarding the Bringing of Legislation in the Field of Protection of Rights to Plant Varieties and Seed and Breeding in line with the Provisions of the Legislation of the European Union' was signed and published (No. 2763-IX dated 16.11.2022)
December	The draft Law of Ukraine No. 4558 'On Amendments to Certain Laws of Ukraine Regarding the Improvement of State Regulation in the Field of Pesticide and Agrochemical Handling' (No. 4558 dated December 30, 2020) was submitted to the President of Ukraine for signature; The draft Law of Ukraine 'On Geographical Indications of Alcoholic Beverages' (No. 2800-IX dated December 1, 2022) was submitted to be signed by the President of Ukraine; Adopted as a basis the Law of Ukraine No. 5840 dated 05.08.2021 'On Amendments to the Code of Ukraine on Administrative Offences to Strengthen Responsibility in the Field of Handling Genetically Modified Organisms'

Such steps not only contribute to the development of the domestic market and increase the competitiveness of Ukrainian products but also strengthen Ukraine's position as a reliable partner in the international arena. The biggest problem for all subjects of the agrarian sector under martial law was the complication of logistics at each stage of the chain. Since the beginning of the full-scale invasion, the volume of exports of agricultural products of Ukraine has shown gradual growth, which indicates the adaptation of logistics routes and effective coordination of actions of the government and international partners. If in March 2022, only 331.6 thousand tons were exported, then in September and October the indicator reached 6.87 million tons. In general, during the period there was a constant increase in export volumes, with the exception of November, where a slight decrease (up to 5.91 million tons) was recorded, which may be due to seasonal or logistical factors. Efforts to open new routes, the implementation of the grain initiative and international support have become key factors in stabilizing and activating exports (Table 2).

Table 2
Agrologistics since the beginning of a full-scale invasion

Months of 2022	Export, tons	Characteristics
March	331557	Negotiations between Turkey and Ukraine on uninterrupted supplies of agricultural products to traditional export-dependent markets
April	968316	The European Commission announced the abolition of duties and quotas for Ukrainian exports for the year; The Coordinating Council on Logistics in Agriculture was created, headed by the Minister of Agrarian Policy and Food of Ukraine (Resolution of the Cabinet of Ministers of Ukraine No. 427 of April 9, 2022)
May	1742621	Ukraine and Poland signed a joint statement on the export of Ukrainian grain; The work of EU leaders on the creation of green corridors; Ukraine's negotiations on the establishment of the Organization of Grain Exporting Countries; Agreement on the diversion of goods that went through Ukrainian ports to the sea terminals in Gdansk and Constanta

June	2168434	Launch by the European Commission of a platform to optimize the export of Ukrainian grain – Grainlane; Consideration by EU governments of the possibility of providing Ukraine with temporary storage facilities for grain; The Verkhovna Rada of Ukraine ratified the Agreement on the abolition of duties and quotas in trade with the United Kingdom (The Verkhovna Rada of Ukraine, 2025)
July	2751656	Construction of more than 20 transshipment companies in areas where new logistics routes were built – Poland, Romania, Hungary, Slovakia; The passage for vessels transporting agricultural products through the channel of the mouth of the Bystre was restored; Signing of a grain agreement between Turkey, the UN and Ukraine
August	4563043	During the full-scale war, the first ship with 26 thousand tons of corn left the port of Odesa
September	6867997	During the month of operation of the grain corridor, Ukraine shipped more than 60 thousand tons of wheat as part of the WFP; Between the UN, Ukraine and Poland agreed to build an oil duct to Gdansk
October	6867997	Ukraine simplified the procedure for grain fumigation for export
November	5910039	The grain corridor was extended for 120 days. The EU allocated up to 1 billion euros for the 'Ways of Solidarity' (European Commission, 2024a). Ukraine launched the program 'Grain from Ukraine'

In order to alleviate the logistical difficulties faced by domestic producers and exporters after Russia's unjustified military aggression, in May 2022 the EU agreed to suspend import duties, quotas and trade protection measures for Ukrainian exports to the EU – 'autonomous trade measures' (ATM).

Due to the emergence of logistical difficulties in Bulgaria, Hungary, Poland, Romania and Slovakia caused by wheat, corn, rapeseed and sunflower seeds originating from Ukraine, exceptional and preventive measures for their import began on a temporary basis on May 2, 2023. In 5 countries bordering Ukraine, there were no more market distortions, so these precautionary measures expired on September 15, 2023. Nevertheless, Ukraine agreed to introduce effective measures to control the export of four groups of goods from September 16 to prevent market distortions in neighboring member states.

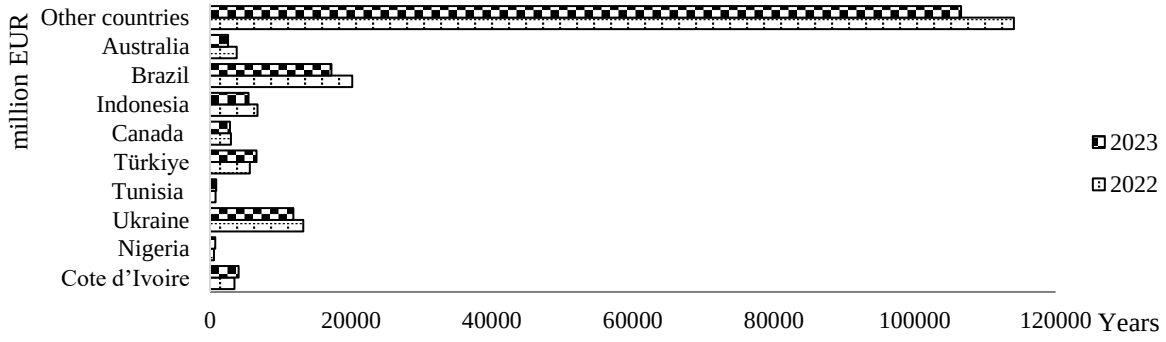
On June 6, 2024, the European Union introduced updated autonomous trade measures for trade with Ukraine, under which all duties and quotas for Ukrainian exports to the European market were suspended for another year. At the same time, the updated ATZs contain preventive restrictive measures to protect the European market, which can be applied to products such as chicken eggs, chicken, sugar, oats, corn, cereals and honey. Fuses were automatically applied if the volume of imports of these goods reached the average annual volume of imports from Ukraine to the EU in the period from July 1, 2021, to December 31, 2023.

Ukraine continues to be among the three most influential exporters of agricultural products to the EU countries, while Ukraine accounts for 8% of the total agricultural imports of the European Union (Ukrinform, 2024).

The EU is reducing imports from some traditional suppliers, such as Brazil, Indonesia and Australia, instead increasing imports from African countries (Nigeria, Cote d'Ivoire, Tunisia) and Turkey Ukraine retains an important role in the supply of agricultural products, although its volumes decreased slightly in 2023, Figure 1 (European Commission, 2024b).

Figure 1

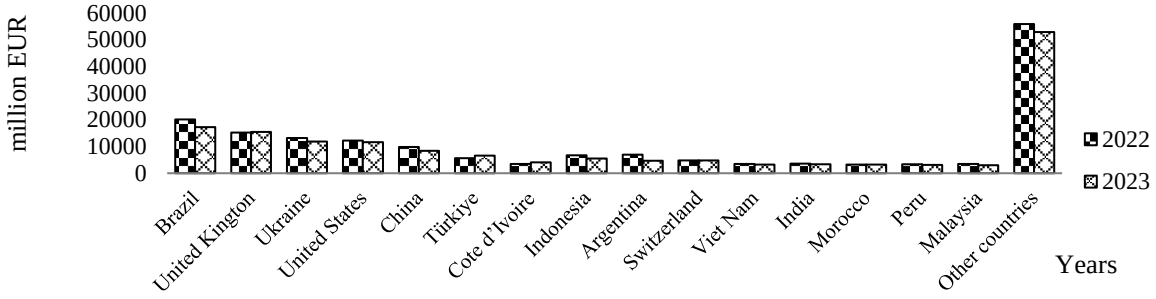
Import of EU agri-food products - countries with the most important changes in 2022-2023 (million euros)



In 2023, the import of EU agri-food products decreased compared to 2022, as evidenced by the reduction in the indicators of most countries such as Brazil, Indonesia, Australia, while there was an increase in imports from some countries (Nigeria, Ivory Coast, Tunisia, Turkey). Ukraine is characterized by a slight decrease in imports

from 13.214 million euros (2022) to 11.816 million euros (2023), but the country is still a key partner of the EU. In terms of the absolute volume of agricultural exports to the EU, in the period from January to August 2024, Ukraine was second only to Brazil and Great Britain and was ahead of countries such as the USA, China and Turkey, Figure 2.

Figure 2
Import of EU agri-food products (total rating) in 2022-2023



This trend indicates the stability of global agricultural markets and the growing importance of Ukraine as a supplier of agricultural products. Table 3 shows changes in EU agri-food imports for January-August 2023 and January-August 2024.

Table 3
Imports of EU agri-food products - countries with the most important changes (million euros) (January-August 2023, January-August 2024)

Trading Partners	Jan 2023-Aug 2023	Jan 2024-Aug 2024	Difference	
Total agri-food	107907	111009	3102	3%
Cote d'Ivoire	2733	4166	1433	52%
Nigeria	468	1144	676	144%
Ukraine	7964	8583	619	8%
Tunisia	539	998	459	85%
Türkiye	4163	4598	435	10%
Canada	1973	1556	-417	-21%
Indonesia	3831	3048	-783	-20%
Brazil	11901	11307	-594	-5%
Australia	2070	1349	-721	-35%
Other countries	72265	74260	1995	3%

Thus, total imports increased by 3% (+3.1 billion euros), while the largest growth was shown by Nigeria (+144%), Ivory Coast (+52%) and Tunisia (+85%). Ukraine increased exports by 8% (+619 million euros), confirming its important role in the EU's food security. There was a decrease in imports from Australia (-35%), Indonesia (-20%), Canada (-21%) and Brazil (-5%). In general, the EU agri-food import market demonstrated growth dynamics of supplies from key partners, in particular Ukraine. In January 2024, the European Commission recommended extending autonomous trade preferences for Ukraine from June 2024 to June 2025. However, the new project also included a clause on 'automatic precautions' (restoration of tariff quotas) for Ukrainian goods that could significantly affect EU markets. The final list of goods covered by these measures included poultry, eggs, sugar, oats, corn, cereals and honey. In 2023, these goods accounted for 16.6% of the value of Ukrainian exports to the EU, of which 14.1% was corn. With the exception of the latter, the precautionary measures do not apply to other key items of Ukrainian exports to the EU, in particular, sunflower oil and wheat, which in 2023 accounted for 7.7% and 5.2% of the total value of Ukrainian exports to the EU, respectively. The main European partners for Ukraine in 2024 were Spain, Poland, the Netherlands, Germany, Italy, Romania, France and Belgium. These countries accounted for 80% of the total domestic trade turnover of agri-food with the European Union.

In the value of food imports from the EU countries, 61% were the following product groups:

beverages – for 484 million dollars USA; tobacco products – for 385 million dollars USA; products for animal feeding, residues and waste – for 356 million dollars USA; cocoa and chocolate products – for 289 million dollars USA; dairy products – 277 million dollars USA (8% more than in 2023). In particular, the import of cheeses amounted to 225 million dollars USA; ready-made products from grain – 258 million dollars USA. As for the export of organic agricultural products to the EU, according to the report of the

European Commission, Ukraine retains its place among the five largest suppliers, occupying the fifth position among 125 countries. Ukraine has consistently maintained its place in the TOP-5 since 2018, which indicates a high level of exports of organic products to the EU. The total volume of imports of Ukrainian organic products to the EU in 2023 was 173,720 tons, which is 20.7% less than in 2022, when the volume of imports amounted to 219,125 tons (Table 4). The dynamics of foreign trade depends on macroeconomic factors, in particular global crises, changes in the geopolitical situation, trade restrictions and internal economic reforms (Sirenko et al., 2024).

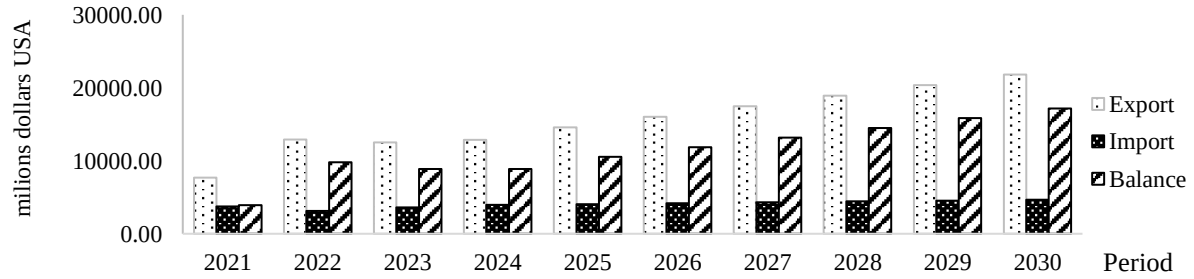
Table 4
Export of organic products by country of export

Exporting country	Years		Change (%)
	2022	2023	
Ecuador	345522	359554	4.1
China	194101	200170	3.1
Dominican Republic	251378	191788	-23.7
Peru	197297	182270	-7.6
Ukraine	219125	173720	-20.7
Turkey	104041	150012	44.2
Colombia	120875	120189	-0.6
Togo	125619	104068	-17.2
India	139243	68109	-51.1
United Kingdom	52917	56471	6.7

A comparative analysis with the dynamics of trade in other countries of Eastern Europe (e.g., Poland, Romania) shows that while the economies of these countries experienced structural failures, the export of agricultural products of Ukraine demonstrated comparatively greater adaptability, mainly due to EU solidarity measures and rapid logistics restructuring. The results of the forecast of the cost of exported and imported agricultural products by Ukraine with EU countries for the period up to 2030, see Figure 3, coincide with the forecasts obtained in other empirical studies (e.g., Rose et al., 2023), which suggests that countries that have access to diversified trade corridors and regional agreements will see a faster recovery of export opportunities for agri-food products. These results also confirm the conclusions of Motorniuk and Yaremchuk (2022) regarding the effectiveness of harmonization of certification and investment in logistics as key factors in restoring exports under martial law.

Thus, to ensure the sustainable development of the economy, it is necessary to comprehensively improve trade policy, in particular in terms of stimulating exports and reducing critical dependence on imports.

Figure 3
Actual data (2021-2024) and forecast values (2025-2030) of the value of exports, imports and trade balance of Ukraine



The analysis of actual and forecasted data indicates a stable growth in Ukraine's foreign economic activity in the period up to 2030. The volume of exports increased from 7674.0 million dollars USA in 2021 to 12906.6 million dollars USA in 2022, which is associated with the gradual overcoming of logistical barriers caused by the war and, according to forecasts, will reach 21835.25 million dollars USA in 2030. Imports show moderate growth – from 3,764.1 million dollars USA in 2021 to the projected 4675.39 million dollars USA in 2030. The positive balance of foreign trade for this period will increase from 3909.9 million dollars USS to 17159.86 million dollars USA, which indicates an increase in export potential and a general economic recovery of the country. In order to improve the trade balance, it is advisable to stimulate export activities, reduce dependence on imports and develop our own production of competitive goods. In

order to promote exports to foreign markets, the Office for Entrepreneurship and Export Development provides entrepreneurs and exporters with assistance in establishing partnership and cooperation between domestic and foreign business, promoting domestic goods and services in the external market environment, and developing export competencies of domestic business. The strategic directions for the development of Ukraine's trade relations with the EU include the following factors: deeper integration into the European market (expansion of the Association Agreement); development of logistics infrastructure (modernisation of transport corridors, customs procedures and border infrastructure to facilitate trade); diversification of the export structure by reducing dependence on raw material exports by supporting the production of goods with high added value, in particular in the field of processing agricultural products; support for small and medium-sized business programs and digitisation of trade, as well as adapting the Ukrainian economy to EU environmental standards. The prospects for the import of agricultural sector products in Ukraine largely depend on domestic production and trade policy of Ukraine. Taking into account the production volumes of domestic agricultural products, several key trends and challenges can be identified:

- dependence on domestic production and demand (import of fruits, vegetables, meat and dairy products increases due to insufficient level of own production or seasonal factors);
- the impact of external factors on imports (logistical restrictions caused by the war lead to an increase in the price of imported products);
- currency fluctuations and economic instability may restrain imports due to an increase in the cost of production (changes in the customs policy of the EU and other partners after 2025 may affect the conditions of food imports);
- competition between imported and domestic products (producers in Ukraine are trying to replace imports by expanding domestic capacities; however, the import of exotic products remains stable due to the impossible or economically disadvantageous production in Ukraine).

Conclusions

In the context of a full-scale war, Ukraine continues to be among the three most influential exporters of agricultural products to the EU countries, while Ukraine accounts for 8% of the total agricultural imports of the European Union.

The gradual integration of Ukraine into the EU single market will be facilitated by deepening cooperation within the Deep and Comprehensive Free Trade Area (DCFTA), which may include the establishment of quotas for certain categories of agricultural products and additional regulatory mechanisms.

The study conducted by the authors allows us to draw the following conclusions:

1. The overall state and dynamics of export-import operations of agricultural products by domestic agricultural commodity producers underwent changes in the conditions of a full-scale invasion, which manifested itself in a reduction in export volumes in 2023 compared to 2022. The EU took an important step in overcoming logistical difficulties by introducing 'ATM' in May 2022.
2. According to the results of the forecasting of the value of exported and imported agricultural products by Ukraine with the EU countries for the period up to 2030, it was established that the value of both exports and imports will increase significantly, which indicates the overall economic growth and expansion of Ukraine's foreign economic activity. The balance of foreign trade will remain positive throughout the period, which is evidence of the excess of exports over imports and indicates the competitiveness of national goods on the international market.
3. The strategic directions of development of trade relations between Ukraine and the EU include: deeper integration into the European market, development of logistics infrastructure, diversification of the export structure, support for small and medium-sized business programs and digitisation of trade, as well as adaptation of the Ukrainian economy to EU environmental standards. The prospects for the import of agricultural sector products in Ukraine largely depend on the domestic production and trade policy of Ukraine, which are influenced by the factors of indirect action of the external environment.

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POTENTIAL IMPACTS ON NATURE CONSERVATION AND TOURISM FROM THE BORDER BARRIER IN THE BIALOWIEZA FOREST

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Abstract
The aim of this study is to determine the potential effects of migration restrictions at the Polish Belarusian border on the objects of protection residing in protected areas and the nature tourism implemented on their basis. The migration restrictions discussed in the paper include the border barrier and the prohibition of temporary stay in border areas. The key rationale for undertaking this analysis are the specific legal conditions under which the border barrier was created, which exclude standard impact assessment procedures for projects that may have a significant impact on the wider environment, and thus the unrecognised potential impacts of its creation and operation. The specific legal and factual conditions resulting from the course of the border barrier through naturally valuable areas, including those under nature protection, and at the same time constituting the state and EU border - subjected especially in recent years to migratory pressure - force increased activity of services, which puts pressure on natural resources. On the other hand, the introduced temporary bans on staying in the border area have the effect of minimising the movement of other people, including tourists. The authors of the study aimed to identify the effects of the introduced migration restrictions on the natural resources (values) and, consequently, on the tourism carried out on their basis. The identified effects were arranged according to the problem tree technique, from the direct effects on people and animals to the more far-reaching, indirect consequences.
Keywords: border barrier, EU border, migration, nature tourism.

Introduction

A prerequisite for the proper functioning of animal populations, especially those with high individual mobility, is the presence of their preferred habitats and the ability to migrate between refuges. Migration is also a prerequisite for effective nature tourism, based on the values of the environment explored in the modes of migration, often carried out in the areas of nature protection, such as national parks. However, migration does not only have a naturalistic form – there is an increasingly emphasized need to decrease the value of migration in connection with the threat posed by politically and economically motivated - migratory movements of people between the borders of countries and their unions. The implementation of migration barriers for people, both physical and organizational, result in difficulties in natural migration. This applies to both animal migration, desirable due to the need for sustainability and stability of ecosystems, and human migration - aimed at learning about natural values and constructing environmental awareness. Restricted natural migration can become both a destabilizing factor for migratory animal populations and a general factor degrading natural resources and values. Thus, in view of the need for human migration barriers, limiting their negative effects on the environment becomes a key challenge. Although the achievement of environmental and political goals (in terms of internal security) seems to collide - the needs in this realm should determine adequate actions. In turn, these actions, should result from an assessment of the effects of the introduced changes, to the extent its possible, based on the environmental principle of foresight and precaution.

Materials and Methods

The aim of the study is to indicate the direction and mechanism of potential impact of human migration restrictions introduced on the Polish-Belarusian border (border barrier and prohibition of temporary stay in border areas) – on the protected species: The European bison (*Bison bonasus)*, wolf (*Canis lupus)*, and lynx (*Lynx lynx)*, and, thus on the potential for nature tourism associated with the presence of these animals in the restricted area.

The key rationale for undertaking this analysis are the specific legal conditions for the creation of the border barrier, which exclude standard environmental impact assessment procedures, and thus the unrecognized potential effects of its creation and operation. The border barrier in question runs through naturally valuable areas, including those under nature protection and at the same time constituting the state and EU border - subjected to migration pressure, which forces increased activity of state services, which puts pressure on natural resources. On the other hand, the introduced temporary bans on staying in the border area may result in minimizing the movement of other people, including tourist traffic, both due to actual restrictions and psychological barriers.

The authors of the paper, for the purposes of this article, understand the concept of nature tourism as tourism aimed at learning about the natural values of areas covered by various forms of nature protection. In particular, the paper pays attention to faunal tourism aimed at animal species under species protection, implemented within the boundaries of the Bialowieza National Park. These animals have a significant impact on the natural values of the area and thus shape its touristic attractiveness.

Based on the available data and literature on the subjects of the study, the potential effects of migration restrictions introduced on the Polish – Belarusian border were identified. The identified effects of the environmental problem, which undoubtedly is the introduction of technical and organizational migration

restrictions along the Polish – Belarusian border, were arranged according to the criterion of mechanism and scope into direct and indirect effects, considering the causal relationships existing between them (corresponding to the problem tree analysis).

The study developed a theoretical model with a cascade structure of the potential effects of the introduction of physical (technical) and organizational migration restrictions on the Polish – Belarusian border, which allowed for a systematic presentation of the mechanisms of the impact of migration barriers on ecosystems and related socio-economic aspects. The developed model presents a system of cause-and-effect connections resulting from the introduction of migration restrictions. The main elements of the model include feedback (health and population, economic and ecological) that amplify the negative consequences for the ecosystem and local communities.

For the quantitative data presented in Tables 1 and 2 we performed linear regression (ordinary least squares) to assess long-term trends. Abundance of European bison, lynx and wolf (years 2000–2023) and numbers of tourists in Polish national parks, including Bialowieza NP, for the years 2019–2023, were regressed on calendar year. For each species/series we report the slope (annual change), coefficient of determination (R^2) and p-value testing H_0: slope = 0. Analyses were carried out in Python (SciPy) at significance level $\alpha = 0.05$.

Given the theoretical nature of this study and its explicit aim to construct a conceptual cascade model of impacts on European bison, wolf, lynx and nature tourism, no advanced inferential statistics beyond trend analysis were applied; regression served to illustrate the direction and strength of observed changes. Instead, model construction relied on qualitative synthesis of literature, problem-tree analysis and expert findings (IOŚ-PIB 2024), ensuring a systematic mapping of cause–effect relationships in line with the study objectives.

To build the model, a hierarchical ordering of causes and effects was made, indicating the resulting relationships. The main initiating factor (root cause) that leads to the first level of consequences was identified. Then, the subsequent consequences generated by the first level of effects were identified, creating a logical sequence of relationships. The model uses dependency flowcharts to visualize the flow of information and the impact of changes on subsequent levels of the system (Sterman, 2000). Feedback was also included in the developed model (their reinforcing nature leading to self-reinforcing effects was indicated (Meadows, 2008). In practice, cascade models are used in systems analysis, ecology, economics and crisis management, where it is necessary to predict the effects of changes in each ecosystem or social structure (Epstein, 2006).

The identified potential effects of the analysed problem were verified by the results of the first signalling research on the actual impact of the border barrier on natural resources, two years after its creation presented in the expert opinion titled *'Oddziaływanie zapory granicznej na granicy polsko-białoruskiej na Obiekt Światowego Dziedzictwa 'Białowieża Forest' - Ssaki i rośliny inwazyjne'* (Schmidt et al., 2025).

Legal conditions of migration restrictions on the Polish – Belarusian border

The border barrier, which purpose is to secure the state border (which is also the external border of the EU), also against illegal crossing, was established under the provisions of the Law of October 29, 2021, on the construction of state border security. According to Article 6 (1) of this law, separate regulations, including, among others, the Law of April 27, 2001, do not apply to the investment *(Environmental Protection Law and the provisions of the Act of October 3, 2008, on providing information on the environment and its protection, public participation in environmental protection and environmental impact assessments)*. Information on the construction, safeguards and technical parameters of the barrier is not public and is not subject to release under separate regulations (Article 7). This means that an assessment of the project's impact on the environment was not conducted during the implementation of the barrier. However, the unique legal conditions for the implementation of the barrier do not result in the abolition or reduction of the general principles of nature protection under the Law of April 16, 2004, on Nature Protection. The goals, principles and forms of nature protection still apply - with the understanding that achieving these goals may be difficult and may require modifying the way they will be achieved.

In addition to the technical border barrier, migration restrictions include a temporary ban on staying in the border zone, which is imposed periodically based on the authorization set forth in Article 12a of Law on State Border Protection of October 12th, 1990. According to this provision, in the event of a need to ensure security or public order in the border area in connection with a threat to human life or health, or property, resulting from crossing the state border in violation of the law or attempting to do so, or a justified risk of committing other criminal acts, a temporary ban on staying in a specific area in the border area adjacent to the state border constituting an external border within the meaning of the Schengen Borders Code may be imposed. The last (fifth) restrictions, regarding the temporary ban on abiding in a particular area within the border zone between the state and Belarusian Republic border, were introduced by the Minister of Internal and Administrative Affairs on March 6, 2025, and were fully enforced on March 10, 2025, for 90 days (Dz.U. 2025 poz. 281).

Barrier effect on nature

The created border barrier between Poland and Belarus is about 187 kilometres long and takes the form of an approximately 5-meter-high steel fence set on a concrete foundation dug into the ground to a depth of

1 meter. The barrier runs through the dense forest complex of the Bialowieza Forest. Its transboundary location makes it interfere with the network of major ecological corridors of pan-European importance, crucial for large mammals. Major corridors are the most important migration and migratory routes for species in the country and at the same time provide habitat and population connectivity on a continental scale. Interference with the course of such corridor means reducing the connectivity of habitats and populations of which animals use it.

In addition to the long and practically continuous border barrier built by Poland, the barrier effect is also due to its connection with the barrier created by Lithuania and Latvia, which cumulatively isolates animal populations migrating through the Belarusian territory. In addition, since the 1980s, there has already been a border fence on the Belarusian side, the so-called *'sistiema*', the offset of which from the course of the border has resulted in the creation of natural enclaves between the Polish border and the Belarusian *'sistiema'*, with no possibility of human entry (except for Belarusian border services). Poland's construction of a border barrier across the state border line has deepened the isolation of these enclaves. The degree of this isolation will be determined by the possible ability of animals to overcome all these terrain obstacles and the existence of alternative routes of movement.

Population of large mammals under species protection

Over the past nearly quarter century, the estimated abundance of bison, lynx and wolves in Poland has increased significantly: 4-fold, 2-fold and nearly 5-fold (Table 1), respectively.

Table 1

Changes in the abundance of bison, lynx and wolf in Poland in 2000-2023

Species	Number of animals in years						
	2000	2005	2010	2015	2020	2022	2023
Bison*	715	901	1,224	1,553	2,316	2,603	2,820
Lynx*	285	231	285	390	580	558	630
Wolf**	1,086	800	770	1,484	3,530	4,328	5,046

According to Environmental Protection (2020, 2021, 2022, 2023, 2024); *estimates of the Directorate-General for the Environment - not based on field work carried out according to a single methodology but collected periodically once a year from the same sources; **abundance indicated according to data from the Bison Pedigree Book.

Only a small part of the national population of bison, lynx and wolves occurs in Poland's national parks, and this occurrence is spatially unevenly distributed. Jamrose's (2008) study based on observations by national park field staff shows that wolves and lynxes are found in roughly half of Poland's 23 parks, but bison are found in only two of them (Bialowieza and Bieszczady). Data published by the Central Statistical Office (2024), on the other hand, show that in 2023 less than 8% of bison individuals occurred in their territory (210 individuals), with a significant majority (154 individuals) in Bialowieza National Park. Slightly higher (9%) was the share of individuals occurring in Polish national parks in the lynx population (59 individuals), of which only 2 individuals were recorded in Bialowieza National Park. Only 5.5% of the wolf population in Poland occurs in national parks (28 individuals), of which 19 individuals were recorded on the territory of the Bialowieza Park. On the other hand, in Podlaskie Voivodeship in 2023, there were 1,269 bison (45% of the national population), 52 lynx (8%) and 290 wolves - 6% of the national population (Environmental Protection, 2020, 2021, 2022, 2023, 2024).

Based on data from CSO (Environmental Protection, 2020, 2021, 2022, 2023, 2024), a linear model of species abundance against year was fitted. Results show highly significant positive trends for all three species:

- **European bison:** slope = 81 individuals/year, $R^2 = 0.98$, $p < 0.001$
- **Lynx:** slope = 15 individuals/year, $R^2 = 0.90$, $p = 0.003$
- **Wolf:** slope = 244 individuals/year, $R^2 = 0.93$, $p < 0.001$

These strong, statistically significant increases confirm the rapid post-2000 recovery of protected large mammals in Poland and underscore the potential for border barriers to disrupt otherwise expanding populations.

Migration needs of protected migratory animals

Migrations play an essential role in the functioning of animal populations, as they enable the exchange of individuals necessary for population sustainability. Contact between individuals and species is carried out using ecological corridors (Bernatek, 2011), whose functions are limited by: excessive narrowing, cutting with anthropogenic fragments, environmental fragmentation, or simplification of the landscape structure of the area (Korytarze, 2011).

Long-distance migration of individuals is a prerequisite for the proper functioning of wolf and lynx populations. The average size of the territory of wolves is about 230 km^2 and that of lynxes is about 100 km^2 (Jędrzejewski et al., 2004). The reappearance of the wolf in Kuyavia and Pomerania is undoubtedly the result of migratory behavior characteristic of this species. The animals most likely arrived here from the Bialowieza Forest using the north-central corridor starting there (Kaminski et al., 2011). However, while useful areas for wolves and lynx are plentiful in

Poland, numerous migration barriers hinder their recolonization (Jędrzejewski et al., 2004).

Lynxes move exclusively through forested areas during their migrations (Jędrzejewski et al., 2004), which has to do with the way these cats hunt. They need cover to be able to get closer to their prey and carry out a successful attack (Schmidt & Kowalczyk, 2012). Thus, an essential feature of the environment that enables lynxes' permanent existence is the continuity of forest complexes, which ensures adequate numbers and maintains high genetic diversity in the population (Schmidt & Kowalczyk, 2012). The abundance and condition of predators is also determined by the availability of a food base (Jędrzejewski et al., 2004). The lynx is a typical carnivore. Its food can be a variety of animal species, but it is dominated primarily by large ungulates - roe deer and deer (Schmidt & Kowalczyk, 2012).

In turn, the free roaming bison populations living in both parts of the Bialowieza Forest were formed at different times and developed independently of each other. Crossing the border strip was recorded relatively rarely, and after the construction of a fence along the border on the Belarusian side in 1980, both populations developed in complete isolation. Migrations of bison in the eastern part took place in the eastern direction towards fields, meadows and small forests. In the Polish population, during the early period of restoration, the bison migrated westward towards fields of rapeseed, winter crops or corn. Until the late 1970s, both populations occupied relatively small acreages, located in the centre of both parts of the Forest (Krasiński et al., 2016).

The natural effects of migration restrictions

The state border itself is an obstacle for animals, primarily bison and deer, which negatively affects the gene pool and narrows the gene base of the population (Paszko & Sialverstava, 2022). In addition, the border barrier built by Poland results in a full physical ecological barrier with the disruption of ecological connectivity, which can lead to effects at individual, habitat and species level. The significant barrier effect is due to the construction used and its parameters, probably completely preventing the movement of terrestrial species. As a result of the existence of the barrier, there is habitat fragmentation and isolation of local populations, restriction of the use of individual areas (for obtaining food, seeking shelter, access to breeding sites). The inhibition of the possibility of free movement across the barrier (including local migrations, long-distance migration, and dispersal of individuals) results in a lack of colonization of new habitats and range expansion, the range of gene flow decreases, and the genetic variability of local populations is reduced, leading to their weakening and gradual disappearance.

With the previously identified complete isolation between the bison populations on the Polish and Belarusian sides, Poland's construction of a new border barrier does not seem to be as critical for achieving the species' conservation goals as in the case of the wolf and especially the lynx. The built border barrier limits the influx of new wolf and lynx individuals from the east, enriching the gene pool of these populations. The barrier causing the effect of their isolation is a factor aggravating the already existing problems of development and even preservation especially of those species in which, as in the case of the bison - the gene pool is poor, and thus, migration (in addition to inbreeding) is a key source of its sustainability.

In terms of long-term environmental effects - the barrier physically divides the site into smaller patches and the dividing line follows the state border - regardless of natural conditions, it causes effects that vary with the natural values of the site and their sensitivity to change. The introduced physical (technical) division of the land, at the level of effect, hinders or prevents the penetration and contact with each other of individuals of the same species and species dependent on each other, residing in fragmented habitats creating the so-called ecological barrier effect. At the level of impact on individual animal species, fragmentation and isolation limit the availability of the food base and gene flow that determines genetic variation within a population and thus its stability and sustainability. As a consequence, there may be a quantitative reduction and, in extreme situations, extinction of local populations and a reduction in biodiversity. This is particularly true for the area located between the border barrier on the Polish side and the *'sistiema*' on the Belarusian side (the total area of cut off areas on the Belarusian side is about 50 km^2). Areas of natural value located on the Polish side of the border barrier remain functionally linked to areas to the south, north and west.

The wolf and lynx populations isolated by the border barrier may rapidly reduce local populations of wild ungulates, which in the long term may endanger themselves - due to the depletion of the food base. In the case of wolves in such a situation, there may also be increased killing of livestock. However, assuming the trend of migration of the wolf located on Polish territory towards the western borders and greater freedom of movement in this direction, the population of wild ungulates does not appear to be threatened.

Disruption of corridor functions in extreme cases leads to isolation, manifested, among other things, by a decrease in disease resistance and ability to adapt to changes in the environment (Paszkiewicz, 2021). Isolated populations may experience overcrowding, and this, already recorded in the Bialowieza Forest, is a likely cause of the high intensity of lungworm in resident bison resulting from the significant accumulation of invasive larvae of the disease-causing parasite (Demiaszkiewicz et al., 2009).

The wolf's high ability to overcome terrain obstacles (thus, it is not excluded that also barriers through animal crossings, or places devoid of them) and the limitation of its migration towards Belarus, where it is

exterminated - as a result of the creation of another barrier on the border - should not affect the reduction of its numbers and inhibit the growth of its population. Moreover, it could be argued that the border barrier (also due to its design) will reduce the possibility of shooting wolves that would attempt to migrate eastward from the EU area and the possibility of injury if they become entangled in the wires of the concertina *'sistiema*' (nevertheless, for wolves migrating from the east, it will provide an additional barrier effect). Thus, the primary direction of spatial expansion of the wolf will be westward, and the primary factor limiting its numbers is likely to be mortality caused by collisions with vehicles on roads.

The border strip and the fence running along it on the eastern side prevent bison migration. On the northeastern side, the Siemianowka reservoir is a migration obstacle, and on the western side the barrier is the 20,000-strong town of Hajnowka and villages, settlements and farmland. The area of the Ladzka Forest, which could provide a link between the Bialowieza Forest and the Knyszyn Forest, is only occasionally visited by bison. This situation indicates the high degree of isolation of the Bialowieza Forest from other large forest complexes in Poland and the poor development of ecological corridors in its vicinity. The development of the population and thus counteracting the overabundance of bison requires the maximal improvement of existing and potential ecological corridors (Krasiński et al., 2011). The separation of the two bison populations (western and eastern) is historically determined and their definitive separation by a barrier functioning since 1980 on the Belarusian side indicates that the new barrier created on the Polish side - is not the first significant restriction of transboundary migration of these animals, but affects the shifting of the boundary of land availability on both sides and creates an enclave between the existing barriers with a hitherto undocumented function in the existence of this species.

Tourism in the Bialowieza National Park

Bialowieza National Park occupies the central part of the Bialowieza Forest, more than 40% of which is within the administrative boundaries of Poland and the remainder of which is in Belarus. In addition to its unique natural value, an additional attraction appealing to domestic and foreign tourists to the Bialowieza Forest region was, until recently, the possibility of visiting the areas on the other side of the state border with Belarus, thanks to the Bialowieza-Perererov border crossing, opened in 2005 – and allowed crossing without a visa, with simplified clearance (Rąkowski, 2022). After the outbreak of the migration crisis on the Polish – Belarusian border and the creation of the border barrier, this became impossible. Moreover, the creation of the barrier coincided with the start of a full-scale war in Ukraine (2022). At the same time, this was the year with the lowest rates of nature tourism realized in the Bialowieza National Park in 2019-2023 (Table 2). Comparing the number of tourists in 2022 to 2019 (before the Covid-19 pandemic), the scale of decline reached 50%, practically recovering in the following year.

Table 2

Changes in the number of tourists in national parks in Poland in 2019-2023

	2019	2020	2021	2022	2023
Number of tourists in Poland's national parks					
Thousand people	14,149.7	13,411.3	16,068.2	16,031.0	15,554.5
Persons/ha	44.5	42.2	50.5	50.4	48.9
Number of tourists in the Bialowieza National Park					
Thousand people	173.5	158.2	142.0	97.0	144.0
Persons/ha	16.5	15.0	13.5	9.0	14.0

In our research, a trend-analysis to tourist numbers was applied. For all Polish national parks combined a non-significant upward trend was observed (slope = +543 000 visitors/year, $R^2 = 0.51$, $p = 0.17$), reflecting COVID-19 and geopolitical fluctuations. In Bialowieza NP, data reveal a slight but non-significant decline (slope = –12 000 visitors/year, $R^2 = 0.44$, $p = 0.22$), consistent with 2022's lowest attendance since 2019 and partial recovery in 2023.

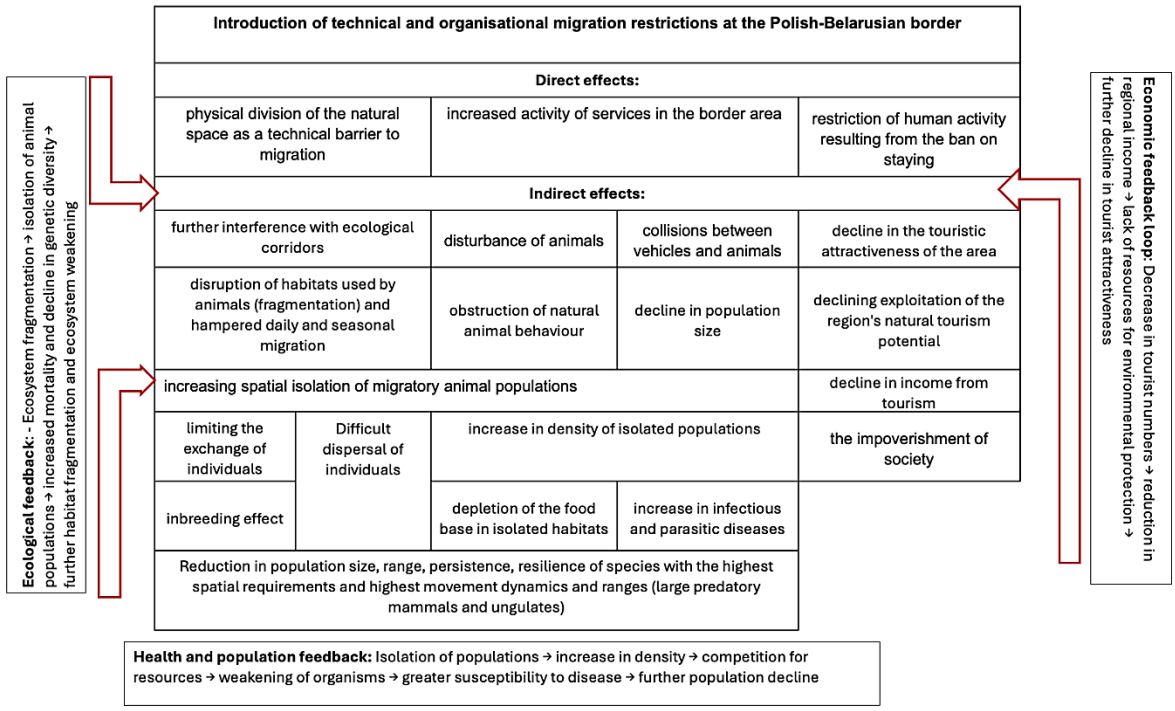
Although the tourism trends did not reach statistical significance ($p > 0.05$), the observed decline in Bialowieza NP visits in 2022 and the slower recovery in 2023 correspond to the overlapping effects of barrier construction, temporary stay bans, and the war in Ukraine.

Rakowski's (2022) analysis shows that, despite numerous reservations about the representativeness of the CSO's data on tourism in national parks, it can also be used as some measure of the size and dynamics of tourist traffic in the Bialowieza Forest region. Based on these data, he showed that the traffic is characterized by significant fluctuations: from 82,300 in 2007 up to 248,700 in 2017. Rakowski (2022) emphasizes that the decline in the number of visitors in recent years has certainly been influenced by the Covid-19 epidemic that began in our country in the spring of 2020, and the migration crisis on the Belarusian border that began in 2021, as well as the restrictions on staying and moving in border areas introduced due to this crisis and the construction of a fence on the Belarusian border. With an awareness of the vast yet untapped tourism potential of the regions, Rakowski (2022) sees numerous threats to the

development of tourism due to the specifics of the location, in connection with the migration crisis, the construction of the barrier and the war in Ukraine, while he also links the threats to the natural environment of the Białowieża Forest itself to the barrier. The current state of knowledge on potential influence of migration restrictions on the Polish-Belarusian border on nature and tourism allows modelling of potential consequences, as displayed in Figure 1. The direction, mechanism and the scale of these consequences require monitoring and consequently implementing actions which limit their negative influences. Furthermore, it cannot be ruled out that the proposed model fully exhausts the list of potential consequences of the enforced migration restrictions.

Figure 1

Model of potential consequences of introducing technical and organizational migration restrictions on the Polish – Belarusian border



The model above shows the cascading effects of migration restrictions, which lead to a weakening of both the ecosystem and the local economy.

Feedback makes the negative effects accumulate over time, amplifying the initial problems. The ecological imbalance also affects people, especially communities that depend on ecotourism and the region's natural resources.

The first results of a study conducted by the EIA-PIB (2024) on the actual impact of the border barrier two years after its construction show measurable effects on the distribution and movement of mammals (especially bison and deer), confirming the identified potential effects of the introduced migration restrictions. In addition, the impact of the border barrier on the occurrence of invasive plant species in the Bialowieza Forest and increased concentrations of foxes, raccoons and domestic cats near the border have been proven. The authors of this research link the increased activity of small predators near the border strip to the presence of permanent military posts on the border, which are a source of food waste, which can promote the spread of diseases carried by wild and domestic mammals.

The most worrisome conclusion of the EIA-PIB study (2024), is that the barrier will significantly contribute to deepening the isolation of the Bialowieza lynx population and its exposure to further loss of genetic variability and threats to its sustainability.

Conclusions

The aim of this study was to indicate the direction and mechanism of potential impacts of migration restrictions introduced at the Polish–Belarusian border on three protected species (European bison, wolf and lynx) and on nature tourism dependent on their presence.

Currently, there is no indication that the technical and organisational barriers on the Polish-Belarusian border will be removed or reduced, which allows us to assume that their effects and impacts will be long-term.

Our qualitative, cascade-model analysis—grounded in problem-tree methodology and expert findings—demonstrates that both physical (steel fence) and organizational (temporary stay bans) migration barriers generate pronounced ecological barrier effects. These include:

1. **Habitat fragmentation** and isolation of local wildlife populations, leading to reduced gene flow and weakening of population resilience.
2. **Altered migration dynamics**, with wolves and lynx diverted to alternative routes and bison confined to enclaves, exacerbating genetic bottlenecks.
3. **Decline in tourism** within Bialowieza National Park, as restricted access and perceived security risks discourage visitors—thereby undermining both conservation funding and local livelihoods.

These conclusions address directly the study's aim by tracing the causal pathways through which migration restrictions affect both wildlife and tourism.

They highlight the necessity of:

- **continuous monitoring** of animal movements and tourist flows,
- **adaptive management** to mitigate negative ecological and socio-economic outcomes,
- **policy measures** that reconcile border-security needs with the conservation of transboundary ecological corridors.

Future research should build on this theoretical framework by incorporating empirical field studies and, where appropriate, quantitative analyses to validate and refine the proposed cascade model.

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THE DEVELOPMENT OF THE BIOECONOMY CONCEPT IN UZBEKISTAN IN TERMS OF POLICY IMPLEMENTATION

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Abstract
In recent years, the bioeconomy has gained prominence as a strategic approach to addressing global challenges related to sustainable development, resource efficiency, and economic diversification. Rooted in the sustainable use of biological resources, the bioeconomy offers significant potential for balancing economic growth with environmental stewardship. Agriculture, as both a primary source of biomass and a key contributor to rural livelihoods, plays a vital role in this transition. The primary aim of this study is to analyze the current state and development prospects of the bioeconomy in Uzbekistan, with a specific focus on the agricultural sector. It seeks to evaluate national strategies aimed at fostering a green economy, assess their implementation within agriculture, and identify the key challenges and opportunities associated with advancing a sustainable bioeconomy model. Drawing on the country's predominantly agriculture-based bioeconomic structure, the study outlines the main directions for sustainable development, highlighting the role of sectoral growth in driving the bioeconomy. Findings point to positive trends in agricultural productivity and intensification across key subsectors. However, the analysis reveals that further progress is contingent on the establishment of a clearer and more coherent policy framework—one that supports the adoption of sustainable and circular practices and encourages foreign investment, particularly in value-added bioeconomic activities.
Keywords: bioeconomy, green economy, agriculture, Uzbekistan.

Introduction

There is a growing emphasis on sustainable development and environmental conservation, particularly in agriculture. While the agricultural sector is crucial for sustainable practices, it can also have negative environmental consequences, such as soil and water pollution, deforestation, and reduction of biodiversity. These issues are further compounded by global climate change, which can result in natural disasters. The concept of bioeconomy has gained global momentum as a solution to sustainable development problems. Bioeconomy involves using biological resources to meet societal needs while maintaining ecological balance and socio-economic progress. Central Asia, which is rich in natural resources and agricultural potential, could play a central role in promoting sustainable practices and transitioning to a sustainable bioeconomy in the region. The development of the bioeconomy in Central Asia is currently facing challenges due to a lack of systemic approach and institutional support and also a developing policy framework. It has been observed that many countries in the region do not have well-defined strategies and regulations for the sustainable use of biological resources. This situation has hindered the growth of bio-based industries and deterred investments. Moreover, it appears that the bioeconomy's complete potential is currently being hindered by certain infrastructure inadequacies, such as a shortage of bio-refineries and processing plants, which in turn limits the value-added potential of biological resources. Additionally, there seems to be a lack of funding available for innovation, technological advancements, and capacity-building initiatives that are necessary for the growth of this sector. Central Asia possesses substantial yet underutilised agricultural resources that could significantly contribute to the bioeconomy. However, there are certain obstacles that need to be overcome, such as insufficient knowledge transfer, limited market access, and underdeveloped value chains. To fully realise the potential of agriculture, it is important for Central Asian countries to invest in improving practices, supporting market access, and fostering innovation. Addressing these challenges effectively would require the implementation of robust policies, increased investment, capacity-building initiatives, and practices, in e.g. organic agriculture and sustainable waste management, ensuring the bioeconomy becomes a driving force for the region's sustainable development.

Materials and Methods

This paper provides a review of bioeconomy strategies and practices implemented worldwide that gives a context for analysis of the development of the bioeconomy strategy for Uzbekistan. The article also includes agriculture data analysis from the Statistics Agency of Uzbekistan and calculation of trends for selected indicators in agriculture and a SWOT analysis.

Results and Discussion

The concept of bioeconomy

Policies in general provide a structured approach to decision-making by defining goals and establishing procedures for implementation. Effective policies are designed to align with the overall vision and objectives of the entity, providing a basis for consistency, transparency, and accountability in decision-making and actions. According to the scientists of University of Eastern Finland and Fern Universitat in Hagen

(Ramcilovic-Suominen & Pulzl, 2018), the Bioeconomy policy aims to foster innovation, promote the efficient use of natural resources, and create a balance between economic growth and environmental conservation. Key elements of the bioeconomy policy include supporting research and development in biotechnology, encouraging the development of bio-based industries, promoting sustainable agricultural practices, and addressing ethical and social considerations related to biological advancements. A well-crafted bioeconomy policy contributes to job creation, technological advancement, and the overall transition towards a more sustainable and resilient economy that harnesses the potential of biological resources.

In a narrower sense, bioeconomy can be defined as the 'green economy' with the underlying idea that the green economy is aimed at ensuring the wellbeing of society through the effective use of natural resources, as well as returning the end-use products to the production cycle, thus encompassing both the concepts of bioeconomy as well as circular economy. It can be also noted that this is the interpretation often associated with the term 'bioeconomy' in Uzbekistan.

The general concept of 'bioeconomy' (or bio-based economy, which is often considered as a synonym) is that of an economy based on the sustainable exploitation of biological resources (Viaggi, 2018). The concept of bioeconomy began to take shape long before this currently well-known term appeared. Birner, (2018) describes the discrepancy in definitions that have been formed over the years. The bioeconomy concept began to develop in the middle of the 20th century when scientists and economists began to pay attention to the importance of using biological resources for production and economic development. The reasons for the conscious introduction and understanding of this term came due to its potential and the possibilities of solving certain issues, namely, the solution of replacing fossil resources with bioresources and the need to increase agricultural productivity to meet future food and biomass needs. The future bioeconomy is largely determined by the visions that countries and international bodies have embedded in the policy framework (Viaggi, 2018). Currently, many countries are still in the process of building their bioeconomy strategies, while others have already well established bioeconomy strategies and goals. Table 1 demonstrates the difference in explanation and understanding of bioeconomy in selected countries that have adopted their bioeconomy strategies.

The development of a bioeconomy strategy is a way to formalise and prioritise the development of bioeconomy and particular sub-sectors and approach that the particular country sees fit to adapt.

Table 1

Definitions of the concept of 'bioeconomy' in strategies of different countries

Country	Title of the document	Definition
Latvia	Latvia Bioeconomy Strategy 2030 (2016)	Bioeconomy is a part of the national economy where renewable natural resources (plants, animals, microorganisms, etc.) are used in the production process in a sustainable and thoughtful way to produce food and feed, industrial products and energy.
Germany	National Bioeconomy Strategy (2021)	The bioeconomy encompasses the full range of economic activities and innovations based on the use of biological resources and processes. It brings together the sectors of agriculture, forestry, fish farming, food processing, bioenergy production, biotechnology, and related research and infrastructure.
Italy	Bioeconomy in Italy (2019)	The bioeconomy refers to the set of economic activities relating to the invention, development, production and use of biological products, services and processes across four macro-sectors.
Norway	Familiar resources – undreamt of possibilities The Government's Bioeconomy Strategy (2016)	The concept includes sustainable, efficient and profitable production, extraction and use of renewable biological resources for food, feed, ingredients, health products, energy, materials, chemicals, paper, textiles and other products.
Japan	Bioeconomy Strategy of Japan (2022)	The bioeconomy is a collection of economic and scientific activities that relate to the production, use and trade of biotechnology products, as well as related services and infrastructure.
Singapore	Singapore Green Plan 2030 (2021)	The bioeconomy is integrated use of biological agents (microorganisms, plants, animals) and their components to create products, services and solutions that contribute to economic and social well-being.

Country	Title of the document	Definition
Austria	Bioeconomy. The strategy for Austria (2019)	Bioeconomy stands for an economic concept that aims to replace fossil resources (raw materials and energy sources) with renewable raw materials in as many areas and applications as possible. It covers all industrial and economic sectors that produce, process, handle or use biological resources.

Source: created by the authors based on the bioeconomy strategies of the selected countries.

Table 2

Priority areas of the above countries

	Nat. Res. (Forests)	Nat. Res. (Water)	Nat. Res. (Land)	Nat. Res. (Air)	Health	Climate	Energy	Innovation (Biotechnology)
Latvia	●		●				●	
Germany	●					●	●	
Italy	●	●	●					●
Norway		●	●					
Singapore			●			●		
Japan					●			●
Austria	●		●			●	●	

Source: created by the authors based on the bioeconomy strategies of the selected countries.

Bioeconomy has emerged as a pivotal component of sustainable development, aiming to harmonize economic growth with ecological balance. Latvia positions itself to harness its natural resources, with a focus on sustainable forestry practices and biomass utilization. The country's strategy emphasizes enhancing resource efficiency and fostering innovation in forestry and agriculture. As a global leader in the bioeconomy, Germany places a strong emphasis on sustainability and resource efficiency. Its strategy encompasses research and innovation in biotechnology, bioenergy, and bio-based materials with a concerted effort to strengthen the synergy between industry and agriculture. Germany and Japan include areas with strong industrial structures, and bioeconomy is considered in line with its innovation potential and as a potential boost for industrial use of biomaterials. The focus is mainly on replacing fossil fuels and reducing CO2 emissions to combat climate change, as well as achieving economic and technological advantages from new way of processing biomass. Other countries see the bioeconomy as a strategy to further develop their bioscience research towards strengthening their competitiveness in high-value industries (Viaggi, 2018), (Table 2). The Italian strategy is underpinned by a commitment to research and innovation, aiming to enhance the competitiveness of its burgeoning bio-based industries. Singapore's unique urban context shapes its bioeconomy strategy, emphasizing sustainable food production, waste-to-resource initiatives, and technology-driven urban solutions. The city-state aims to address urban challenges through innovative approaches, contributing to resource efficiency and environmental sustainability. Norway's bioeconomy strategy revolves around the sustainable management of biological resources, particularly in fisheries, aquaculture, and forestry. The nation strives for a delicate balance between economic growth and environmental sustainability, investing significantly in research and development. Italy charts its bioeconomy course by promoting sustainable agriculture, forestry, and the efficient utilization of resources. Japan's approach to the bioeconomy is characterized by cutting-edge technology and innovation. With a keen focus on bioenergy, bioplastics, and sustainable agriculture, Japan seeks to foster the creation of new industries and revitalize rural areas through the principles of the bioeconomy. Austria boasts a well-developed bioeconomy strategy that integrates forestry, agriculture, and industry seamlessly. The country's focus spans bioenergy, bio-based materials, and sustainable land use, with an overarching goal of promoting innovation and fostering regional development. Obtaining bioenergy and biomaterials from renewable bio-based instead of limited natural resources through waste biorefining is the fundamental principle of the bioeconomy strategy. The European bioeconomy approach provides sustainable solutions to the transition to a greener, fairer, and more responsible economy (Le Pera et al., 2022). These countries exhibit diverse bioeconomy strategies tailored to their unique socio-economic and environmental contexts. While some prioritize the sustainable use of natural resources, others place a premium on technological innovation. The common thread among these nations is a commitment to striking a balance between economic growth and environmental stewardship, illustrating the multifaceted nature of the bioeconomy on the global stage. As the bioeconomy landscape evolves, ongoing research and policy adaptations will be critical to ensure the continued success of these strategies in fostering sustainable and resilient economies.

Uzbekistan and the ability to transition to bioeconomy

In 2018, the Republic of Uzbekistan ratified the Paris Agreement accepted in Paris, on December 12, 2015, and made a quantitative commitment to a nationally determined contribution to its implementation - reducing the specific emission of greenhouse gases per unit of gross domestic product by 10% from the level of 2010 by 2030. The main goal of the Strategy is to achieve sustainable economic progress that contributes to social development, reduction of greenhouse gas emissions, climate and environmental sustainability by integrating the principles of a green economy into ongoing structural reforms.

However, the state has not yet adopted a bioeconomy strategy, which can play an important role in implementation of the Strategy, becoming one of the key tools for the transition to a green economy. Thus, the transition to the green economy as well as fully unlocking the potential of the Uzbekistan natural resources and adaptation of more sustainable practices in agriculture, bio-based industry and waste-management is work in progress. According to Kardung et al. (2021), the interactions between the concepts of bioeconomy, bio-based economy, circular economy, and green economy are all interconnected and share similar goals of promoting sustainability, resource efficiency, and reduction of environmental impact. The bio-based economy is seen as a part of the bioeconomy and relates to the conversion of biological resources into products and materials. This is also referred to as bio-based production. The authors have found that in some definitions of the bio-based economy, an emphasis is put on innovative bio-based products such as biopolymers and bioplastics, while in others, traditional bio-based products such as bio-based textiles, wood products, pulp, and paper are explicitly included as well. Recently, the term circular bioeconomy that has been introduced by the European Commission, among others, to intertwine the bioeconomy and circular economy concepts and emphasize the use of a circular approach in bioeconomy, also shows its limitations and overlap. In turn, green economy is a concept of economic development aimed at ensuring sustainability and environmental safety. It seeks to minimize the negative impact of human activity on nature and maximize the use of renewable resources.

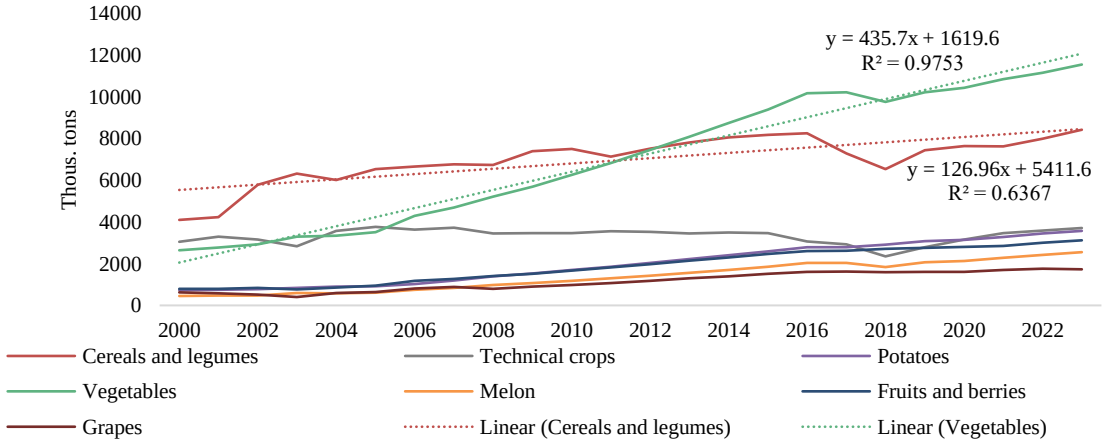
Bioeconomy in Uzbekistan

The current structure of bioeconomy in Uzbekistan is dominated by agriculture amounting to 404.6 trillion soums. Forestry and fisheries contribute to a much smaller rate – 10.4 and 4.3 trillion soums accordingly (Socio-economic situation…, 2024). The whole agriculture sector is divided almost in two halves, namely, livestock and crop production. In 2023, the crop production amounted to 50.1% of the whole agriculture sector (2.02 trillion soums) and the livestock production – 49.9% (2.01 billion soums) respectively (Socio-economic situation …, 2024).

Within the crop production sector ‘Figure 1’, the main cultures grown are vegetables (mainly carrots, tomatoes and onions), which also has the highest growth rate among other cultures, and thus this sector has had a rather steady increase during the last two decades. A trendline with a linear equation can be used to reflect the direction of this sector (R^2_{veg}=0.9753), and thus this equation could be used to assess further development of the vegetable production. It is followed by cereals and legumes – a sector that has seen an overall increase in the produced volumes over the last few years; however, there has also been a rather sharp decline in the production in 2017-2019 due to low harvests in those years. Low harvests had also affected the group of technical crops, which is predominantly cotton in Uzbekistan; fortunately, the harvest of this crop is recovering in the recent years.

Figure 1

Crop production of the Republic of Uzbekistan, 2000-2023, thou. tonnes

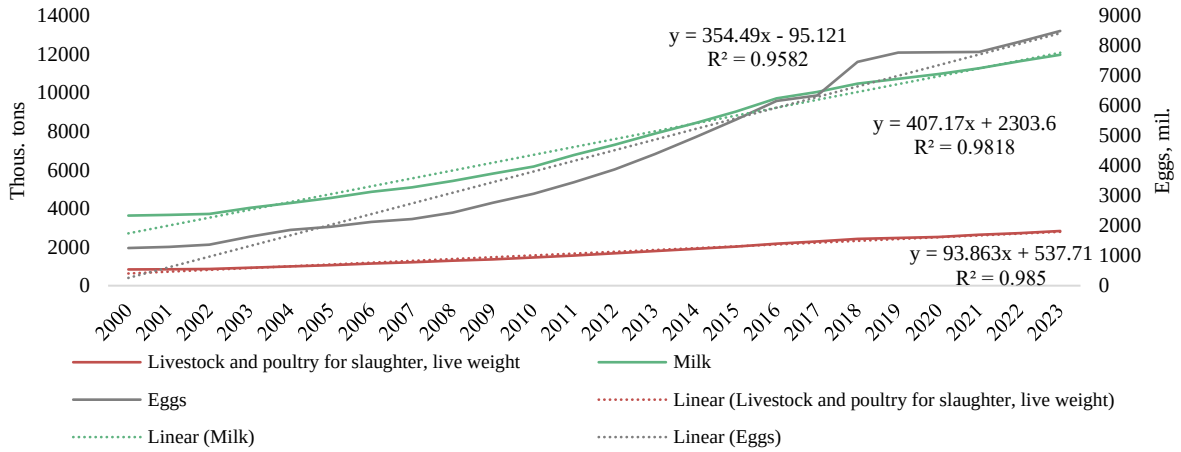


Source: calculation by the authors using the data of the Statistics Agency of Uzbekistan, 2024.

Livestock production sector is also experiencing a steady increase in production volumes, especially regarding milk and eggs, also meat - the increase is steady for meat but much slower due to the rapid

growths of production of dairy and eggs. All three of the goods reflected in 'Figure 2' exhibit a very close correspondence with a linear trend, showing an upward trajectory with R^2_{milk}=0.9582; R^2_{eggs}=0.9818; $R^2_{livestock}$=0.985, thus they can be used in developing a future outlook for the production of these goods.

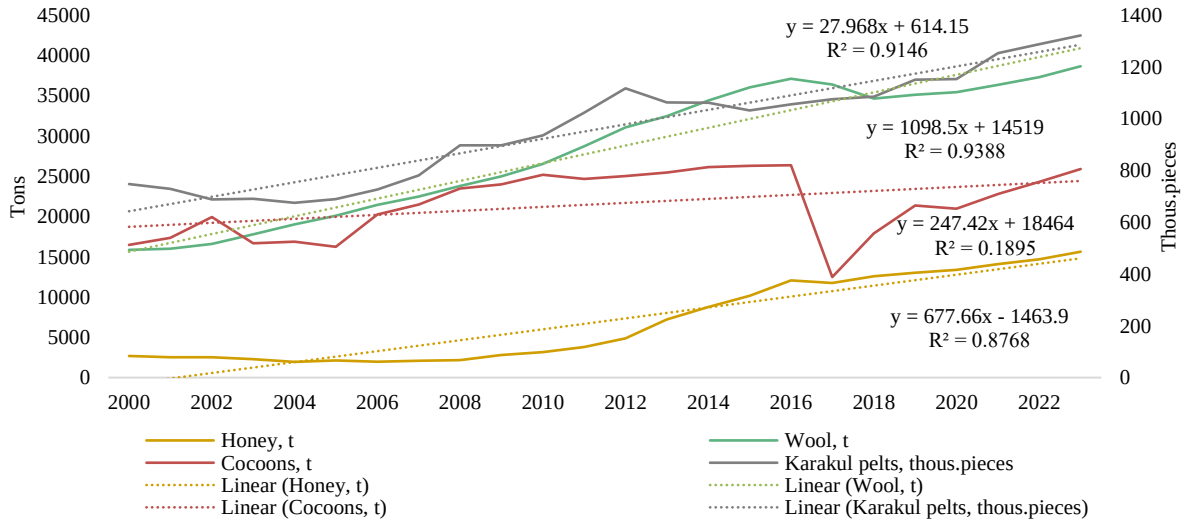
Figure 2
Livestock production of the Republic of Uzbekistan, 2000-2023, thou. tonnes; mil. eggs (secondary axis)



Source: calculation by the authors using the data of the Statistics Agency of Uzbekistan, 2024.

Apart from the production of the main goods of the livestock sector (milk, meat and eggs), other goods include honey, wool, cocoons and karakul pelt. The volumes of all of these goods show an overall upward tendency although it can be noticed that production of silkworm cocoons fluctuates strongly and had a sharp decline in 2017, but has been restoring the production volumes in the recent years 'Figure 3'.

Figure 3
Production of other goods within the livestock sector of the Republic of Uzbekistan, 2000-2023, tonnes; thou. pieces (secondary axis)



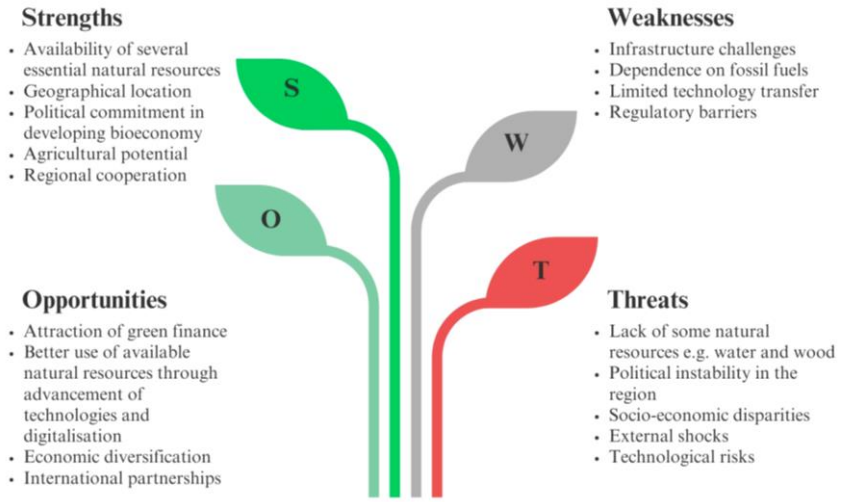
Source: calculation by the authors using the data of the Statistics Agency of Uzbekistan, 2024.

Uzbekistan's transition to a green economy can be analysed through a SWOT perspective in 'Figure 4'. The country has significant strengths, particularly in its availability of several essential renewable energy resources, e.g. arable land. Furthermore, the government commitment to green initiatives and investment in renewable energy projects provides a strong foundation for further development of sustainable bioeconomy. Uzbekistan's agricultural sector also presents opportunities for sustainable practices, contributing to the green economy and is important provider of agricultural products in the region. However, it is important to consider notable weaknesses. Infrastructure challenges, particularly in management of water resources, waste management and renewable energy production and distribution, may impede progress. Economic and technological dependence on

fossil fuels poses a significant obstacle, along with limited access to advanced green technologies and bureaucratic barriers. Also, lack of experience in the development and implementation of green technologies may pose an obstacle to the implementation of the strategy. The growing interest in green technologies and sustainable practices creates opportunities to attract investment and develop new industries (Raimjanova & Popluga, 2023).

Cooperation with other countries can provide access to technology and expertise. The need for significant investments for the introduction of green technologies may face limitations in the country's financial resources and price fluctuations for traditional energy resources may affect the economic feasibility of green investments (Meyer, 2017).

Figure 4
SWOT analysis of Uzbekistan's strategy for the transition to a green economy



Despite these challenges, there are promising opportunities for Uzbekistan. International partnerships and funding can accelerate the transition to green industries, creating jobs and attracting investment. Investing in green infrastructure and a better use of advanced and digital technologies (Zeverte-Rivza et al., 2023) can also enhance climate resilience and enhance a more effective use of available natural resources. Also, diversification of economic activities can improve the resilience of the businesses affected by climate threats, e.g. drought and development of local food consumption in the unprocessed food, locally specific and prosocial value food segments. As concluded in previous studies in these segments, demand is inelastic, creating a relative advantage of local food in competition with global food products (Naglis-Liepa et al., 2022).

However, there are potential threats that must be addressed. Political instability in the region could disrupt long-term sustainability efforts, and socio-economic disparities may widen during the transition. External factors such as fluctuating energy prices and technological risks pose additional challenges. Also, lack of some much needed resources as, for example, water resources and wood should be taken into account. Meyer in 'Bioeconomy Strategies' (2017) explores challenges in implementing the strategy, citing potential goal discrepancies due to insufficient communication with other industries. The lack of coordination between ministries may further impede strategy execution.

The literature review indicates that the transformation of the economy into a bioeconomy involves adopting strategies that harness biological resources, promote sustainability, and drive innovation in biotechnology; and it can be done through: 1) development of biotechnologies; 2) transitioning from fossil fuels to renewable energy; 3) sustainable agriculture: involves developing methods that minimize environmental impact and maximize biological resource utilization, including transitioning to organic farming and alternative soil cultivation methods; 4) development of biodiversity: emphasizes protecting and restoring life diversity in ecosystems through nature reserves, protected areas, and species restoration programs; 5) development of ecological tourism: focuses on tourism designed to preserve the natural environment, mitigating environmental impacts and generating income for local populations.

Conclusions

1. The bioeconomy in Uzbekistan is predominately dominated by agriculture accounting for 96.5% of Uzbekistan's bioeconomy among the primary sectors of agriculture forestry and fisheries with a growing tendency in almost all subsectors of agriculture with the fastest growth in vegetable, milk and egg production.
2. Clear and transparent regulatory frameworks would facilitate the growth of bioeconomy industries in Uzbekistan, ensuring attraction of investments and developing circular and sustainable practices.

3. Facilitating collaborations between bioeconomy producers and potential end-users, such as industries utilizing biomass-based products or renewable energy sources, is essential. Creating awareness among consumers about the benefits of bio-based products is equally important for sustainable development.
4. International collaboration should be strengthened by forming partnerships with global organizations, allied nations, and investors.
5. Establishing a robust monitoring and evaluation framework is crucial for regularly assessing the progress of bioeconomy policies. Collecting data on key performance indicators and making necessary adjustments will ensure continuous improvement.

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CLUSTER ANALYSIS OF THE DAIRY SECTOR IN EUROPE

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Abstract
The European dairy sector has an important role in the global agricultural market and is influenced by various economic, political and environmental factors. The aim of this study is to analyse the structure and market dynamics of the dairy sector in European countries using cluster analysis. The study uses Eurostat (2023) data, which were grouped in 3 categories: dairy production capacity, market dynamics and economic and demographic indicators. The study uses factor analysis and hierarchical clustering methods to identify similarities and differences across European countries based on dairy production levels, trade balance and macroeconomic environment. The results reveal significant differences in the European dairy sector, highlighting that countries with well-developed production systems have a greater export orientation. The cluster analysis shows that Central and Western European countries demonstrate higher efficiency and stronger market performance, while Eastern and Southern European countries show lower competitiveness due to structural and economic constraints. The results suggest that specific policy measures are needed to improve the resilience of the dairy sector, especially in regions facing production and market challenges.
Keywords: factor analysis, cluster analysis, dairy sector, Europe.

Introduction

European countries are major players in the world dairy markets, and dairy farming is one of the most profitable agricultural sectors in the Europe (Arendok & Liinamo, 2003). Accordingly, European countries compete with large dairy producing countries (e.g. China and Brazil); therefore, it is essential that the European dairy industry follows the trends in this sector, as well as for the sector to be developed. Another factor to be considered is that on a global scale the dairy industry is probably one of the most distorted agricultural sectors, exposed to various crises (e.g. environmental, social ang economic crises) (Knips, 2005; Pappa, 2019). This is due to the fact that the sector is influenced by both external factors (e.g. Covid, the Russian-Ukrainian war), as well as political decisions made at the Europe Union (EU) level (e.g. the introduction and later abolition of quotas), and the sector is also influenced by the internal regulations of each individual European country and even the geographical location of the country. Furthermore, the sector can vary within a country and across regions (Otte & Chilonda, 2006). Overall, the dairy sector has undergone several structural changes over the past 20 years, driven by rapid technological developments and intense policy interventions (Rytkönen et al., 2020). Such EU actions are partly due to the fact that the world population continues to grow and there is a tendency to consume more dairy products in the regions that historically had lower dairy consumption, e.g. Asia. So the dairy sector needs to adapt to ensure a greater supply of livestock products and improve the efficiency of the sector, while paying attention to animal welfare and balancing environmental sustainability, e.g. emissions reduction policy (in line with the European Green Deal). To achieve these goals (i.e., to ensure a greater supply of products and improve the efficiency of the sector), as already mentioned, technologies and farming practices are being developed to make milk production more efficient (for example, automated feeding systems, milking robots and various manure management solutions are being introduced on farms), and cows with high genetic potential are also being selected to increase their milk production during lactation, thus ensuring the goal set by the farms – to increase productivity indicators (Neethirajan & Kemp, 2021). The EU offers farmers various subsidy options that directly promote technological development and, accordingly, the competitiveness of the sector. Since the sector is subject to various types of influences, it is important to identify the factors that affect milk production, as this helps to monitor and predict how the sector is changing (Otte & Chilonda, 2006). These factors are especially important for policymakers who would create short-term or long-term policy planning documents based on such data. The dairy sector can be analysed using various indicators, and some of the main indicators are the total number of dairy farms, the number of dairy cows per farm and the average milk yield per cow. In general, milk yield per cow is widely accepted as the primary measure of farm productivity, as it reflects the efficiency of dairy operations and the effectiveness of herd management practices (Viira et al., 2015). However, another significant factor indicating changes in the dairy sector is the structural composition of dairy farms. Such an indicator provides valuable insight not only into the distribution of herds, but also into the overall efficiency and sustainability of the sector. For example, there are countries with intensive dairy production sectors, with a larger number of cows (300 and more) dominating, but there are also countries where the number of large farms is decreasing and the number of small farms (up to 50 cows) is increasing. Such trends may indicate, for example, that larger farms are more likely to adopt new technologies faster and invest in their integration into their farms, thereby increasing production volumes and achieving higher productivity. In addition to production capacity, market conditions also significantly affect the profitability of the dairy sector (Otte & Chilonda, 2006). External influences, such as global market instability, fluctuations in feed costs, changes in transport logistics,

also affect the dairy sector in Europe, affecting farmers' incomes and the resilience of the sector (Bórawska et al., 2021). It is also important to remember that production volumes and milk prices are interrelated, reflecting the interaction of market supply and demand. Milk prices vary around the world, as they are influenced by various economic, social and environmental conditions, the average number of dairy cows on the farm and the average milk yield, supply/demand relationships, the level of production per capita, as well as various political circumstances (Popescu et al., 2019).

Identifying trends in farm structure, production efficiency and market dynamics helps policymakers and stakeholders to develop targeted strategies that support the sustainability of the sector and its ability to adapt to new challenges.

Materials and Methods

Data were collected from Eurostat (Eurostat, 2023) and are grouped in 3 categories - Dairy Production Capacity, Market Dynamics and Economic and Demographic Indicators (Table 1). Data is gathered for all EU countries for the year 2023.

To optimise the further calculations, in particular cases, when data for 2023 is missing for individual countries, it is replaced by the data from the same indicator and same country for the previous years or a neighbouring country if they have been comparable considering the historic data. The group Dairy Production Capacity focuses on factors that influence the overall capacity of dairy farming, such as the number of dairy cows, milk collection, and the production of various dairy products (for example cheese and butter). The group Market Dynamics includes economic and trade-related indicators that influence the pricing, cost structure, and trade balance of dairy products.

And the group of Economic and Demographic indicators provide insight into how economic growth, employment trends, and population dynamics influence the dairy sector.

Table 1

Data classification

Group	Indicator
Dairy Production Capacity	number of dairy cows; collection of cow's milk; milk treated-distribution; production of cheese; production of butter; production of acidified milk; skimmed milk powder; whey; organic cows raw milk prices
Market Dynamics	selling prices of milk; selling prices of crop products; fresh milk export; fresh milk import; compensation of employees; agricultural land prices
Economic and Demographic	GDP per capita; growth in GDP; employment rate; unemployment rate; share of GV, agriculture; share of employment, agriculture; population change; population; area

The indicators were further used in this study for the factor analysis and cluster analysis described further in the Results and Discussion section, this was done by using the IBM SPSS Statistics 30.0.0.0 software.

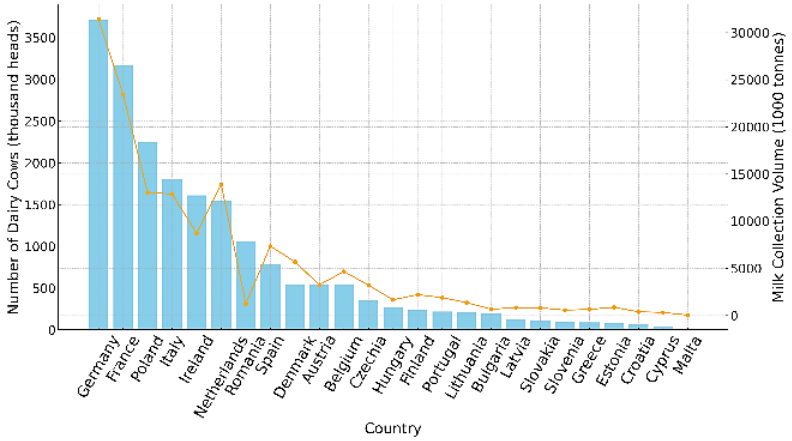
Results and Discussion

By examining the individual indicators included in Table 1, it is possible to observe some of the main indicators that affect the dairy industry. Further, the article assesses and compares such indicators as the total number of cows, milk yield per cow, fresh milk imports and exports, as well as milk prices in Europe (Figure 1, Figure 2, Figure 3).

Figure 1 shows the relationship between the number of dairy cows (represented by bars) and the volume of milk collected per cow (represented by a line) in EU member states (excluding Sweden and Luxembourg, as data were not available for these countries).

Figure 1

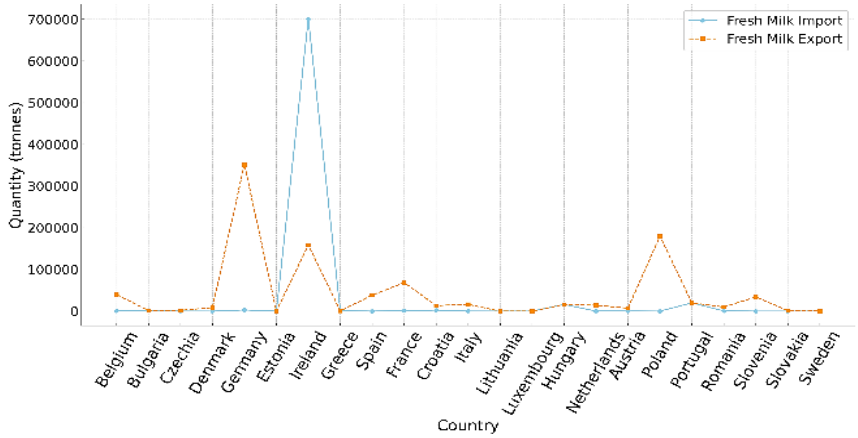
Dairy cows and milk collection volume in Europe (2023)



Countries with larger number of dairy cows have a higher volume of milk collected, indicating a direct relationship between herd size and production capacity. However, some differences also indicate differences in productivity and efficiency between countries. For example, in some countries (e.g. the Baltic states) the average milk yield per cow is higher than the number of cows being milked. Such dynamics may indicate improvements in the efficiency of the industry. Such a trend may be explained by the fact that farmers began to run productive livestock more accurately and select cows with the highest genetic potential, which can produce more milk during lactation. Genetic selection has led to significant increases in milk yield, which in turn has increased the productivity of the dairy industry. However, it also has negative consequences, for example, cows that have been genetically selected for higher milk yield are more likely to suffer from health problems such as mastitis, metabolic disorders and reproductive problems (Hansen, 2000; Berry et al., 2003).

The dairy market is very dynamic and is influenced by various factors: economic factors (e.g. GDP and income levels), trade policies and regulations (e.g. tariff policy), geographical and logistical factors and market structure, and production factors (e.g. number of dairy cows and milk yield). These factors together create complex dynamics in the global milk market, affecting both supply and demand and consequently also affecting countries' exports and imports (Bai et al., 2023).

Figure 2
Comparison of fresh milk import and export (2023)



The dairy sector plays a significant role in the food industry; the export of dairy products also plays an esential role in the overall agricultural and food trade of almost all European countries, as well as in the global dairy trade (Bojnec & Ferto, 2014). The imbalance between milk demand and supply in the world creates new export opportunities, especially for the countries with a developed dairy industry. In contrast, countries where demand for dairy products exceeds local production are dependent on imports (Kondaridze & Luckstead, 2023).

Figure 2 shows the distribution of fresh milk imports and exports in different European countries, which provides an insight into the trade flows of milk. This comparison allows to identify which countries are mainly milk importers and which are exporters. For example, countries such as Germany, Poland and France are exporting countries, while Ireland and Bulgaria are importing countries. Countries with higher imports than exports show a greater dependence on external markets, while countries where exports exceed imports demonstrate an export orientation and a lower dependence on external markets. In general, countries with a developed dairy production infrastructure are the main exporters, while countries with less developed domestic production rely on imports to meet domestic demand.

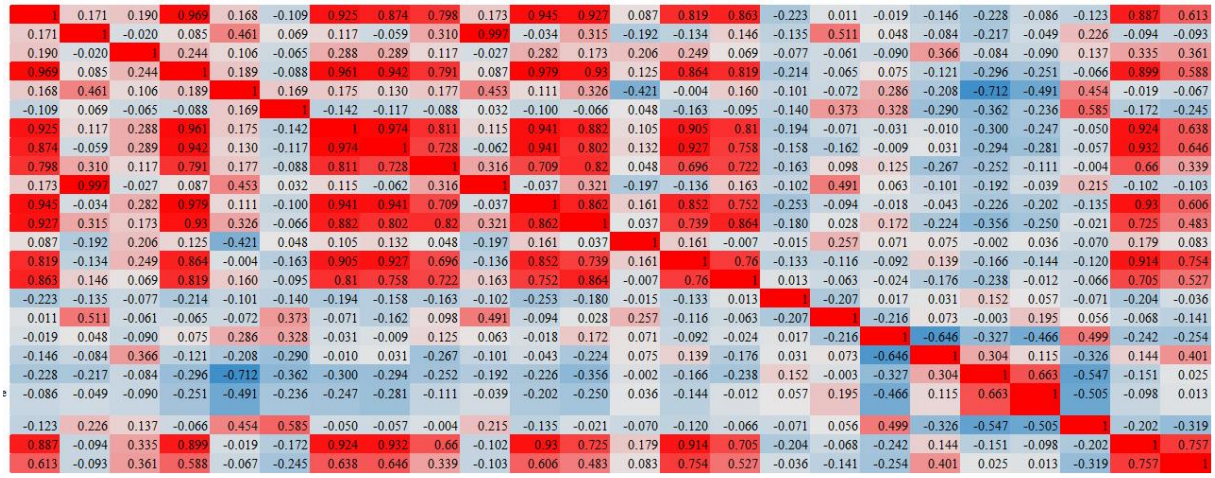
As mentioned earlier in this article, the dairy market is subject to external factors and for this reason, milk prices also change, influenced by various global events. As mentioned earlier in this article, the dairy market is subject to external factors and for this reason, milk prices also change, influenced by various global events. Figure 3 shows milk prices in Europe from 2015 to 2023, and global events such as the end of milk quotas, Covid-19 and the Russian-Ukrainian war that have affected prices in the sector.

Figure 3
Milk prices and global events (2023)

One of the recent events that significantly affected milk prices is the Russia-Ukraine war, which began in 2022. The war disrupted production and supply chains, leading to significant increases in fertilizer and energy prices, which increased the costs of milk processing, which in turn was reflected in higher dairy product prices. Export and import restrictions also significantly affected dairy prices, as countries were forced to review their trading partners (Hassen & Bilali, 2022).
To carry out the cluster analysis, first the factor analysis was done and complex factors were made.

For measuring sampling adequacy the Kaiser–Meyer–Olkin (KMO) test and Bartlett's test of sphericity was taken into account to proceed to factor analysis. The result of the KMO =0.632 > 0.5, meaning that the sample is adequate. Bartlett's test result shows a p-value (Sig.) of 0.000, which is less than 0.05, indicating that the variances are significantly different. To optimise the results, a correlation analysis was carried out and the indicators with weak mutual correlation were excluded from further analysis. A correlation matrix visually represents the relationships between different variables, Figure 4.

Figure 4
Correlation heatmap



A positive correlation (red color) indicates a strong relationship between two variables, a negative correlation (blue color) indicates an inverse relationship between the variables, and gray color indicates that there is no significant correlation.
For identifying the number of factors, the extraction method of the principal component analysis and the Kaiser criterion were used, which allowed the identification of indicators that constitute three complex factors. The Rotated Component Matrix (Table 2) presents the results of this analysis, highlighting the relationship between the main indicators and their factors.

Table 2
Rotated component matrix

Indicators	***F1***	***F2***	***F3***
Number of dairy cows	0.959	0.006	0.169
Collection of cow's milk	0.972	0.136	0.052
GDP per capita	0.097	0.677	0.440
Milk treated-distribution	0.976	0.104	0.069
Compensation of employees	0.959	0.131	-0.117
Fresh milk export	0.789	0.092	0.325
Fresh milk import	0.025	0.100	0.976
Production of cheese	0.960	0.061	-0.065
Production of butter	0.886	0.190	0.306
Production of acidified milk	0.933	-0.012	-0.178
Skimmed milk powder	0.849	0.002	0.189
Population change	-0.162	0.778	0.131
Population	0.951	-0.097	-0.138
Employment rate	-0.071	0.687	-0.009
Share of GV, agriculture	-0.222	-0.816	-0.135
Share of employment, agriculture	-0.148	-0.838	0.113
Area	0.711	-0.245	-0.153
Selling prices of milk	0.025	0.110	0.972

The extraction method was the Principal Component Analysis and the rotation method was Varimax with Kaiser normalization.

Rotated Component Matrix analysis shows how dairy sector indicators are related to three identified factors. Based on the indicators, F1 could be labelled **Dairy production** and includes the following indicators: number of dairy cows (0.959), collection of cow's milk (0.972), milk treated-distribution (0.976), compensation of employees (0.959), production of cheese (0.960), production of butter (0.886), production of acidified milk (0.933), and skimmed milk powder (0.8495). All factors are positively correlated with F1. F2 could be labelled **Market**, which is positively correlated with GDP per capita (0.6771) and population change (0.778).

Macroeconomic Environment, which is positively correlated with fresh milk import (0.976) and selling prices of milk (0.972).

Cluster analysis was performed based on the factor analysis. ANOVA results indicate that all factors are significant for cluster analysis (Table 3) with Sig. < 0.05.

Table 3
ANOVA

	Cluster		***Error***		***F***	***Sig.***
	Mean Square	***df***	***Mean Square***	***df***		
REGR factor score 1 (Dairy production)	4.451	5	.178	21	24.940	.000
REGR factor score 2 (Market)	4.501	5	.166	21	27.035	.000
REGR factor score 3 (Macroeconomic Environment)	5.034	5	.039	21	127.685	.000

The Europe countries were grouped into 6 clusters. The number of clusters was determined based on the Elbow rule. Cluster 3 consists of a larger number of countries – 11 and represents countries with well-developed dairy production, but with challenges in market development and macroeconomic environment. The cluster centres (Table 4) illustrate the key characteristics of the identified clusters.

Based on the cluster analysis of the dairy sector, the country closest to the Cluster 3 centre is Finland, while Belgium is the furthest from the cluster centre. Countries in this cluster have moderately developed market, but they have weaker milk production.

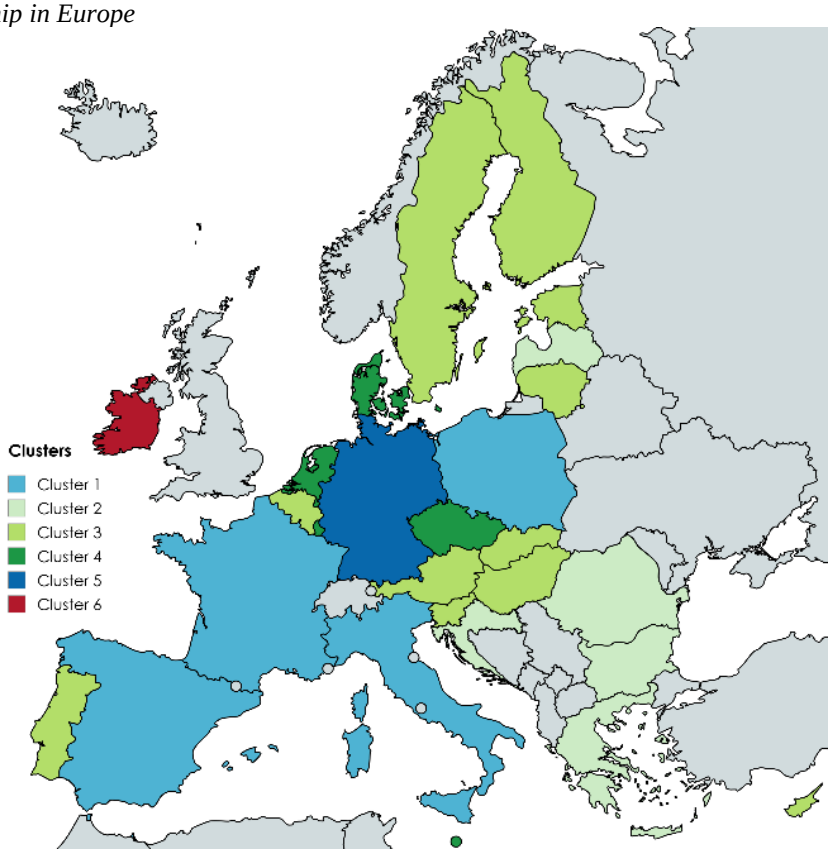
Table 4
Final Cluster Centres

	Cluster					
	1	***2***	***3***	***4***	***5***	***6***
REGR factor score Dairy production	1.30707	-.42551	-0.43863	-0.36611	3.42190	0.13288
REGR factor score Market	-0.56052	-1.53199	0.19556	1.26530	0.90221	0.52220
REGR factor score Macroeconomic Environment	-0.29574	0.05319	-0.24288	-0.21530	-0.22136	4.88655

Countries in clusters 1, 5 and 6 have relatively well-developed dairy production. Moreover, the country in cluster 6 has stronger macroeconomic indicators. There is 1 country in cluster 6 - Ireland, which is a typical representative country of this cluster. Cluster 5 also has only 1 country - Germany, which is a typical representative country of this cluster, with well-developed dairy production and a moderately developed market. Cluster 4 has 5 countries, with Denmark closest to the centre. This cluster represents countries with a well-developed market, but with weak dairy production. Macroeconomic indicators are also relatively low in this cluster. And finally, cluster 2 has 5 countries, with Bulgaria closest to the centre. The countries in this cluster have the weakest dairy production and the least developed market, making them the most vulnerable group. The mapping (Figure 5) of the cluster membership allows us to distinguish four characteristic regions: Mediterranean and Central European countries with medium production and market levels, Eastern European and Balkan countries with weaker indicators in production and market, Nordic and Western European countries with moderately developed milk production and a moderately developed market, and Central European countries with moderately developed dairy production countries with a well-developed market while Germany and Ireland are typical representative countries of their cluster.

Overall, this shows that regional differences in the dairy sector of European countries are significant. Figure 5 shows an interesting trend in which the Baltic states are not in the same cluster - Estonia and Lithuania are in cluster 3, while Latvia is in cluster 2. This indicates that Lithuania and Estonia are in the same cluster as countries with well-developed dairy production, but Latvia is in the cluster with weakest dairy production.

Figure 5
Cluster membership in Europe



As Poland is one of the largest milk producers in Europe and, according to the EU Agricultural Outlook 2024-2035, has the potential to continue the growth trend in milk production (Agricultural outlook, 2024; Parzonko &Bórawski, 2020), it is in Cluster 1. Latvia, which is not in the same cluster as Estonia and Lithuania, has the opportunity to improve its dairy sector (improving market competitiveness and increasing milk productivity) and join Cluster 1.

Conclusions

1. In major European countries (including the Baltics countries), milk yield is higher than the number of cows being milked. This trend may indicate an improvement in the efficiency of the industry, for example, by farmers selecting cows with the highest genetic potential, which can produce more milk during lactation.
2. Global events, including abolishment of milk quotas, the COVID-19 pandemic and the Russia-Ukraine war, have had a significant impact on milk prices and trade model. This has resulted in disruptions in supply chains, rising raw material and energy costs and changes in trade relations. This shows that the dairy sector is at risk of crises.
3. Cluster analysis allowed dividing European countries into 6 clusters, which shows that regional differences in the dairy sector of European countries are significant. The weaker indicators in dairy production are in Eastern European and Balkan countries, but Mediterranean, Central European, Nordic and Western European countries are with medium dairy production. Germany and Ireland are typical representative countries of their cluster with well-developed dairy production.
4. The fact that the dairy sector differs among European countries is also visible among the Baltic countries, where Latvia is not in the same cluster as Lithuania and Estonia. Considering that Poland is one of the largest milk producers in Europe and is in a more competitive cluster, Latvia should aim to join this cluster. By adopting best practices from Poland, Latvia could strengthen its dairy sector and achieve greater competitiveness in the European market.

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SMART AND RESPONSIBLE MARKETING COMMUNICATION: A LITERATURE REVIEW OF THE FOUNDATIONS, CHALLENGES, AND FUTURE DIRECTIONS

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Abstract
Creating a culture of responsible marketing communication is vital to the long-term survival of any organization or product. Clarity and accuracy in the presentation of a business will improve customer relations and improve the company's reputation. The aim of this study is to explore the theoretical discourses of marketing communication through a broad analysis of the on-going scholarly work focused on integration of sustainability goals into consumer behaviour frameworks. The authors have conducted a narrative literature review highlighting the latest theoretical foundations, challenges and future directions of marketing communication by using articles from high-ranking marketing journals through co-citation analysis and qualitative thematic analysis. The authors' extensive literature studies lead to the conclusion that the development of marketing communications is closely linked to new vectors of consumer behaviours, perceptions, and sustainable consumerism which motivates enterprises to proactively adapt their marketing strategies in alignment with sustainability goals. In essence, this study provides a valuable synthesis of the latest trends and theoretical advancements in marketing theory, which could support marketing researchers and business professionals in further development of their conceptual frameworks around sustainability issues and consumer expectations.
Keywords: sustainable marketing, enviropreneurial marketing, corporate responsibility, consumer behaviour.

Introduction

In a time of increased digital transformation, consumer awareness, and sustainability goals, marketing communication is experiencing a significant transformation.

When building competitive advantage through sustainable marketing, it is essential to evaluate how it may affect a company's reputation and consumers' willingness to purchase (Puma-Flores & Rosa-Diaz, 2024).

All sectors of economy, with agrarian economics playing a central role among them due to its direct interaction with natural resources and ecosystems, need smart and responsible marketing communication that connects marketing innovation, sustainability, policy coherence and consumer trust. In order to support sustainable growth, the literature review can serve as a baseline for developing new strategies. Still, despite the increasing significance of sustainable and digital marketing, there is a lack of integrated concepts that combine smart and responsible marketing communication.

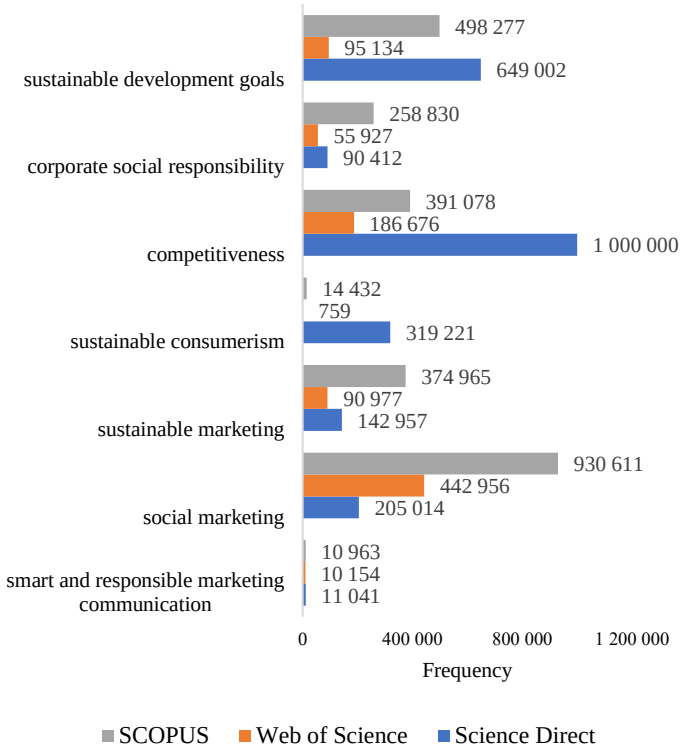
'Green,' 'environmentally conscious', and 'active' consumption has been the subject of debate in Western Europe and North America since the 1980s. Battery companies, beverage companies, automobile companies, cleaning product companies, detergent makers and food entrepreneurs share a common interest in the environment as a competitive factor. In response, eco-marketing developed, addressing the aim audience of 'green' consumers willing to pay more for environmentally-friendly products (Bianchi et al., 2023). Today a number of studies give evidence that consumers' interest in environmentally friendly products and services is growing. For example, already in 2020, a study conducted by NielsenIQ found that 78% of US consumers say that a sustainable lifestyle is important to them (Frey et al., 2023). Whereas Simon-Kucher latest Global Sustainability Study (2024), which is not limited solely to the US market but is a multinational study, covering 17 countries across the Americas, Europe, and Asia, shows that 71% of consumers say they have made at least some sustainable purchases over the past year, and 66% say they are willing to pay more for sustainable products. Therefore, the authors conclude that consumers' expectations for brands and businesses to engage in sustainable marketing practices are evolving globally (Simon-Kucher, 2024). As a method to prevent the harmful impacts of recent patterns of living on social inequalities, biodiversity loss, and climate change, sustainable consumption is currently being positioned as a fundamental priority within far-reaching policies around the world; this emphasis can be successfully used as one of the marketing components if the goods or services produced by the company are in line with sustainable consumption. In this context, sustainable marketing refers to a marketing approach that promotes sustainable development or considers sustainability issues in a particular frame of reference anchored on developing long-lasting relationships with customers. As a result, sustainable solutions provide superior value to customers as a result of the analysis of their needs and wishes. They must also be communicated and distributed effectively to the selected target groups, taking into account social and ecological factors throughout the entire process (Peattie & Belz, 2010; Zeverte-Rivza, 2016). In fact, businesses must implement four 'S' into their marketing activity: customer satisfaction, good or service safety, social acceptability, and sustainability (Altinbasak-Farina & Burnaz, 2019). Consequently, only those businesses who control their damaging impacts on civilization and the environment will have the ability to endure nowadays and henceforth (Daub & Ergenzinger, 2005). This study explores the role of smart and responsible marketing communication in enhancing the ability of enterprises to compete within a sustainable development framework.

Materials and Methods

The aim of the study was: to reveal the foundations, challenges, and future directions of the marketing domain. Based on a narrative literature review the specific research tasks were posed as follows: 1) to characterize the evolution of marketing communication in line with factors that influence consumer behaviour; 2) to identify new impactful vectors that influence the adaptability of enterprises' marketing communication to reach sustainable development goals; 3) to summarize recent marketing discourses that promote a balance between consumer behaviour and sustainability. This study consists of a narrative literature review to explore theoretical frameworks behind smart and responsible marketing communication. By a narrative literature review authors provide a wider perspective on the importance and relevance of the topic with sustainability trends, to capture a wide scope of perspectives and theories. The data was collected from various academic databases and literature sources, including Science Direct, Web of Science, Google Scholar, and Taylor & Francis eBooks. These repositories were chosen because they offer a comprehensive collection of representation of quality - reviewed academic research publications in marketing and sustainability. For instance, Web of Science and Scopus provide comprehensive access to globally accredited journals, whilst Google Scholar offers large search that includes relevant policy documents and new approaches to sustainable marketing. Taylor & Francis, and Science Direct were selected due to their strong collections in the social sciences and eco-friendly focused marketing. The following key words and combinations of key words were used in the most relevant literature search: smart and responsible marketing communication, social marketing, sustainable marketing, sustainable consumerism, competitiveness, corporate social responsibility, sustainable development goals. The frequency of use of these keywords in Science Direct, Web of Science, and SCOPUS is shown in Figure 1.

Figure 1

Keyword frequency of use in Science Direct, Web of Science, and SCOPUS in total



As Figure 2 shows, corporate social responsibility as a keyword has a steady growth in such academic databases as SCOPUS, Web of Science, and Science Direct. This pattern represents the importance of corporate social responsibility.

Similarly to Figure 2, Figure 3 shows the increasing frequency of the use of sustainable marketing in all three academic databases as an important keyword and dimension to study.

This indicates the increasing importance of research in this area, driven by a growing interest from businesses and researchers in understanding the influences on consumer attitudes and perceptions, and their interrelationships.

Figure 2
Corporate social responsibility as a keyword frequency of use in Science Direct, Web of Science, and SCOPUS 2020-2024

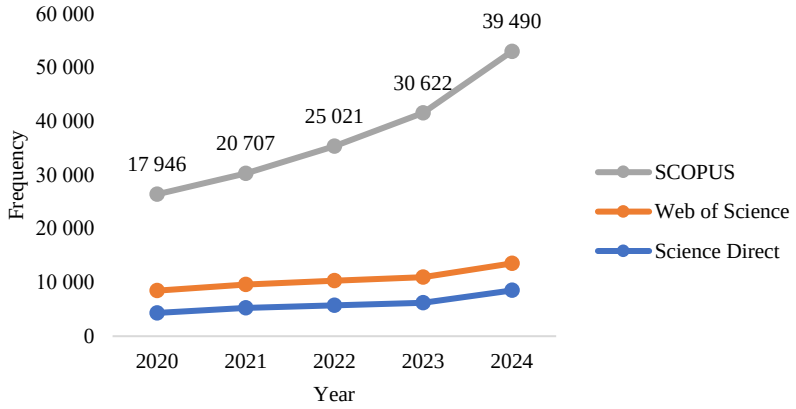
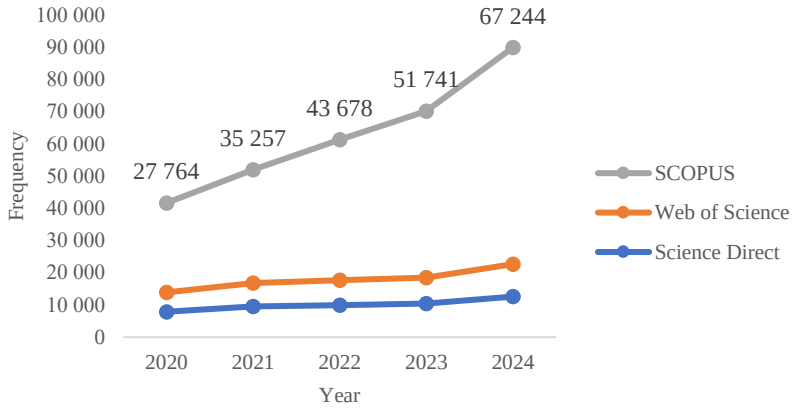


Figure 3
Sustainable marketing as a keyword frequency of use in Science Direct, Web of Science, and SCOPUS 2020-2024



In this study, multiple data sources were used to enhance validity and reliability.

Results and Discussion

Corporate social responsibility (CSR) is able to give many benefits to companies - customer loyalty, corporate reputation, and profitability. To achieve business objectives, it is essential to understand how stakeholders perceive these activities. As a result, most CSR definitions emphasize stakeholders' needs. For example, the European Commission says that CSR refers to corporations incorporating societal and environmental issues into their everyday business practices and interactions with major stakeholders (Mubushar et al., 2021). By embedding social, environmental, ethical, human rights, and consumer concerns within their businesses and key strategies in close participation with stakeholders, enterprises can achieve full CSR compliance (Tamvada, 2020). To meet this aim, CSR is defined as 'the responsibility of companies for their influence on society' (Mubushar et al., 2021). Many authors have connected the concepts of CSR with the concepts of sustainability and circular economy, regarding CSR as a corporate management philosophy that is more inclusive of sustainability. Through these CSR definitions, the Sustainable development goals (SDGs) and sustainable behaviour in general are achieved for citizens, institutions and organizations (Dahlsrud, 2008).

Social marketing can help to achieve SDGs while improving the regulatory framework and awareness campaigns which are traditionally the most widespread environmental strategies.

Currently, climate change and its implications are one of humanity's major problems. This is where consumption behaviour plays a crucial part (Escario, 2020). Research indicates that high-intensity environmental awareness campaigns are effective in increasing supportive attitudes. For instance, social marketing simplifies complicated messages and presents them in a way that they are easily understood by certain audiences (Sewak et al., 2021) as well as providing society with specific steps and tips to help resolve challenging issues (Schultz, 2014). There are many in-depth analyses of the influencing factors (such as beliefs, values, moral obligation, social norms, self-efficacy, problem awareness) on the adoption of pro-environmental behaviours provided by

social marketing. This type of analysis helps understand possible barriers and examine opportunities to overcome them. As part of social marketing, analysis is also conducted to determine who or what influences the target audience's behaviour, particularly in competitive environments (Andreasen, 2002). The competition analysis can be carried out in a variety of ways, including through comparable schemes or promotions, other behaviours, goods and services, reports. Implemented analysis of competition is important as it provides social marketing specialists with wider view on the strengths and weaknesses of analysed programmes or campaigns in comparison to their competitors. Consequently, marketers are able to improve strategies, messages, identify opportunities to reach and engage with the target audience.

Social marketing is capable of proposing an efficient approach to the design and implementation of environmental programs that can enhance how governments and public institutions frame and select public policies; additionally, it can build longer-lasting relationships with society and other stakeholders (Tkaczhynski, 2020).

Through smart and responsible marketing communication, companies can promote pro-environmental behaviour by informing, educating and persuading a target audience to reshape its behaviours, thereby influencing their values, perceptions, and societal stance.

In the study about shifting markets for Climate-smart growth exploring tips for effective marketing communication, the authors used Stimuli-organism-response (S-O-R) theory which provides those environmental stimuli (incentives) that influence such cognitive processes as attention, perception, and evaluation, which leads to such behavioural reactions as attitudes, beliefs, and actions (Shaik et al., 2024).

S-O-R theory proposes that connection between environmental stimuli and behaviour reactions is determined by internal factors such as motivation, behaviour and values. Individual interpretation and response to environmental stimuli can be influenced by these internal factors. Consequently, this approach recommends organizations to use marketing communication to affect the internal factors that determine environmental stimuli and behavioural reactions connection (Shaik et al., 2024). For instance, in smart and responsible marketing communication transparent and appropriate sustainability-related advertisements, CSR and legal framework have been identified as main stimuli impacting awareness and perceptions among consumers. Then consumers use internal psychological components such as values, attitudes, perceptions and social standards to reprocess these stimuli. For example, CSR reports and messages will be treated more favourably by consumers with environmentally conscious consumption and eco-friendly life values. By these interconnected stages enterprises are able to achieve higher loyalty to the brand, consumers' intention to purchase environmentally friendly goods and services or support for sustainable actions that can be measured through customer feedback.

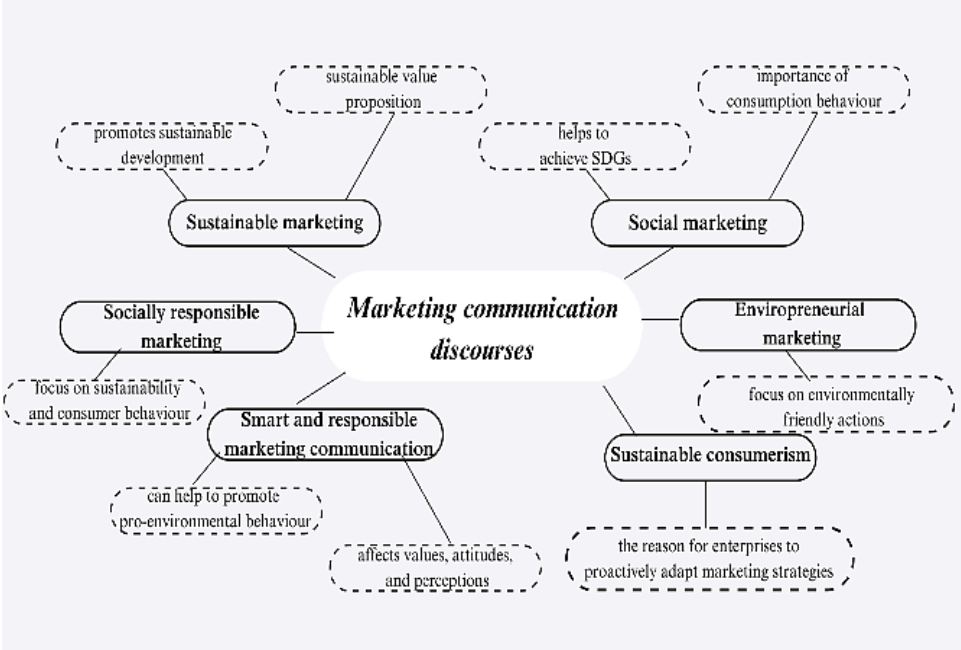
Marketing campaigns modelled after environmentally-conscious consumers' values and perceptions are considered part of an entrepreneurial marketing strategy. Through the influence of marketing communication, enviropreneurial marketing strategies and strategic plans are affected by perceptions of climate change. Enviropreneurial marketing refers to the practices of marketing by enterprises that are focused on environmentally friendly actions in response to their competitive advantages and their responsibility to serve people and the environment (Jaini, & Hussin, 2019). Socially responsible businesses by choosing an appropriate marketing communication, green marketing strategy, are able to achieve new business opportunities and competitive advantages, as well as making an important investment to protect environment and the world from environmental disasters. Consequently, those companies who choose green and smart marketing as a part of the socially responsible marketing communication by focusing on sustainability and consumer behaviour, are able to achieve the important benefits of it, for instance, a competitive advantage, increase of company's value, improved brand loyalty, as well as engage and attract new investors (Nadanyiova et al., 2020).

One of company's strategic approach called socially responsible marketing (SRM) increases inclusion of ethical, environmental, and socially conscious principles into their marketing practices (Ferrell & Ferrell, 2022). With this approach businesses can reach high level of clear communication between business and customers. Moreover, SRM helps implement diversity, equity, and inclusion (DEI) within organizational settings (Trkulja et al., 2024).

Marketing communication discourses seek to address and respond to evolving trends in environmental requirements, evolution and changing consumer behaviour. Marketing techniques that use honest and transparent communication to reach consumers are evolving as green thinking and sustainable values become more prevalent.

Based on their 2024 study, Braga et al. identified several key cornerstones for responsible sustainability communication in marketing: sustainability reporting and advertising, consumer responses and perceptions, promoting pro-sustainable behavior, integration across the value chain, strategies of small and medium-sized enterprises (SMEs), internal communication of sustainability strategies, and effectiveness in behavioral change.

Figure 4
Concise marketing communication discourses through lense of impact of changing values, attitudes, perceptions, and policies



The main focus of these discussed themes are transparency and accountability of environmentally friendly actions made in line with institutional and stakeholder theories, possible approaches to impact perceptions and behaviors of consumers toward sustainability, underlining challenges in avoiding greenwashing. These cornerstones help to maintain strong connection with consumers and focus on how initiatives of sustainability and marketing communication integrated across the value chain can stimulate market shifts towards sustainable consumption (Braga et al., 2024; Popluga & Grinberga-Zalite, 2022).

In the field of the responsible marketing, there is another additional helpful tool to implement ethical approaches in marketing communications and that is the International Chamber of Commerce (ICC) Advertising and Marketing Communications Code used worldwide, including such countries as Switzerland, Poland, Finland, United Arab Emirates, Canada, Mexico, Portugal, Bulgaria, Greece, Romania, Italy, Spain, France and others. Founded in 1937, it has provided consumers with legal, honest, decent, and truthful advertising, promoting both advertising freedom and consumer protection (Chatterjee, 2024). This proves that a common worldwide shared agenda of smart and responsible marketing communication can build strong long-term relationships between enterprises and consumers. The EU commits to fair and ethical trade, which also means that the voluntary labelling of products can provide consumers with more information about their sustainability, increasing conscious sustainable consumerism. It is possible to promote more sustainable trade by implementing transparent schemes.

Conclusions

1. Smart and responsible marketing communication involves a certain list of impactful factors which influence consumer perceptions and behaviours toward sustainability, environmentally friendly actions, and greenwashing.
2. A unified legal framework plays a crucial role in helping businesses achieve greater results towards sustainability development goals through their entrepreneurship, while encouraging both existing and potential consumers to make conscious, sustainable consumption choices.
3. Social, green, and responsible marketing is closely linked to the impact on consumer perceptions of possible everyday actions that can reduce human impact on the environment by minimizing unconsidered, unnecessary purchases.
4. Corporate social responsibility, social marketing, sustainable marketing and other keywords and their frequency of use in such academic databases as SCOPUS, Science Direct, and Web of Science show an upward trend of use in research, where responsible marketing communication becomes an increasingly important topic that has strong relation with environment, climate, and policy changes.
5. Enviropreneurial marketing strategies help businesses achieve new business opportunities and gain competitive advantages while they choose to invest into important environment protection practices, promotion pro-sustainable behavior, and upholding corporate social responsibility.
6. By analysing marketing communication discourses, it becomes clearer that sustainability is a common denominator that combines compliance to environmental

and social objectives (e.g. SDGs, environmentally-friendly actions, and conscious consumption).

7. The use of key components of successful smart and responsible marketing – such as transparency, accountability, and relevance to sustainability and climate changes – shapes consumers trust, enhances the credibility of marketing communication, and strengthens consumers engagement.

Acknowledgements

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ENHANCING STATE SUPPORT FOR LATVIAN BIOECONOMY ENTERPRISES: CHALLENGES AND OPPORTUNITIES

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Abstract
The bioeconomy plays a vital role in achieving sustainability goals as an integral part of the European Green Deal. However, transitioning to bioeconomy-driven business models can require significant investments, such as introducing advanced technologies and workforce training, which can pose challenges for small rural enterprises. The aim of this study is to identify the obstacles that Latvian entrepreneurs face when transforming their businesses in alignment with the Green Deal and to assess existing opportunities for state support, ultimately providing recommendations for improvement. The study assesses the European Union and Latvian regulatory frameworks in light of the opportunities presented by the Bioeconomy and Green Deal strategies, with a focus on objectives, outcomes, and support measures. The survey data of existing and future entrepreneurs were statistically analyzed using the SPSS program, which involved central trends and location measures, a T-test, and factor analysis. The findings reveal that although Latvia has updated its regulatory framework to promote the Green Deal, the available state support is insufficient to facilitate enterprises' transition to bioeconomic activities. The surveyed entrepreneurs emphasize the need for enhanced financial support, including funding for advanced technologies, subsidies, and grants to help offset transformation costs. To enhance state support, it is crucial to harmonize policies and implement regulatory adjustments that promote sustainable business development in Latvia's rural regions. Strengthening these measures will enable small enterprises to successfully transition to the bioeconomy, contributing to broader sustainability and economic resilience goals.
Keywords: bioeconomy, enterprises, European Union Green Deal, state support, sustainability.

Introduction

The Small Business Act for Europe, adopted in 2008, emphasizes the diversity of small and medium-sized enterprises. According to the basic principles of this act, state support for enterprises should be tailored to their specific needs and characteristics. Following principle 9 of the Act, Member States should enable SMEs to turn environmental challenges into opportunities. Thus, this principle indirectly indicates the need for state support, for example, by transforming the business model in line with the European Union's Green Deal (GD). Following the practical implementation of the principles of this Act in the Member States, the EC has recognized that access to finance for enterprises remains a challenge despite the measures taken. However, the ambitious European Union (EU) plans for economic development and recovery do not include specific measures specifically to support enterprises, leaving their determination to each Member State.

Moreover, as digital tools evolve, the significance of associated risks becomes increasingly acknowledged by bioeconomy enterprises (Zeverte-Rivza et al., 2024).

Several research studies have found that government subsidies to enterprises, including those supporting green innovation, are effective in easing financing constraints for businesses (e.g., Chen et al., 2024). However, European entrepreneurs often lack state support or incentives that would promote the implementation of bioeconomy principles or efforts to seek business alternatives to bioresources, thereby creating more excellent added value (Dietz et al., 2018; Salvador et al., 2022).

The EU offers support to the Member States to promote the bioeconomy. There are different understandings of what the bioeconomy is and how to promote it in the national economy. The extent to which support measures ensure the growth of a sustainable bioeconomy depends on how well the national bioeconomy strategy is designed (Dietz et al., 2018). There are also different views on the areas or sectors of the bioeconomy. Consequently, the classification of business types or sectors depends on the direction of bioeconomic development accepted in the country, which is outlined in the relevant national strategies. Thus, the framework for promoting the bioeconomy also differs (Dietz et al., 2018).

The concept of the bioeconomy, introduced by the European Commission in 2018, relates to the transition from fossil resources to bioresources. Gradually, areas that apply circular economy principles are being introduced into the bioeconomy, emphasizing innovation and substitute products, using sustainable business processes and services, integrating knowledge from biotechnology, and producing healthy food. Along with improving sustainability practices, the boundaries between bioeconomy industries are also blurring (Salvador et al., 2022).

In Latvia, the bioeconomy refers to those industries within the national economy that utilize bioresources to produce food and feed, energy, goods, and services, as well as the primary production of bioresources and their subsequent processing.

The aim of this study is to identify the obstacles that Latvian entrepreneurs face when transforming their businesses in alignment with the GD and to assess existing opportunities for state support, ultimately providing recommendations for improvement.

Materials and Methods

To achieve the overarching aim of the research, desk research was conducted, involving an in-depth

qualitative analysis of literature sources and EU and Latvian policy documents regarding potential support for businesses operating in the bioeconomy and the Green Deal. The primary EU and Latvian policy documents reviewed are as follows:

1) EU Bioeconomy Strategy (adopted in 2018);
2) EU Green Deal Strategy (adopted in 2019);
3) EU Common Agricultural Policy 2023-2027 (adopted in 2021);
4) Latvian National Bioeconomy Strategy (adopted in 2017);
5) Latvia's Climate Neutrality Strategy by 2050 (approved in 2020);
6) Latvian Common Agricultural Policy Strategic Plan 2023-2027 (adopted in 2022).

The research has found that the objectives, achievable tasks, and measures of the EU Bioeconomy Strategy are included in the EU GD framework (Liobikienė & Miceikienė, 2023).

To continue the research, a questionnaire was developed and distributed among existing and potential entrepreneurs to gauge their awareness and attitude toward the GD in Latvia. The survey aimed to determine the respondents' understanding of the changes to be introduced in business activities, based on whether they had business experience in implementing the GD.

The survey included 10 questions regarding the respondents' awareness of applying the GD requirements in business, the strategies included in the GD concept, and other aspects. The survey received 174 valid responses. The present research presents part of a broader assessment that reveals the challenges identified by the respondents and their views on how the implementation of the GD could affect their future activities, depending on the sector. It also indicates the desired state support measures. It examines whether the financial needs of companies align with those outlined in EU and Latvian policy documents promoting the bioeconomy.

Results and Discussion

It is highlighted that there are still challenges regarding the framework for supporting the effective transformation of business models into bioeconomy ones. Entrepreneurs must make significant investments to adapt their economic activities to meet new environmental standards and expectations (Salvador et al., 2022).

When assessing EU policy documents, it has been found that the EU's planned direction, which promotes economic development and support measures, is geared towards achieving the United Nations climate neutrality goals. It is worth noting that the EU Bioeconomy Strategy and the GD are aligned to promote sustainability, reduce environmental impact, and drive economic growth through the sustainable use of bio-based resources and the implementation of circular economy principles. The European Bioeconomy Strategy and the GD are interconnected with various EU policies, including the Common Agricultural Policy (CAP), the Farm to Fork Strategy, and the Biodiversity Strategy. This integration ensures a cohesive approach to achieving sustainability and environmental goals across various industries. However, the Bioeconomy Strategy focuses more on bio-based resources and related sectors. At the same time, the GD provides a comprehensive framework for transforming the entire EU economy toward sustainability and climate neutrality (Liobikienė & Miceikienė, 2023). While EU public support is included in both the Bioeconomy Strategy and the GD to promote sustainable transitions through financial support and regulatory frameworks, each strategy also includes individual measures tailored to its specific objectives and sectoral focus.

The EU has introduced several state support measures specifically designed to assist small and new businesses in rural areas, thereby facilitating their alignment with the objectives of the EU Bioeconomy Strategy and the European Green Deal (Table 1). This is particularly evident when providing financial measures for a sustainable transition. However, each strategy includes measures tailored to their specific objectives and support focus. Consequently, the state support for investment outlined in the EU's multiannual financial framework sometimes overlaps with subordinate policy documents.

Latvia is one of the few EU Member States to have developed a National Bioeconomy Strategy. It includes specific objectives and measures to support the transition to a bioeconomy with a focus on sustainable agriculture, forestry, waste management, bioenergy production, and biotechnology research. In Latvia, the Bioeconomy Strategy was adopted in 2017, prior to the development of the EU's Green Deal strategy, which in turn promotes the development of the bioeconomy in the EU.

Latvia's Climate Neutrality Strategy, approved in 2020, is a long-term policy document that serves as a basis for policymakers to implement approaches outlined in the EU Green Deal Strategy, including the development of the bioeconomy. The Climate Neutrality Strategy supports measures that promote the development and implementation of climate technology innovations in Latvia. Although these technological solutions are primarily aimed at reducing direct greenhouse gas (GHG) emissions in energy, transportation, agriculture, waste management, and industrial processes, they directly or indirectly affect almost any company in its green transformation of business activities. It is also essential to focus on business management capacity-building skills to bring the green transformation to life (Salvador et al., 2022). It is recognized (Bröring & Vanacker, 2022; Salvador et al., 2022) that companies from various industries may be involved in the bioeconomy production process or chain.

Table 1

Comparison of European Green Deal and Bioeconomy business support measures

Similarities	***Differences***
1. Both strategies benefit from overarching frameworks that streamline state support processes and promote sustainable investments.	1. The Bioeconomy Strategy places a strong emphasis on research and innovation specific to bio-based industries, with earmarked funding to develop sustainable biological resources.
2. Financial instruments and regulatory adjustments are employed in both strategies to encourage innovation and the adoption of sustainable practices across various industries.	2. The GD encompasses a broader range of initiatives, including industrial decarbonization, energy transition, and infrastructure development, with tailored state support measures for industries such as steel manufacturing and clean technology production.
3. The EU CAP is a primary instrument for supporting rural development across the EU. It provides funding and actions aimed at enhancing the vibrancy and economic viability of rural areas, thereby reinforcing their social, environmental, and economic sustainability.	3. The EU's Bioeconomy Strategy includes launching a Strategic Deployment Agenda for Sustainable Food and Farming Systems, which aims to promote sustainable food and farming systems, forestry, and bio-based products. This initiative supports the rapid deployment of local economies across Europe, with a focus on rural areas.
4. As part of the GD, the EU has established the Social Climate Fund to support vulnerable residents and small businesses in the green transition. This fund allocates investments to assist those most affected by energy or mobility poverty, ensuring equitable opportunities in the shift toward sustainability.	4. The GD emphasizes environmental goals and supports small and medium-sized farms, young farmers, and gender balance in agriculture. This support is part of the broader reforms aimed at achieving the GD's objectives.
5. Both strategies support job creation. The bioeconomy is expected to generate numerous green jobs, particularly in rural and coastal regions. The GD also seeks to stimulate economic activity through green investments and sustainable innovation.	5. The Bioeconomy Strategy promotes education and skills in the bioeconomy. It emphasizes research and innovation to drive the sustainable use of biological resources.
	6. The GD provides a wide range of public and private investments to support the green transition.

Consequently, they may face similar barriers, challenges, drivers, and opportunities as companies traditionally focused on bioeconomy industries (Table 2). Therefore, our research study does not focus on the specific needs of individual industries.

Table 2

Key challenges and opportunities for companies in the development of the bioeconomy (based on: Bröring & Vanacker, 2022; Salvador et al., 2022; Thomchick et al., 2024)

Challenges	***Opportunities***
1. Lack of financial resources to move towards more circular practices and difficulties related to logistics	1. State subsidies, financial incentives, and investments
2. Lack of appropriate technology	2. Development of or access to technology
3. Lack of knowledge and specific skills	3. Opportunity to optimize commercial operations while increasing the company's value
4. Lack of awareness and inadequate policy/regulation	4. Opportunities to penetrate new market segments and expand the use of bio-based raw materials, products, and services
5. Lack of or insufficient government support to overcome various obstacles to business transformation	

The survey results demonstrated that significant upfront investments often hampered the transition to sustainable and bioeconomy-friendly business models in technology, infrastructure, and training. This can be a severe financial burden, especially for small businesses.

The survey identified the respondents' opinions: 'In which sectors in Latvia, in your opinion, should measures be implemented to reduce GHG emissions?' The statistical analysis presented includes Levene's test for Equality of Variances and t-tests for Equality of Means across various economic sectors (Table 3).

The Levene's Test was used to determine whether variances were equal across the groups. Significant variance differences were found for 'Waste Management' ($p = 0.001$), 'Trade' ($p = 0.001$), and 'Other' ($p = 0.000$), requiring interpretation using the unequal variances t-test. While most sectors showed no significant differences in means, the 'Trade' sector indicated areas where further investigation might be needed. The results for 'Waste Management' and 'Trade' should be interpreted cautiously due to variance differences.

The 'T-test for Equality of Means' showed that the 'Trade' sector was marginally significant ($p = 0.057$ with equal variances, $p = 0.062$ without equal variances). However, due to the objectives set, in terms of potential impacts, the waste management sector will likely be more affected by the GD requirements than the trade sector.

All other sectors (Construction, Energy, Agriculture, Forestry, Industry, Transport, and Food Production) had non-significant results ($p > 0.05$), indicating no firm evidence of mean differences between the groups.

Table 3

Levene's Test for Equality of Variances and t-tests for Equality of Means across various economic sectors

		Levene's Test for Equality of Variances		t-test for Equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
									Lower	Upper
Waste management	Equal variances assumed	12.153	**0.001**	1.693	169	0.092	0.028	0.017	-0.005	0.061
	Equal variances not assumed			1.424	70.000	0.159	0.028	0.020	-0.011	0.068
Construction	Equal variances assumed	0.839	0.177	-0.709	174	0.479	-0.052	0.074	-0.198	0.093
	Equal variances not assumed			-0.705	149.515	0.482	-0.052	0.074	-0.199	0.094
Energy	Equal variances assumed	5.443	0.021	-1.138	174	0.257	-0.084	0.074	-0.231	0.062
	Equal variances not assumed			-1.149	157.505	0.252	-0.084	0.073	-0.230	0.061
Agriculture	Equal variances assumed	0.182	0.670	-0.210	174	0.834	-0.016	0.076	-0.166	0.134
	Equal variances not assumed			-0.210	153.114	0.834	-0.016	0.076	-0.167	0.135
Forestry	Equal variances assumed	2.024	0.157	-0.696	174	0.487	-0.052	0.075	-0.201	0.096
	Equal variances not assumed			-0.699	155.052	0.485	-0.052	0.075	-0.200	0.096
Industry	Equal variances assumed	0.212	0.645	0.232	174	0.817	0.015	0.065	-0.113	0.142
	Equal variances not assumed			0.230	150.337	0.818	0.015	0.065	-0.113	0.143

Trade	Equal variances assumed	11.392	**0.001**	-1.913	174	0.057	-0.138	0.072	-0.280	**0.004**
	Equal variances not assumed			-1.880	143.013	0.062	-0.138	0.073	-0.283	0.007
Transport	Equal variances assumed	2.256	0.135	-0.738	174	0.461	-0.045	0.061	-0.165	0.075
	Equal variances not assumed			-0.750	161.102	0.454	-0.045	0.060	-0.163	0.073
Food production	Equal variances assumed	0.226	0.635	0.236	174	0.814	0.017	0.072	-0.126	0.160
	Equal variances not assumed			0.236	153.934	0.813	0.017	0.072	-0.126	0.160

Table 4 presents the distribution of answers given by respondents with and without business experience. In their opinion, the GD's requirements for reducing GHG emissions are most applicable to waste sorting, industry, and transportation. This indicates a general understanding among current and future entrepreneurs that the requirement to achieve GHG affects most industries.

The t-test revealed no significant differences between respondents with and without experience in business management. The total responses should be counted; however, we performed a cross-tabulation analysis for a more detailed examination of the results.

Table 4

Distribution of the responses by the respondents with and without business experience regarding GHG emission measure impact on industry

	Waste Management	Construction	Energy	Agriculture	Forestry	Industry	Trade	Transport	Food production
Experience	44	23	30	26	17	42	12	49	17
No experience	69	42	45	43	23	75	22	69	39
Not indicated	0	1	1	2	0	2	0	3	0
Total	**113**	**66**	**76**	**71**	**40**	**119**	**34**	**121**	**56**

The survey identified the respondents' opinions on: 'How, in your opinion, will the introduction of the GD requirements affect the operation and performance of Latvian micro, small, and medium enterprises?'. The statistical analysis included Levene's test for Equality of Variances and t-tests for Equality of means to assess the impact of implementing the GD requirements on business performance. None of the tests for differences in means across the measures, except one, reached statistical significance ($p > 0.05$ for all others). Although some variables, such as 'The company's competitiveness will increase', had p-values closer to 0.05 ($p = 0.092$). The overall findings suggested that there were no significant differences between the two groups for any of the tested perceptions regarding increases or decreases in revenue, expenses, productivity, or competitiveness. An analysis of the number of responses regarding the potential impact of introducing GD requirements among respondents with and without business experience (Table 5) revealed that the majority indicated that business performance expenses might increase. This suggests that one factor contributing to increased competitiveness may be the rising costs associated with the transformation process.

In addition, the survey asked what support measures would help Latvian enterprises to transform or adapt their operations in line with the GD.

The survey results showed that entrepreneurship requires diverse support Figure 1.

Most respondents indicated that they would need state support to obtain financing, subsidies, grants, and employee training. Many found 'green' business best practices applicable, as well as improving digital skills.

The Latvian Common Agricultural Policy Strategic Plan for 2023-2027 envisions balanced state support to achieve national and EU climate objectives, targeting different audiences with a particular emphasis on small and new rural entrepreneurs, as well as organic farmers. Support for rural enterprises in the coming years is intended to:

a) increase value added by cooperating and producing competitive products for the local and export markets;

b) increase farm incomes to the average in the country;
c) promote knowledge-based entrepreneurship by fostering innovation and the implementation of scientific research findings in practice;
d) support farms in effectively using resources and adapting to climate change.

In Latvia, business-focused bank support is problematic from the OECD's perspective in the 2024 review. Financial institutions are avoiding the risk associated with the uncertainty created by the GD.

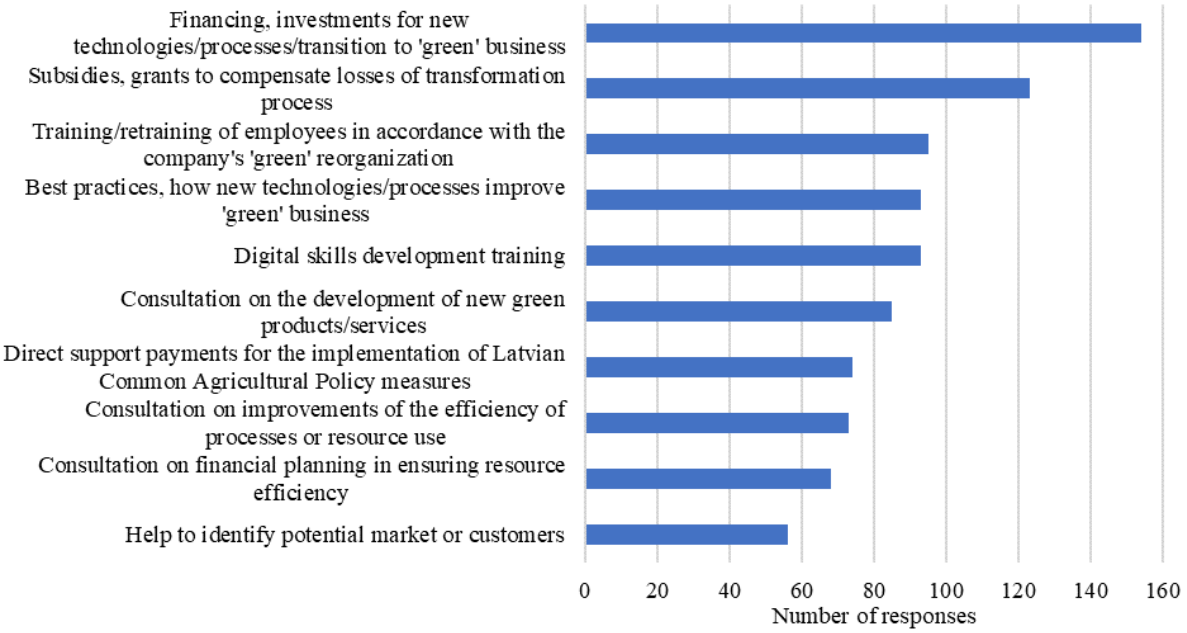
Table 5

Distribution of the responses by the respondents with and without business experience regarding the impact of the implementation of the Green Deal requirements on entrepreneurship

Impact of GD requirements	***Experience***	***No experience***	***Not indicated***	***Total***
revenue will increase	12	13	0	**25**
expenses will increase	43	75	2	**120**
productivity will increase	23	23	0	**46**
company's competitiveness will increase	28	50	0	**78**
other impact	3	1	0	**4**
revenue will decrease	17	26	1	**44**
expenses will decrease	3	8	0	**11**
productivity will decrease	12	15	0	**27**
company's competitiveness will decrease	13	9	0	**22**

Figure 1

Responses on state support within the framework of the European Union's Green Deal (n=174)



Although the OECD does not focus on specific policy strategies, its recommendations can also be applied to support the GD and the bioeconomy. The OECD notes that in Latvia, numerous small-scale programs exist with varying application procedures and requirements. Several ministries and agencies assume support functions. Consequently, comprehensive, centralized, and focused support is lacking. Support policies, in general, should be improved, including an impact assessment of support use. Based on the evaluation, the supply of support programmes should be expanded, and the efficiency of their use should be improved. It is true not only for Latvia, but there is also lack of systematic empirical analysis of how environmental policy promotes the transformation of high-quality green enterprises and the impact that financial constraints may have (Chen et al., 2024). Recognizing that policies and politics are essential elements of sustainability transitions, the authors draw attention to synergies between policy regulation and control instruments (Thomchick et al., 2024). Some authors (Dietz et al., 2018) believe that the primary challenge in developing a sustainable bioeconomy is to establish governance policies that effectively support its growth. These support measures can include research and development strategies, enhancing the competiti-

veness of organic products through subsidies, and implementing awareness-raising campaigns in society to promote more responsible and sustainable consumption. The bioeconomy encompasses a diverse range of stakeholders, including government institutions, industries, manufacturing companies, environmental organizations, and civil society. Developing and improving a thriving bioeconomy depends on the successful involvement and coordinated action of all stakeholders (Thomchick et al., 2024).

Analyzing the factors influencing the transition to bioeconomy, some authors (Zihare et al., 2021) emphasize that for a practical policy framework, it is essential to support the development and implementation of innovations, new technologies, and production methods. In Latvia, compared to other countries, the number of biotechnology companies, including those involved in environmental, industrial, and agricultural biotechnology, is low. The authors recommend establishing a three-fold connection for the successful transition to a bioeconomy in policy, research, innovation, and technology.

Overall, while the EU Bioeconomy Strategy and the European Green Deal offer significant opportunities for business development through sustainable practices and economic diversification, they also pose challenges in terms of implementation costs, regulatory compliance, and market adaptation. Addressing these challenges requires concerted efforts, including financial support and advisory assistance, to enable businesses to transition effectively to the bioeconomy.

Conclusions

1. When creating an effective state support policy, the priority should be based on the locally identified challenges that most entrepreneurs face. Entrepreneurs require a range of support tailored to the unique needs of their industry.
2. Companies that envisage introducing bio-innovative processes and technologies, promoting the development of new 'green' products and services, and attracting new markets should receive focused support.
3. Developing successful bioeconomic support policies requires the involvement of stakeholders, including public authorities, industries, manufacturing companies, environmental organizations, and civil society.

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AGROECOLOGY AS A SOLUTION FOR AGRICULTURAL AND ENVIRONMENTAL SUSTAINABILITY: THE PERSPECTIVE OF BIOREGIONS

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Abstract
Sustainable agriculture is considered a crucial solution for developing technologies and practices that do not harm the environment, are accessible to farmers, and enhance food production. The current lifestyle of societies is widely regarded as the primary cause of environmental issues, leading to a slowdown in overall development, which must be addressed to ensure ecological sustainability. However, societal needs cannot be fully met based solely on the environmental dimension; economic, social, and cultural factors are equally important. This indicates that new approaches are necessary, which integrate biological and ecological processes into food production, reduce the use of non-renewable resources that harm both the environment and human health and effectively leverage the knowledge and capacities of local farmers. The growing interest in bioregions, grounded in agroecology principles, encompasses economic, environmental, and social challenges. It is part of broader discussions on the integration of food systems with local territories and cultural values, aiming to improve the quality of life in rural communities by making agriculture more profitable, creating new markets, promoting local tourism, reducing agriculture's environmental impact, conserving biodiversity, and encouraging local food consumption. However, a key question remains: can agroecology coexist with a highly formalized agricultural model without compromising its sustainability potential? Therefore, this study aimed to synthesise and analyse scientific knowledge on the concept of bioregions as a means of implementation agroecology, with a particular focus on its impact on local economies, social cohesion, and environmental sustainability.
Keywords: bioregions, agroecology, sustainable agriculture, territorial development.

Introduction

Contemporary food production systems are increasingly being subjected to critical evaluation due to their environmental and societal impacts (Proskina et al., 2024). Intensive agricultural models contribute to ecosystem degradation and the decline of biodiversity. In the long term, such an approach threatens environmental balance and reduces the resilience of food systems (Naglis-Liepa et al., 2022). At the same time, current consumption habits often do not align with the principles of sustainable development, reinforcing irreversible environmental and social consequences (Steier et al., 2017).

In this context, agroecology is gaining increasing importance as it offers a holistic approach to addressing the complex challenges faced by contemporary food systems. Scientific research has highlighted the importance of implementing biological and ecological practices that support natural processes, enhance biodiversity, and maintain soil health (Cote et al., 2019). Agroecology encompasses these principles, integrating agriculture and food production with environmental protection and social equity.

Although the theoretical potential of agroecology has been extensively studied, increasing attention is being directed toward its practical implementation in specific territorial contexts. One of the most promising possibilities to implement this approach is by drawing the concept of bioregions, which provides an integrated framework for applying agroecological principles in practice. The bioregional approach is regarded as one of the most effective tools for localizing agroecological principles and aligning them with regional development goals. Bioregions encourage the use of local resources, foster the development of local economies, and contribute to the preservation of cultural values, thereby enhancing the effectiveness and sustainability of agroecological strategies (Guareschi et al., 2020; Dias et al., 2021; Kraljevic & Zanasi, 2023). Although agroecology and the bioregional concept appear to be closely interconnected, their practical integration often faces a range of political, economic, and technological challenges. Furthermore, a limited understanding of the effectiveness of the bioregional approach and the prerequisites for its implementation across diverse contexts remains.

Wezel et al. (2018) observe that the challenges surrounding the implementation of agroecological principles primarily arise from the complex interplay between a diverse array of stakeholders – ranging from local farmers to policymakers, and from economic interests to social movements – all of whom play a vital role in advancing agroecology at multiple levels and in varied contexts. Although agroecological and bioregional approaches are conceptually aligned and share a common aim of fostering sustainable, locally grounded agricultural systems, their practical application is frequently constrained by ideological tensions and prevailing narratives rooted in conventional and industrial agricultural paradigms. Such tensions underscore the need for a balanced governance approach capable of integrating the scientific, practical, and social dimensions of agroecology into bioregional planning processes, while simultaneously respecting local cultural values and ecological boundaries (Matthews, 2022).

This study aims to synthesise and analyse scientific knowledge on the concept of bioregions as a means of implementation agroecology, with a particular focus

on its impact on local economies, social cohesion, and environmental sustainability.

Materials and Methods

This study adopts a qualitative approach to literature analysis, with a particular focus on a structured literature review and thematic analysis. The research examines academic publications from the past two decades featured in internationally recognised journals, alongside policy documents related to the development of agroecology and the bioregion concept across various European countries. The principles, benefits, and challenges of different approaches to sustainable agriculture are systematised in order to facilitate a comparative assessment of agroecology's potential, with particular attention given to the influence of bioregions on local economies, social cohesion, and environmental sustainability.

Results and Discussion

Sustainable agriculture approaches

In recent decades, the concept of sustainable agriculture has become a central topic of discussion among both academics and policymakers. A key issue within these debates concerns how to ensure food production that not only preserves natural resources but also fosters economic stability and social justice. According to the Food and Agriculture Organization of the United Nations (FAO, 2025), sustainable agriculture is defined as a system capable of maintaining high productivity over the long term, while safeguarding ecosystems and promoting social equity. Experts and researchers have proposed several approaches to achieve this goal. A comparison of these methods is provided in the table below to support a clearer understanding of their core principles and effects (Table 1).

Table 1

Key characteristics of sustainable agriculture approaches

Agricultural Approach	***Organic Agriculture***	***Regenerative Agriculture***	***Precision Agriculture***	***Conservation Agriculture***	***Agroecology***
Key Principles	Ban on synthetic chemicals, use of natural fertilizers	Soil regeneration, carbon sequestration, minimal soil disturbance	Digital technologies, GPS guidance, field sensors	Reduced tillage, cover crops, preserving natural cycles	Integration of ecological and social factors, local knowledge
Benefits	Improves soil fertility, promotes biodiversity, and reduces chemical residues in food.	Improves soil structure, increases carbon sequestration	Reduces chemical use, improves yield management	Reduces soil erosion, maintains fertility	Ensures social justice, supports local economy and environmental protection
Challenges	Limited yields, dependence on natural processes	Requires long-term commitment, initially lower productivity	High initial costs, technology accessibility	Requires specific farm management strategies	Requires paradigm shift in policies, market structures, and farmer education
Environmental Impact Indicators	Reduces water pollution, promotes biodiversity	High carbon sequestration, enhances biodiversity, reduces GHG emissions	Reduces input overuse and chemical runoff, but may increase energy use and e-waste.	Significantly reduces erosion, improves soil carbon retention	Promotes biodiversity, low GHG emissions, improves ecological resilience
Scalability & Applicability	Highly suitable for small to medium farms, limited large-scale use	Effective across scales with adaptation; best for medium-sized farms	Highly scalable, suitable for large farms with capital	Widely applicable, adaptable to various farm sizes	Flexible, but more common in smallholder and community farms
Policy/Market Support Availability	Supported by EU subsidies and certification programs	Growing support through climate initiatives and regenerative movements	Increasing support via agri-tech programs and innovation funds	Included in some agri-environment schemes	Recognized in policy discourse, but uneven institutional support
Researchers	Berbec et al., 2018; Özer & Dal, 2023; Naglis-Liepa et al., 2021; Fereira et al., 2020	Paustian et al., 2019; Dudek & Rosa, 2023; Rowntree et al., 2020	Gebbers & Adamchuk, 2010; Koloszycz et al., 2024; Zeverte-Rivza et al., 2024	Hobbs et al., 2007; Gemtaou et al., 2024	Altieri & Toledo, 2011; Wezel et al., 2018; Savels et al., 2020

Among the proposed approaches to sustainable agriculture, agroecology stands out due to its holistic perspective, which not only ensures sustainable production methods but also promotes social justice, local economic development, and environmental protection. The bioregional approach complements the implementation of agroecological principles by supporting agricultural systems tailored to the specific ecological and social conditions of a given region. As demonstrated by studies conducted in European countries, the adoption of the bioregional concept has encouraged the consumption of local products and

generated new economic opportunities in rural areas (Guarnacia et al., 2020; Lamine et al., 2023).

The Concept of Agroecology and Its Development

In its early stages of development, up to the 1950s, agroecology was considered a subfield of ecology with a focus on the interactions between plants and animals within agricultural ecosystems (Wezel et al., 2018). The first ideas of agroecology emerged in the early 20th century when scientists began to examine how biological and ecological factors affect agricultural practices. At this stage, particular attention was given to plant–soil relationships, the role of natural cycles, and the conservation of biodiversity.

In the 1950s, agroecology gained wider recognition as a scientific system that encompassed not only the study of ecological processes but also the analysis of agriculture considering the interactions between plants, animals, the environment, and humans within agricultural practices (Guzman & Woodgate, 2015). At this stage, the emphasis shifted towards the application of ecological principles to agriculture, which helped to develop new methods and approaches to sustainable food production.

Since the 1980s, agroecology has evolved into a multidisciplinary field encompassing environmental, social, and economic challenges. In response to the problems posed by industrial agriculture - such as soil degradation, biodiversity loss, and increasing dependence on chemical fertilisers and pesticides, practical agroecological initiatives began to emerge during this period, including permaculture, organic farming, and integrated pest management (Guareschi et al., 2020).

At the turn of the 20th and 21st centuries, agroecology came to be regarded not only as a scientific discipline but also as a socially driven movement and a set of agricultural practices (Savels et al., 2020). International organizations, such as La Vía Campesina, actively promote agroecological principles, emphasizing its potential to support small-scale farms, protect local ecosystems, and ensure sustainable food production (About La Via Campesina, n.d.). More recent studies increasingly frame agroecology as both a movement and a body of farming practices, rather than merely a scientific domain (Wezel et al., 2018), and highlight its potential as a viable solution for achieving the United Nations Sustainable Development Goals, which aim to reduce poverty (Wicki et al., 2025), ensure food security, and promote ecological well-being (Cote et al., 2019).

The ‘expansion’ of agroecology beyond the boundaries of the scientific sphere also gives rise to varying interpretations and definitions, which may lead to confusion and misunderstanding about how to apply the agroecological system to promote sustainable development. Summarizing scientific findings, the following dimensions of agroecology have been identified:

- Scientific approach – the application of ecological methods in crop cultivation and their interaction with the environment, including environmental, social, economic, and ethical aspects;
- Practical approach – preservation of biodiversity, management of soil fertility, and implementation of environmental protection measures to create productive and sustainable agricultural systems;
- Social movement – the promotion of sustainable agricultural practices and rural area development, mostly carried out by non-governmental organizations and local communities.

Changes within the agroecological system and the broad application of the term reflect a logical process of development. Initially existing solely as a scientific approach, agroecology has evolved into an active tool for the transformation of agriculture and rural development, applied in practice to provide sustainable solutions in both environmental and socio-economic contexts. In fact, the dimensions of agroecology can be interpreted as a reflection of the system’s historical development, with the use of bioregions representing the next logical step in advancing sustainability.

The Role of Bioregions in Sustainable Agriculture

The practical application of agroecology is closely linked to the concept of bioregions - an innovative new approach to rural development that encompasses social, environmental, economic, and ethical dimensions. However, there are notable differences between the concepts of agroecology and bioregions. Agroecology focuses on enhancing the ecological aspects of agricultural systems by integrating both scientific and traditional knowledge. In contrast, the bioregional approach is broader in scope, encompassing not only agriculture but also areas such as tourism development, handicrafts, and the preservation of cultural heritage (Guareschi et al., 2020).

The bioregional approach is based on specific geographic areas by distinct ecological and cultural characteristics (Pezzoli & Leiter, 2016), whereas agroecology can be applied at various scales, independent of territorial boundaries. The concept of bioregions assumes that organic farming and the farmers who practice it play a central role; however, it should be emphasized that a bioregion does not necessarily imply that exclusive use of organic agricultural practices within its territory (Dias et al., 2021). It is important to note that there are also similarities between the two concepts. Both agroecology and the bioregional approach aim to promote sustainable agricultural practices that preserve environmental resources, foster biodiversity, and emphasize the involvement and participation of local communities in decision-making processes, thereby contributing to social cohesion and economic development (Guareschi et al., 2020; Gargano et al., 2021). In bioregions, the promotion of organic products is closely linked to the valorisation of the

territory and its unique attributes, in order to fully realise its economic, social, and cultural potential (Basile, 2014).

Scientific interest in the topic of bioregions has increased alongside their growing popularity in Europe. However, the body of research remains relatively limited and is primarily focused on case studies and comparative analyses (Favilli et al., 2018; Dias et al., 2021; Kraljevic & Zanasi, 2023; Sturla et al., 2024). A number of studies have been dedicated to the classification and identification of bioregions (Zanasi et al., 2020; Guareschi et al., 2020), as well as to the experiences of bioregion implementation.

The definition provided by Harris et al. (2016) 'Bioregions, generally defined as areas that share similar topography, plant and animal life, and human culture, represent an appropriate and consistently applicable scale and framework for sustainable food system analysis, design, and planning', highlights the importance of bioregions in addressing climate change, resource depletion, and environmental degradation, while emphasizing that these regions provide a framework that promotes the sustainability of food systems. In contrast, the definition proposed by Kraljevic & Zanasi (2023): 'Biodistricts, also known as 'organic districts' or 'eco-regions,' are defined as specific geographic areas that integrate organic agriculture with the socio-economic and cultural contexts of their communities', suggests that bioregions are a pragmatic approach to agriculture, based on local needs and cultural values with the aim of supporting local food systems and sustainable agricultural practices. This comprehensive approach aligns with the European Union's initiatives to promote sustainable agricultural development and practice. The EU provides the following definition of a bioregion: 'A 'Bio district' is a geographical area where farmers, the public, tourist operators, associations and public authorities enter into an agreement for the sustainable management of local resources, based on organic principles and practices' (European Commission, 2021).

The application of the bioregional concept in territorial development is illustrated by Stotten and Froning (2023) in their case study of Valposchiavo, Switzerland. They argue that 'biodistricts harness organic agriculture's principles to develop strong local agro-food systems that effectively respond to globalization's impacts, suggesting that a focus on local contexts can facilitate more resilient food systems'. Likewise, Guareschi et al. (2020) define biodistricts as 'local production systems in which organic methods are prevalent but at the same time they are closely connected to other economic, environmental, and socio-cultural elements. This definition highlights that a bioregion operates as a complex network of collaboration, linking organic production with local food systems, entrepreneurship, tourism potential, community involvement, and the preservation of cultural heritage. Such integration fosters a transition towards more sustainable models of agriculture and development, tailored to the specific needs and opportunities of a given territory.

In Latvia, the definition of a bioregion can be found in Cabinet Order No. 238 (2024) 'On the Implementation Plan for the Landscape Policy 2024–2027', where a bioregion in a narrower sense is defined as 'a territory where farming is carried out using organic agricultural practices and methods'. The recommendation provided by the authors of this study is incorporated into a broader definition of a bioregion used in these regulations: 'a territory in which representatives of the local public, private, and non-governmental sectors, as a result of a voluntary agreement, create a living space with the aim of preserving and enhancing biological, socio-economic, cultural, and landscape values by implementing farming and consumption practices that respect local biodiversity and balance the interests of stakeholders in local development planning, sustainable use, and management of local resources'.

Bioregional governance is frequently employed in nature conservation and rural development policy. In the study by Guareschi et al. (2020), the focus is on community well-being and the interaction of agricultural production systems, reflecting a functional approach. Rosa et al. (2024) assess the impact of land use on plant species diversity across Europe. Their findings demonstrate how ecological factors can shape administrative decisions regarding land management, underscoring the need for governance systems to account for ecological boundaries in order to foster biodiversity and sustainability. The study by Lamine et al. (2023) examine Italian bioregions and French territorial food projects, with particular attention to how policy initiatives and public engagement can support the transition towards sustainable food systems. Their results highlight the consolidation of organic farming systems and the recognition of local food identities as key factors in policy development processes.

The economic dimension of bioregional agriculture is reflected in its capacity to strengthen the local economy. By promoting short food supply chains, bioregions enhance local producers' access to market and reduce dependence on larger, often less sustainable, agricultural systems (Guareschi et al., 2020; Kraljevic & Zanasi, 2023). Consequently, localized production systems may prove more profitable, enabling farmers to capture greater value from their products while stimulating regional economic growth and entrepreneurship (Cato, 2011). Furthermore, there is a growing shift towards high-value product markets, such as organic and health-oriented foods, which not only generate higher returns for farmers but also fosters regional identity through gastronomy (Lamine et al., 2023). Simultaneously, Platis et al. (2019) emphasize the reduction of greenhouse gas emissions due to the use of local

resources and shorter transport distances. Support for small and medium-sized farms is another essential aspect of the bioregional strategy, as it reduces competitive pressure from large-scale industrial agriculture, allowing for a more equitable agricultural landscape (Guareschi et al., 2022). By establishing inclusive frameworks that prioritize local agricultural development, bioregions have the potential to reduce economic disparities and enhance community resilience (Stotten & Froning, 2023).

Within the framework of social sustainability, the bioregional approach highlights the importance of community cohesion and local participation in agricultural practices. Engagement in local food initiatives strengthens social bonds and fosters a sense of belonging among residents (Stotten et al., 2018). Moreover, bioregions play a critical role in preserving local culture and traditions, promoting societal diversity and ensuring the continuity of agricultural traditions (Zanasi et al., 2020). Access to healthier food through short supply chains not only promotes better nutrition but also improves public health outcomes, aligning with sustainable development goals aimed at enhancing population well-being (Guareschi et al., 2020).

The emergence of bioregions can be interpreted as a direct response to contemporary trends in economic development, driven by a societal aspiration for improved living conditions. Accordingly, bioregions may be defined as local production systems in which organic and agroecological methods are predominant.

Conclusions

1. The integration of the agroecology and bioregion concepts forms a multidimensional, locally grounded model of sustainable agriculture that simultaneously addresses ecological, economic, and social challenges. The findings of this study confirm that agroecology as a scientific, practical, and social approach, offers effective instruments for facilitating the transition towards more environmentally sustainable and socially equitable food production systems.
2. The concept of bioregions, in turn, provides a territorially specific and structured framework for the practical application of agroecological principles, linking agriculture with cultural heritage, tourism, and local economic development. Collaboration within bioregions among community actors, businesses, and local authorities, facilitates the creation of resilient local food systems and enhance regional economic stability.
3. The reviewed literature confirms that this approach not only enhances biodiversity and reduces environmental pressures, but also fosters community participation, strengthens local identity, and creates favourable conditions for strengthening social cohesion in rural areas. Particularly important is the development of short supply chains and support for small-scale farms, which stimulate regional economies and promote a fairer distribution of income among farmers.
4. Future research should prioritise the quantitative assessment of bioregions' impact, including the application of sustainability indicators, as well as analysing mechanisms for community participation to strengthen agroecological initiatives. In this way, bioregions can become an effective tool for transitioning to a more resilient, human and environment oriented model of agricultural development aligned with sustainable development goals at both national and European levels.

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LOCATION AND STRUCTURE OF THE BIOECONOMY IN THE 13 NEW EU MEMBER STATES

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Abstract
The bioeconomy constitutes a significant part of the economies of many EU countries. Its structure is very diverse in the NMS-13 countries. The study aims to determine the importance of the bioeconomy sector in the new EU member states and to determine countries' specialization in the bioeconomy industries, considering the GVA (Gross value added) creation and employment. The share of the bioeconomy in employment is as much as 14.6% and in GVA—7.5%. This is two times more than the average for the EU. Agriculture recorded the largest employment within the bioeconomy – 63% jobs, while its share in GVA was only 35%. The bioeconomy in NMS-13 was characterized by significant spatial concentration. The forestry and wood processing industry are dominant in the north of the region. In contrast, the countries in the south had a high concentration of agriculture and food processing. Labour productivity in the bioeconomy remained low and amounted to only about 51% of the productivity in the entire economy in 2021. The future development of the bioeconomy should be based on increasing the importance of sectors producing high-value-added products, which now constitute only 8.9% of the bioeconomy's GVA in NMS-13. Depending on the country, this is food or wood processing, as well as biochemicals, biopharmaceuticals, or bioenergy. Economic policy should be directed towards the sustainable use of locally available biomass resources. This will also allow for maintaining rural areas' economic and social vitality. The bioeconomy is still an essential sector in NMS-13 for creating jobs and income in rural areas.
Keywords: bioeconomy, location quotient, spatial concentration, gross value added, employment.

Introduction

Bioeconomy encompasses the production and processing of biomass to supply food, feed, non-food materials, and energy. A portion of the materials and energy currently derived from non-renewable sources in the economy can be replaced by their counterparts, which are partially or entirely produced from biomass (e.g., plants and microorganisms). In the European Union (EU) bioeconomy strategies, substituting fossilbased materials and energy with biomass-based solutions has been identified as a key strategic development direction (European Commission, 2012, 2018). This transition is expected to reduce environmental pressure, increase employment, and enhance the added value of the EU's 'green' economic sectors while also contributing to climate change mitigation (Pascoli et al., 2022). The development of the bioeconomy aligns with efforts to expand the scope of the circular economy, fostering industrial circularity and promoting growth and job creation in rural areas. Implementing the Bioeconomy Action Plan is a crucial component of the Circular Economy Action Plan European Comission, 2020). In EU member states, national bioeconomy development strategies have been formulated to reflect the potential and aspirations of individual countries and regions in advancing the bioeconomy sector.

Measuring the share of bioeconomy in the economy

Different approaches are used to quantify the importance of the bioeconomy. This has led to varying estimates of the importance of this sector (Vandermeulen et al., 2011). They were based on the share in the creation of gross margin or on calculations based on input-output tables (Heijman, 2016). Further activities resulted in a model developed in the EU based on biomass flow between sectors and its share in the final product (Gurría et al., 2020). It was assumed that the importance of the bioeconomy in the sectors is the same as the biomass share in relation to fossil, mineralbased or synthetic feedstock (Ronzon et al., 2020).

The quantification method based on 'bio-shares' allows for the calculation of the share in production, gross value added, and employment and makes it possible to compare the obtained values to gross value added (GVA) and employment in the entire economy. The calculation technique used to assess the bioeconomy in EU countries is based on an integrated 'baseline' approach, i.e., the share of biomass in finished production is taken into account (Lasarte-López et al., 2023).

The importance of the bioeconomy sector in the economy

The basic idea of developing the bioeconomy beyond the traditional sectors, i.e., agriculture, forestry, and fisheries, is to replace non-renewable fossil resources used in industry and the energy sector with renewable biological resources.

Many efforts are being made within the development strategies in the EU and beyond to increase the share of bio-raw materials in final production (Thomchick et al., 2024). However, traditional sectors still dominate in employment and production although more and more attention is now being paid not to resource substitution, but to biotechnological innovations, which enable the use of bio-raw materials to produce products with high added value. This is achieved by supporting investment and research in the bioeconomy, including in traditional sectors. Research funds serve both to improve efficiency and to protect the environment and biodiversity (Muska et al., 2022; Popluga et al., 2015; Zeverte-Rivza & Bulderberga, 2015).

The development of the bioeconomy is also seen as an opportunity to enhance food security (Gawel et al., 2019) and reduce greenhouse gas emissions (Pascoli et al., 2022). On the other hand, it is noted that many technologies have not yet been scaled up to industrial levels (Parajuli et al., 2021), and increasing demand for biomass for energy purposes and the production of advanced bioproducts may lead to competition with traditional biomass applications, such as food production or the manufacturing of paper and wood-based products (Parajuli et al., 2021; Wicki, 2017). Additionally, it should be emphasized that the development of the bioeconomy is often driven by subsidies rather than economic feasibility (Salma et al., 2024). Many proposed solutions lack proven economic efficiency and are therefore associated with a high risk of failure (Czernyszewicz, 2016). It was also confirmed that achieving environmental goals in the bioeconomy through agriculture alone is difficult because of its almost constant emissivity per unit (Bennetzen et al., 2016; Rawa & Pietrzykowski, 2024).

Expectations related to bioeconomy development

In the EU, in accordance with the adopted bioeconomy development strategy, the reaching of both traditional and new objectives is expected. These include:

- Ensuring food security through more environmentally sustainable methods.
- Sustainable use of natural resources to prevent excessive competition for biomass and biodiversity loss.
- Reducing dependence on non-renewable resources, including fossil fuels.
- Efficient processing of organic waste within the circular economy framework.
- Mitigating climate change by reducing fossil energy demand and lowering emissions.
- Creating jobs and maintaining economic competitiveness, including through technological development and innovation.

It should be noted that, depending on their available natural biomass resources, these ambitious goals may be achieved to varying degrees and in different ways across individual countries.

The above premises became the basis for setting the aim of this work. Its aim is to determine the role of the bioeconomy in the economies of new EU member states, identify structural differences, and compare labour productivity in the bioeconomy sector and the economy.

In the EU, the bioeconomy sector employed 17.2 million people in 2021, representing 8.2% of total employment. In NMS-13, the share of jobs in the bioeconomy was higher, amounting to 14.6% in 2021, representing 6.97 million jobs. In the countries surveyed, the importance of the bioeconomy sector is almost twice as high as in the EU as a whole (8.2%), which justifies a more detailed assessment of the changes taking place.

As economies develop, the share of employment in the bioeconomy decreases, and increasingly higher labour productivity is achieved (Faber & Jarosz, 2023). It is also clear that this sector may be strongly localized, and the location depends on the availability of natural resources in individual countries. In some countries, high biomass availability results from good conditions for the development of agriculture; in others, e.g. in Sweden, Finland, and Latvia, from large forest biomass resources. In larger countries, but not only, there is a differentiation of the potential of the bioeconomy in individual regions (Komor, 2018; Muska et al., 2022; Nowak & Kobiałka, 2017).

The use of the wealth of resources in a given region can contribute to economic growth (Refsgaard et al., 2018). The easiest is to observe changes in the internal structure of the bioeconomy, e.g. the increase in the role of food or wood processing at the expense of the importance of agriculture or forestry (Popluga et al., 2024; Wicka & Wicki, 2024). However, innovative sectors of the bioeconomy with high-added value products are expected to develop rapidly, e.g., the production of biopharmaceuticals and biochemicals.

The study aims to determine the difference in the importance of bioeconomy in the new EU member states and to determine changes in the importance of bioeconomy in the creation of GVA and employment. The study covered 13 countries that joined the EU in 2004 and later. These are Bulgaria, Croatia, Cyprus, Czechia, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia and Slovenia (NMS-13). The research period covers the years 2008–2021.

Materials and Methods

The source data was obtained from the bioeconomy database: *Jobs and wealth in the EU bioeconomy / Joint Research Centre – Bioeconomics* (Lasarte López et al., 2022). Following the applied methodology there, the output-based approach is used.

Data on employment, output, and GVA were collected for each of the bioeconomy sectors distinguished in the database. Based on the gathered data, the significance of the bioeconomy in national economies was determined by assessing its share in the total economy. The dynamics of changes in the bioeconomy's importance within national economies from 2008 to 2021 were analyzed regarding employment, turnover, and GVA.

Labour productivity in the bioeconomy was also determined and compared. It was defined as the value-added divided by the number of people employed. The specialization of countries in the bioeconomy and bioeconomy spatial concentration were determined using the location quotient (LQ) (Billings & Johnson, 2012; Carroll et al., 2008). The following formula for LQ was used:

$$LQ_{b,c,y} = \frac{\frac{B_{b,c,y}}{E_{c,y}}}{\frac{B_{b,y}}{E_y}} \quad (1)$$

where:
$B_{b,c,y}$ – size of sector *b* in country *c* and year *y* according to a specific variable (e.g. employment, GVA),
$E_{c,y}$ – total value of the variable in country *c* and year *y*,
$B_{b,y}$ – total size of sector *b* in year *y* in all the countries studied according to a specific variable,
E_{y} – total value of the variable in year *y* in all the countries studied.
LQ values above 0.9-1.1 indicate average or higher than average concentration/specialization of a given country in a specific production (Miller et al., 1991).

Results and Discussion

In the NMS-13, the significance of the bioeconomy varies across countries. Figure 1 illustrates the contribution of individual sectors to employment and GVA within the bioeconomy in studied countries. Agriculture is the largest sector in terms of employment and GVA, followed by food processing. Sectors related to forestry and wood processing also play an essential role. Notably, processing industries have a higher share of GVA than employment.
Agriculture accounted for as much as 63% of total employment in the bioeconomy. The second-largest sector, food processing, employed 17%, while wood processing accounted for approximately 9%. The contribution of agriculture to GVA was nearly half of its share in employment (35%), whereas food processing accounted for 29%, and wood processing and paper production contributed 14% to GVA. High-value-added sectors accounted for 4.6% of the bioeconomy employment share and generated 8.9% of its total gross value added. This means that labour productivity in these sectors was 1.93 times higher than the bioeconomy average.
In the NMS-13, the importance of the bioeconomy in the economy declined between 2008 and 2021. Employment fell by 2.4 million people (26%) while remaining at a similar level in the total economy. Turn over and GVA increased at just over 3% per year (Table 1), but this was about 0.5 percentage points lower than that observed in the entire economy. It can be stated with some approximation that the bioeconomy, as a whole, maintains a similar share in the turnover and creation of GVA, but its share in employment is declining.

Figure 1
Share of bioeconomy sectors in employment and gross value added of total bioeconomy in NMS-13 countries in 2021

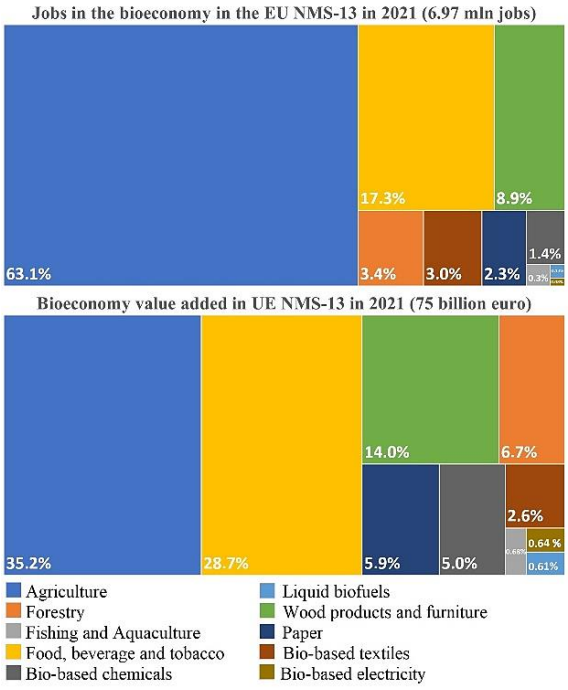


Table 1
The importance and dynamics of bioeconomy on the background of total economy in NMS-13 in 2008–2021

Year	Bioeconomy			Total economy		
	jobs (million)	GVA (billion euro)	turnover (billion euro)	jobs (million)	GVA (billion euro)	turnover (billion euro)
2008	9.37	75.0	265.8	46.83	943.9	2221.3
2009	8.96	64.7	223.4	45.94	847.8	1908.1
2010	8.75	67.8	241.2	44.74	901.6	2085.4
2011	8.46	75.2	266.3	44.52	945.7	2235.8
2012	8.39	71.7	270.7	44.61	956.8	2244.1
2013	8.16	75.6	278.5	44.53	963.1	2252.2
2014	8.07	77.1	281.3	45.19	995.4	2312.9
2015	7.84	76.6	284.5	45.63	1050.4	2419.3
2016	7.42	79.3	286.9	46.06	1074.6	2457.7
2017	7.41	87.7	308.7	46.86	1170.1	2685.8
2018	7.32	91.8	330.2	47.33	1260.4	2907.7
2019	7.11	96.9	342.1	47.54	1352.3	3088.9
2020	7.02	98.5	336.7	47.02	1324.0	2951.3
2021	6.97	108.8	381.5	47.62	1455.6	3362.5
CAGR in 2008–2021, in percent	–2.27	3.34	3.21	0.40	3.86	3.69

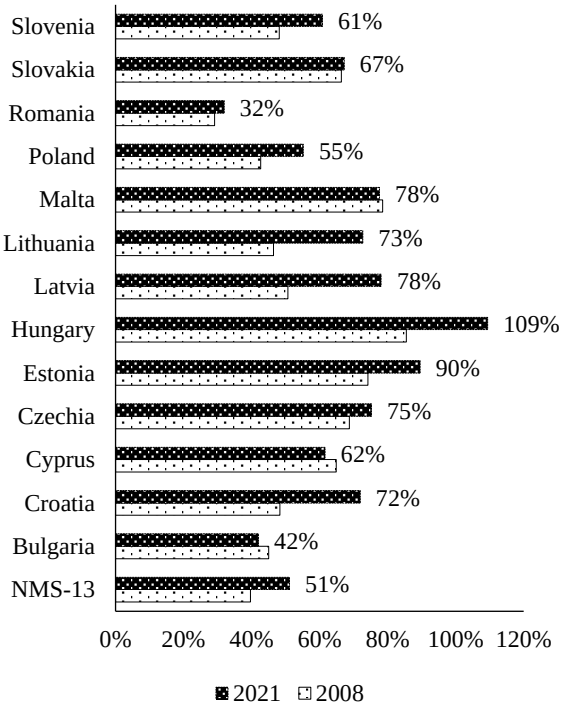
The decline in employment levels within the bioeconomy should be considered a positive trend. Given the significant share of traditional sectors, particularly agriculture, this indicates an increase in labour productivity in agriculture, which is a necessary condition for improving competitiveness. In 2008, the average labour productivity in the bioeconomy within NMS-13 was relatively low, amounting to only 39.7% of the overall economy's productivity. By 2021, labour productivity had increased by 11 percentage points, reaching 51.1% of the economy-wide productivity level (Figure 2).

The highest increases in labour productivity were observed in Croatia, Estonia, Hungary, Latvia, and Lithuania, where productivity rose by more than 20 percentage points. In contrast, countries such as Bulgaria and Romania did not experience any growth in bioeconomy labour productivity, and their productivity levels remained low.

Figure 3 illustrates the spatial concentration of the bioeconomy's significance in the economies of NMS-13 countries. Based on GVA generation, it was found that, in spatial terms, the bioeconomy is most concentrated in Latvia, Lithuania, Croatia, and Bulgaria. In contrast, its importance was relatively low in more industrialized countries such as the Czech Republic, Slovakia, and Slovenia, as well as in Cyprus and Malta, where the location quotient (LQ) was significantly below 1.

Figure 2

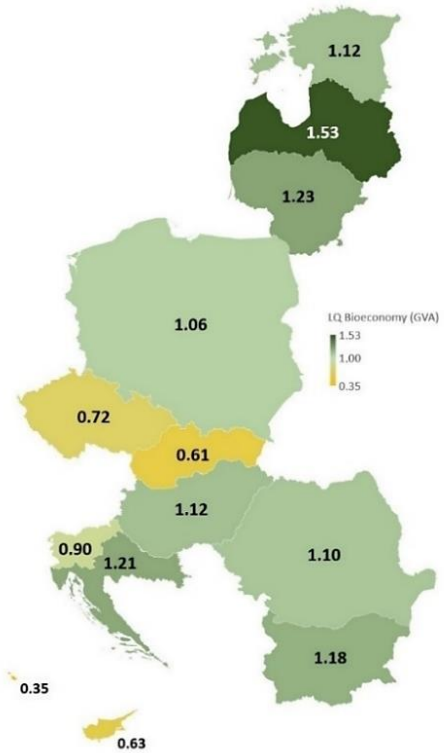
Changes in the level of labour productivity in the bioeconomy sector in NMS-13 in 2008–2021 (economy=100%)



The spatial concentration of the bioeconomy differs when analyzed in terms of employment. The highest importance of the bioeconomy in employment was observed in Romania, Bulgaria, Poland, and Latvia, where the share of jobs in this sector reached 15% (Table 2).

Figure 3

Geographical distribution of bioeconomy location quotient in NMS-13 states in 2021 (based on GVA)



On the other end of the spectrum, countries such as Cyprus, the Czech Republic, Hungary, Malta, and Slovakia had only about 7% of their workforce employed in the bioeconomy, which is half the level observed in the leading countries.

The significance of the bioeconomy, measured by total turnover, also varied. The highest shares were recorded in Latvia, Estonia, and Poland, while the lowest was observed in the more industrialized countries mentioned above.

The share of the bioeconomy measured by GVA was lower than the share in turnover in all the countries studied. This means that this sector is characterized by a lower-than-average capacity for creating added value in economies. This is primarily due to the large share of raw material sectors—agriculture and forestry. The importance of sectors with high added value (e.g., biobased chemicals) amounted to no more than 5% on average. Different type biorefineries are important in creating high-value-added products and waste recycling. It allows to reach cascading use of biomass (McCormick & Kautto, 2013; Sirkin & Houten, 1994).

Only in four countries namely Hungary, Latvia, Lithuania, and Slovenia was an increase in the significance of the bioeconomy within the economy

observed, considering its share in generated GVA. This indicates that the sector has undergone modernization and plays an important role in the development of these countries.
In contrast, in several countries, such as Bulgaria, Romania, and Estonia, the opposite trend was observed, with a significant decline in the share of GVA from the bioeconomy in the overall economy.
Overall, the bioeconomy is losing significance in most of the studied countries. Its share in employment is particularly decreasing, along with its contribution to turnover and GVA generation.

Table 2
Share of bioeconomy in NMS-13 countries in 2008-2021 and observed dynamics of change

Country	2008			2021			CAGR#		
	employ-ment	GVA	turnover	employ-ment	GVA	turnover	employ-ment	GVA	turnover
NMS-13	20.0%	7.9%	12.0%	14.6%	7.5%	11.3%	-1.34	-1.12	-1.35
Bulgaria	25.4%	11.4%	15.1%	21.0%	8.8%	12.6%	-1.34	-1.12	-1.35
Croatia	19.9%	9.6%	13.5%	12.6%	9.0%	12.5%	-5.01	-0.65	-0.79
Cyprus	9.0%	5.8%	8.1%	7.6%	4.7%	6.1%	-1.43	-1.16	-1.75
Czechia	8.4%	5.8%	8.6%	7.2%	5.4%	8.1%	-1.23	-0.36	-0.81
Estonia	11.6%	8.6%	13.6%	9.4%	8.4%	15.1%	-1.31	-0.81	0.24
Hungary	9.1%	7.8%	11.8%	7.6%	8.4%	11.5%	-1.02	**0.44**	-0.39
Latvia	14.4%	7.3%	11.4%	14.7%	11.5%	17.1%	-0.54	**1.91**	**1.90**
Lithuania	15.9%	7.4%	13.8%	12.6%	9.2%	14.6%	-1.85	**1.43**	-0.08
Malta	5.5%	4.3%	4.7%	3.4%	2.6%	3.3%	-4.45	-5.14	-4.08
Poland	19.3%	8.2%	13.6%	14.3%	7.9%	13.4%	-2.35	-0.28	**0.03**
Romania	36.4%	10.6%	14.5%	25.8%	8.2%	11.2%	-3.21	-2.64	-2.08
Slovakia	7.6%	5.1%	7.5%	6.8%	4.6%	6.6%	-1.19	-0.75	-1.24
Slovenia	13.9%	6.7%	9.5%	11.0%	6.7%	8.9%	-1.67	**0.58**	-0.18

Note: # - the annual rate of change was determined based on the exponential function for the entire time series, i.e. 2008–2021.

Individual countries exhibit varying significance of specific bioeconomy sectors within the overall structure. On average, in NMS-13, as much as 63% of those employed in the bioeconomy work in agriculture. In some countries, employment is dominated by agriculture and food processing, while in others, forestry and wood-processing sectors play a more significant role. The highest share of employment in agriculture within the bioeconomy was observed in Romania (80%), Bulgaria (74%), and Poland (61%). The forestry sector employed up to 15% of the workforce, with the highest shares in Slovakia and Latvia. Employment in high-value-added sectors reached up to 8%, with the highest shares in the Czechia, Slovenia, Hungary, Estonia, and Lithuania, compared to an NMS-13 average of 4.6%.
The structure of GVA by bioeconomy sectors exhibited different patterns compared to employment. In seven countries, the share of food processing in GVA was higher than in agriculture, indicating a shift toward a more modern structure, where raw food materials are processed on a larger scale (Table 3). The highest share of food processing in bioeconomy GVA was observed in the Czech Republic, Poland, and Croatia, as well as in the Cyprus and Malta. A similar trend was noted for forestry and wood processing. In countries such as Latvia, Lithuania, Estonia, and, to some extent, Slovakia and Slovenia, wood processing was even more significant than food processing. This reflects the specialization of these countries in wood production and processing, driven by the availability of natural resources. The basis of the bioeconomy in any of the countries analysed is food security, which is based on the role of food production (Aguilar et al., 2019).
The share of high value-added sectors in bioeconomy GVA in NMS-13 averaged around 9% in 2021, with Slovenia having the highest share (25%). Such a low proportion of the innovative sector in the bioeconomy indicates that in the studied countries, the bioeconomy still maintains a traditional structure based on agriculture and forestry.

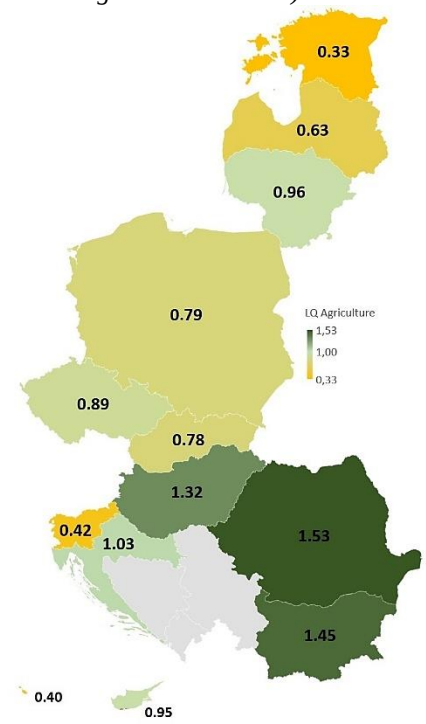
Table 3
The structure of GVA creation in bioeconomy sectors in NMS–13 in 2021

Country	***Agri-culture***	***Forestry***	***Food proces–sing***	***Wood proces-sing***	***HVA bioeco-nomy***
	in percent				
NMS-13	**35**	7	29	20	9
Bulgaria	**51**	5	25	7	11
Croatia	**36**	5	33	15	8
Cyprus	34	3	**43**	10	8
Czechia	**31**	6	**31**	22	9
Estonia	12	14	**20**	47	6
Hungary	**46**	3	27	11	13
Latvia	22	17	14	**40**	5
Lithuania	**34**	7	22	26	11
Malta	14	0	**42**	7	13
Poland	28	5	**36**	24	8
Romania	**54**	9	17	12	7
Slovakia	27	16	**28**	21	7
Slovenia	15	14	24	23	**25**

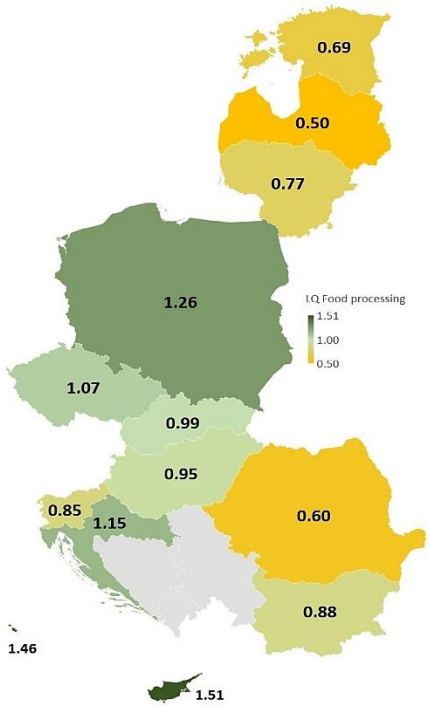
The geographical distribution of the bioeconomy's sectoral location quotient based on GVA is illustrated in Figure 4. A concentration of GVA generation from agriculture is evident in southern countries such as

Romania, Bulgaria, Hungary, and Croatia, whereas GVA from food processing is predominantly concentrated in Poland and the Czech Republic.
This pattern may be influenced, among other factors, by differences in agricultural production. In southern countries, there is a higher production of ready-to-eat food products, vegetables, and fruits, while in countries where food processing dominates, livestock production and crop production intended for processing play a more significant role.

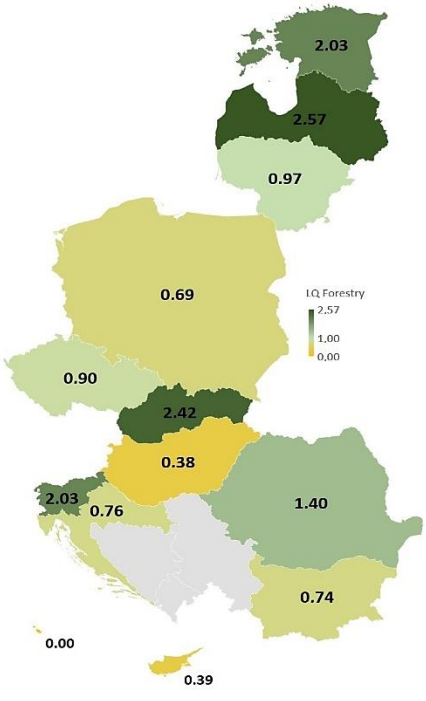
Figure 4
Geographic distribution of the bioeconomy location quotient by main bioeconomy sectors in NMS-13 in 2021 (based on gross value added)



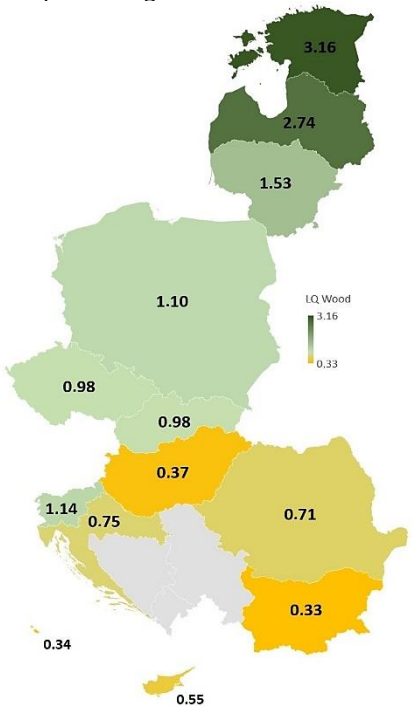
Agriculture



Food processing



Forestry



Wood industry

Forestry and wood products are sectors with strong spatial concentration. The location quotient for forestry reaches over 2 for Estonia, Latvia, Slovakia and Slovenia. Wood processing and paper production are similarly

strongly concentrated. In this case, there is also a concentration in Estonia, Latvia, and Lithuania. Poland also has a high indicator due to the relatively strongly developed production of paper, furniture and other wood products. In NMS-13, there is a great diversity in the development of bioeconomy sectors, which results from the natural resources available. Forestry and wood processing dominate in countries in the north, along with those with a large share of mountainous areas with large forest cover and wood resources for use. Agricultural production is concentrated in countries located in the south, with better soils and climate. Food processing plays a most considerable role in countries with strong agriculture, where the structure of agribusiness has also been modernized towards the production of food with higher consumer and export suitability. This concerns the countries in the centre of the study area, mainly the Czech Republic and Poland.

Conclusions

Based on the research and analyses conducted, it is possible to present several key conclusions.

1. The bioeconomy is an essential sector in the economies of NMS-13 countries. It generates about 7.5% of its GVA. Employment amounted to as many as 6.97 million people, which constituted 14.6% of total employment. For comparison, in the entire EU-27, it was 5.6% and 8.2%, respectively.
2. The importance of the bioeconomy in economies decreased. On average, the share in employment decreased from 20 to 14.6%, and the share in creating GVA decreased from 7.9 to 7.5%. Only in four countries, Latvia, Lithuania, Slovenia, and Hungary, did the share of GVA from the bioeconomy increase. In Latvia, it increased the most, from 7.5 to 11.3%. This means that these countries still have great potential in the development of the biomass-based industry.
3. The location of the bioeconomy is strongly concentrated in the countries studied. Bioeconomy was highly represented in countries such as Latvia, Croatia, Lithuania, Bulgaria, and Estonia. Bioeconomy was of relatively low importance in Slovakia, the Czech Republic, and Slovenia.
4. There is a significant differentiation between countries in sectoral specialization. Agriculture and food processing are strongly localized in Poland, the Czech Republic, Bulgaria, and Romania. Poland had the highest localization coefficient of food processing. Forestry and wood products production are concentrated in Latvia, Lithuania, Estonia, Slovakia, and Slovenia. Latvia and Estonia had the highest localization coefficient of bioeconomy sectors based on forest resources (above 2).
5. Labour productivity in the bioeconomy sector remained low, due to the high importance of traditional sectors, such as agriculture. The level of labour productivity reached only 51% of the productivity in the entire economy. Only in modern sectors of the bioeconomy, producing products with high added value, labour productivity was higher and close to the average for the entire economy.
6. The bioeconomy remains important to most national economies in NMS-13. Appropriate use of biomass resources can lead to increased prosperity in these countries and contribute to maintaining rural areas' vitality and environmental protection.

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NATURAL RESOURCE TAX AND ITS EFFECTS ON PACKAGING INDUSTRY TRENDS

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Abstract
One of the main tools for promoting sustainability and reducing environmental pollution is the Natural Resources Tax (hereinafter NRT). It influences the development trends of the packaging industry, promoting the transition to sustainable solutions, for example, reducing the amount of solid household waste produced and disposed of in the environment and significantly reducing the quantity of resources used in production. The aim of the study was to investigate and assess the impact of the NRT on the sustainability of the packaging industry and provide recommendations for its more effective implementation. This research paper used a narrative review and scoping review of the analytical literature, which provided an understanding of the operating principles of the NRT and its impact on packaging trends, paying close attention to tax policies aimed at both recyclable and non-recyclable plastic packaging. In addition, the motivation of packagers to prefer recyclable packaging solutions was studied. The study includes an analysis of the operating principles of the NRT, discusses practical aspects related to the choice of plastic packaging, and addresses the challenges faced by manufacturers in adapting to the new tax regulations. The study used the monographic method, analysis and synthesis methods as well as the graphical method. An in-depth assessment revealed that the NRT is an indirect determinant that influences and shapes trends in the packaging industry, as in the current situation, market demand has a more significant role in the choice of packaging materials.
Keywords: packaging industry, food industry, environmental policy, environmental tax, sustainability.

Introduction

Nowadays, an increasing amount of attention is being paid to packaging sustainability issues, with the main emphasis being on the choice and recycling of packaging materials. According to the Statistical Office of the European Union's Eurostat data, the amount of packaging waste has been gradually decreasing in recent years, however, in the period from 2011 to 2022, it had a tendency to increase. In the European Union in 2022, a total of 83.4 million tons of packaging were used, which is approximately 186.5 kg packaging waste per capita (Eurostat, 2024).

There has always been a certain contradiction between industrial development and its impact on the environment. In the modern entrepreneurship world, the main goal is profit, leaving the environmental impact of the production process in the background. This approach has led to rapid resource loss and environmental pollution, negatively impacting the overall ecosystem. Research conducted to this date has shown that Environmental taxes play an important role in contributing to the symbiosis of the economy and ecology (Hua, 2024). They are one of the sustainability policy instruments that limit environmental pollution, promoting economic growth (He et al., 2023).

In the European Union, Environmental taxes are referred to four large groups: transport, energy, resources and pollution. The packaging industry affects both the number of resources and the amount of pollution caused by its activities. As countries with the most effective implementation of Environmental taxes, the Scandinavian and Baltic countries are indicated (Ziolo et al., 2019).

Nowadays, the packaging industry rapidly develops to meet the needs and demands of consumers. Additionally, plastic pollution in the environment is a growing concern, despite efforts to reduce plastic waste. According to data provided by the global data and business intelligence platform Statista.com, the plastic packaging market is on a growing route – in 2023 it was 396 billion US dollars, but in 2034 it is predicted that the market size will be almost twice as large as 637 billion US dollars (Statista, 2025).

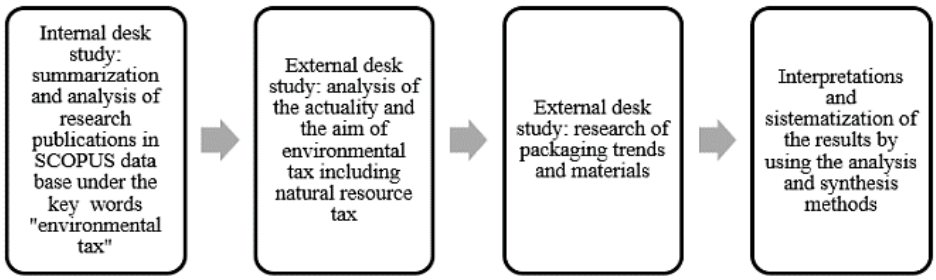
Nowadays, a tendency to view packaging as a sustainable solution for protecting food products and reducing waste, emphasising packaging and sustainability, but not sustainable packaging is visible (Verma et al., 2024).

Thus, the authors set the goal of the study to assess the impact of Environmental tax, entailing Natural Resource tax on the choice of packaging materials and design. Research tasks: 1) analyse previously conducted studies on the principles of operation of Natural Resource tax in the packaging industry, 2) collect information on packaging trends in the food industry, 3) provide a summary of problems, weaknesses and recommendations for improvement.

Materials and Methods

The study used a narrative review to provide a comprehensive overview of Environmental tax based on the authors' perspective. The monographic method was used to obtain a comprehensive overview of the publications published in the scientific database Scopus in the period from 2011 to 2024, which were searched for using the keywords 'environmental tax' and 'packaging trends' mentioned in scientific studies published after 2023. In this current study, the author concentrated on Scopus database papers because Scopus is one of the largest abstract and citation databases, including both papers, book chapters and patents, trade publications across multiple disciplines, which was particularly important for the current study. The methods of analysis and synthesis were used to assess the impact of the Natural Resource tax on packaging industry trends, and the graphical method to reflect the information obtained 'Figure 1'.

Figure 1
Research methodological steps

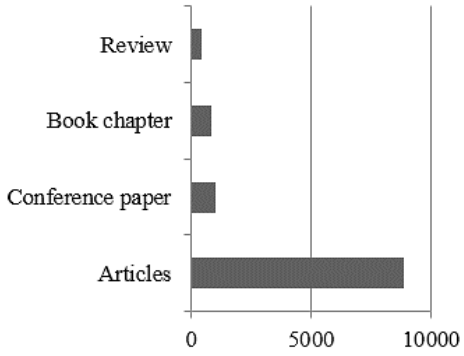


Source: author's compilation based on research steps.

Results and Discussion

When conducting the research based on the keyword Environmental tax in the scientific publication database Scopus, for the period from 2011 to 2024, 11,477 documents were available, of which: 8,875 (77.3%) articles, 985 (8.6%) conference papers, 823 (7.2%) book chapters and 403 (3.5%) reviews 'Figure 2'.

Figure 2
Types of documents published in the scientific publication database Scopus under the keyword 'environmental tax'



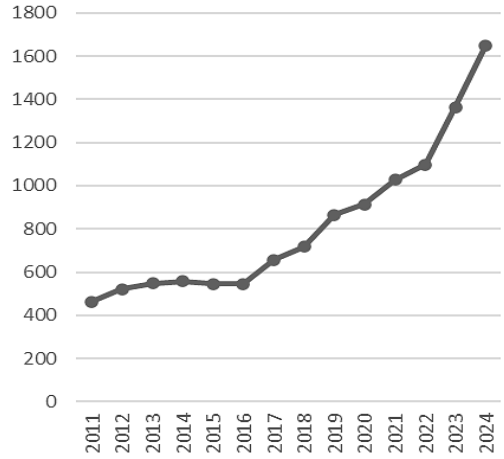
Source: author's compilation based on Scopus data.

In the period from 2011 to 2024, Environmental taxes remained a relevant research topic, as indicated by the increase in the number of publications during this period. The initial increase in research was observed after 2016, which continues to this day 'Figure 3'.

The increase in the number of publications could be explained by the adoption of the Paris Agreement, which is an international treaty on climate change, at the UN Climate Change Conference (COP21) in Paris, France on 12 December 2015, which came into effect on 4 November 2016. It was the first legally binding global climate agreement to combat climate change. The implementation of the Paris Agreement required social and economic changes that facilitated the development of science to establish long-term strategies. The next rapid increase in publications can be observed after 2022.

The explanation for this increase in the number of publications is the European Climate Law, which came into effect on 29 July 2021. Contrarily, at the United Nations Climate Change Conference (COP27), held on 20 November 2022 in Sharm el-Sheikh, no agreement was reached on new measures that would facilitate faster progress towards achieving the goals set out in the Paris Agreement.

Figure 3
Number of papers published in the Scopus scientific publication database from 2011 to 2024 under the keyword 'environmental tax'



Source: author's compilation based on Scopus data.

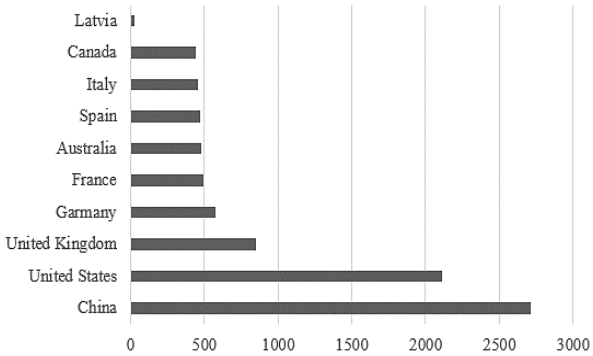
The rapid increase in the number of publications after 2022 indicates the efforts of scientists to explore and find new solutions to improve the situation (European Parliament, 2024).

When assessing the number of publications by the country where the research is conducted, China takes the leading position, followed by the United States, the United Kingdom and Germany 'Figure 4'.

During this period, Latvia had only 26 publications published in the scientific publication database Scopus under the keyword 'environmental tax'.

When evaluating publications by subject area, the majority of publications under the keyword 'environmental taxes' are associated with Environmental Science (5328 publications), followed by Economics and Finance (3116 publications) and Social Science (3106 publications), with practically the same number of publications.

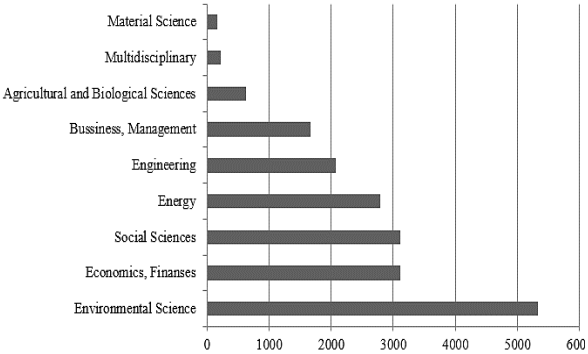
Figure 4
Number of documents published in the scientific publication database Scopus by country under the keyword 'environmental tax'



Source: author's compilation based on Scopus data available under the keyword 'environmental tax'.

Energy has 711 publications more than Engineering. However, Business, Management and Accounting have 1672 publications 'Figure 5'.

Figure 5
Number of documents published in the Scopus scientific publication database by sector from 2011 to 2024 under the keyword 'environmental tax'



Source: author's compilation based on Scopus data.

During the period from 2011 to 2024, only 163 publications in materials science with the keyword 'environmental tax' were published in the scientific publication database Scopus. In contrast, there were 223 publications from an interdisciplinary perspective, which is 60 publications more than in the materials sciences.

In the European Union Member States, Environmental taxes are one of the instruments of sustainable management. Revenues from Environmental taxes are used to solve the environmental management problems of each EU Member State (Leibus & Filipova, 2024).

The Environmental tax system includes a resource tax on raw materials, tax incentives for recycling and repair, and taxes after the end of the product life cycle. The impact of the above-mentioned tax can be seen from all stages of the product life cycle: production, product use, and disposal (Milios, 2021).

The Natural Resource tax is part of the Latvian Environmental tax system. It is applied to packaging, which is one of the objects of the tax. The purpose of the Natural Resource tax is to promote the sustainable and efficient use of natural resources, limit environmental pollution and promote the introduction of environmentally friendly technologies. Tax rates for packaging are determined based on the packaging material used. The tax exemption is applied if the amount of packaging used by the company does not exceed 300 kg per year, and the manufacturer participates in the waste packaging management system. As well if the taxpayer ensures compliance with the waste packaging recovery norms set out in environmental protection regulations or chooses one of the options, either establishing or applying an extended manufacturer responsibility system for the management of used packaging or concluding an agreement with a registered manager from an existing management system (The Saeima, 2006).

The management of packaging waste in Latvia, in accordance with the requirements set out in regulatory enactments, and the reduction of pollution in the environment is ensured by a set of measures or an extended manufacturer responsibility system (EMRS). This is ensured following the Natural Resources Tax Law, the Law on Reducing the Consumption of Plastic-Containing Products and the Regulations of the Cabinet of Ministers. Manufacturers and importers of packaging or EMRS objects must pay the Natural Resources tax on the quantity of goods released in the market.

By entering into a contract with EMRS, an exemption from paying the Natural Resources tax can be received and ensuring the management of used packaging waste (Latvian State Environmental Service of the Republic, 2024).

To reduce the amount of plastic packaging waste, European Member States are required to pay mandatory contributions proportional to the amount of plastic packaging not recycled (Waszczylko-Milkowska et al., 2024).

This is in line with the 'polluter pays' principle, which encourages manufacturers to review the efficiency of the material used in packaging and the environmental impact after its use. Waste management in Europe is ensured by public and private sector cooperation, the main task of which is not only to ensure waste reduction and management but also to stimulate secondary recycling of raw materials (Mattson et al., 2024).

Packaging material and its production technology are factors that determine its attractiveness in the eyes of consumers. From the consumer's point of view, environmentally friendly packaging is not only visually attractive but also meets their requirements regarding packaging materials and a responsible production process. With the increase in consumer awareness of environmental issues, the demand for environmentally friendly products increases in the market. However, as researchers point out, there is a difference between

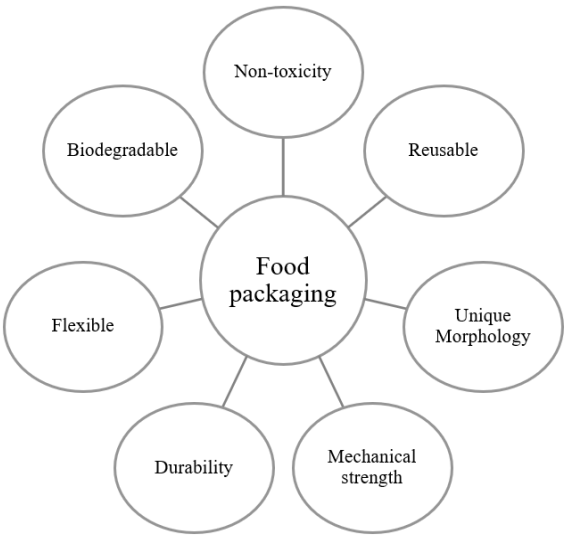
scientists' and consumers' understanding of environmentally friendly packaging. Consumers think about the impact of packaging on the environment after its end of use, without paying attention to the overall packaging life cycle - the production, packaging, transportation and end-of-life phase. As the better packaging material, the more widely known and used materials are chosen. Therefore, while consumers understand the negative impact of plastic on the environment, they still highly value the protective properties of plastic packaging. Without understanding the packaging production processes and the impact of materials on the environment, it is difficult to objectively evaluate environmentally friendly packaging (Nguyen et al., 2020).

As scientists point out, education is a significant factor influencing the choice of packaging materials based on waste management (Eslami et al., 2023).

Since the ingress of plastic into the environment cannot be completely prevented, it is important to pay attention to the environmental sustainability of the selected materials during the packaging design. This allows to reduce the negative impact on the environment after the product is used. As researchers point out, it is important to reduce ecological risk at the design stage itself, without linking it to consumer behaviour or waste management systems (James et al., 2024).

As one of the options for reducing the use of plastic in the market, biological materials are increasingly being offered in packaging production. By replacing conventional materials with biological (biomaterials), environmental pollution and consumption of non-renewable resources in the packaging industry are reduced. By studying and evaluating the properties of biomaterials in food packaging 'Figure 6', these materials are increasingly being used in other industries as well.

Figure 6
Advantages of biomaterials for food packaging



Source: authors' compilation based on Mahmund et al., 2024.

As researchers indicate, the food packaging industry is more often using biomaterials such as polymers, metals and alloys, ceramics and composites. According to researchers, the biggest challenge in introducing bio-based materials is cost-effectiveness and sustainability. To improve the quality assurance of food products and extend their shelf life, the use of nanomaterials in the packaging industry is becoming increasingly popular. However, as scientists point out, there are still many challenges associated with the use of nanomaterials (Mahmund et al., 2024).

Bioplastics are propounded as another environmentally friendly alternative to plastic. However, not all bioplastics are environmentally friendly. It can be either biodegradable or not. This difference is determined by their composition. This feature is often used in marketing communication, misleading consumers about the composition of the material and endorsing them to make wrong choices, thinking about environmental pollution and sustainability. Therefore, it is essential to label bioplastic packaging so that the consumer can determine the type of bioplastic by its composition. As researchers point out, biodegradable plastic is a more expensive material, as its production process requires greater resource and energy consumption (Parveen et al., 2024).

In the study by Petrenko et al., as environmentally friendly packaging materials the following are mentioned: bioplastics, paper, cardboard, glass and metal. In the context of sustainability, attention is paid not only to materials but also to the use of environmentally friendly technologies and solutions, such as the use of nanoparticles, plants, biodegradable and recycled materials and 3D printing. Such solutions expand the use of environmentally friendly packaging, reducing the damage caused to the environment. According to researchers, the main factors that contribute to the development of the market for environmentally friendly and biodegradable packaging are the growing demand, the provision of legal regulation and government support (Petrenko et al., 2024).

From the context of sustainability, Caner C. et al. in their study put forward three main factors that determine the sustainability of packaging: packaging recycling, the use of innovative materials and design (Caner et al., 2024).

Innovation of packaging materials and design is one of the ways to reduce the negative impact of packaging on the environment while maintaining the basic functions of packaging. Packaging must ensure product quality, its preservation, storage and transportation functions. In turn, from the consumer's point of view, it must be easy to use. From the perspective of sustainability and design, packaging must be of appropriate size. To ensure the functions mentioned above, more than 80% of the total environmental impact of packaging is already determined at the design phase. During the design phase for food packaging, it is important to pay

additional attention to the type of food for which the specific packaging is intended. Smart packaging is offered as a modern solution that could ensure sustainability requirements, but as the problem, its cost, functionality and safety are recognized (Versino et al., 2023).

According to statistical data, the total value of the global sustainable packaging market in 2024 was around 293 billion U.S. dollars and is expected to grow by 130 billion U.S. dollars in 2029, composing approximately 423 billion U.S. dollars (Statista, 2025). A factor that contributes to the effectiveness of Environmental taxes is price elasticity since the demand is sensitive to price changes. Natural Resource taxes do not reflect the costs of packaging but promote the choice of sustainable materials. From the perspective of the packaging industry, the goal of Environmental tax policy is to reduce the market demand for packaging made from materials that are subject to Environmental taxes (Cela & Kaneko, 2011).

Conclusions

1. The number of studies on Environmental taxes has tripled in the time period from 2011 to 2024. Most of the research is in environmental science and comes from China and the USA. However, this issue is also becoming increasingly relevant in Europe, faced with environmental pollution and the transition to a circular economy.
2. A current trend in the packaging industry is a holistic approach. The choice of packaging materials is made by evaluating the entire life cycle, thinking about packaging and sustainability as two different concepts.
3. The author's study revealed that, despite the ambitious goal of the Natural Resource tax, it currently does not significantly affect packaging trends, because market demand has a more significant role in the choice of packaging materials.
4. The Natural Resource tax introduced in Latvia mainly promotes packaging waste management by ensuring a process of accounting and recycling, which promotes the reduction of the amount of pollution created in the environment. However, it does not significantly contribute to the introduction of new technologies in the packaging industry, since the choices of manufacturers are much more significantly influenced by product quality assurance and the amount of total costs. A significant factor that would influence the choice of packaging manufacturers is consumer demand for environmentally friendly materials. Therefore, it is important to educate consumers about packaging materials and their impact on the environment and health.

Acknowledgements

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ECONOMIC ASPECTS OF SHEEP FARMING IN LATVIA

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Abstract
The aim of the study is to identify the development of the sheep farming sector in Latvia, to identify problems, challenges and future research directions. The study conducted an extensive data analysis using the monographic and descriptive methods, analysis and synthesis, quantitative and qualitative research methods and the graphic method. Sheep farming is a traditional livestock farming sector in Latvia. The number of sheep on farms has been variable, but recent years have shown a downward trend. The number of sheep on farms and the number of farms are decreasing by 14.9% and 20.9% in last 5 years. The trends in the sheep meat market are positive - sheep meat prices increased up to 688.94 EUR/100 kg in 2024, but the profitability of farms is limited, which is reflected in the variable gross margin: the ability of farms to cover variable costs. The gross margin for fattening lambs and breeding lambs has an increasing trend, but for ewes it is decreasing. In sheep farms in general the ability of farms to cover variable costs is hampered, with the result being at the break-even point or negative. Despite the uncertain situation in the economic field, the sector faces several challenges in the coming years: climate risks, an increase in the number of predators and the risk of infectious diseases. It is expected that only the most efficient farms in the sector will be able to ensure their sustainability. In the context of the sector, challenges of a legal meat market are also emerging, as a large part of the meat produced is obtained outside slaughterhouses.
Keywords: sheep farming, economic aspects, gross margin, sustainable development.

Introduction

The agricultural sector, as a food production base, is the foundation of human existence. Balanced and always available food ensures the existence of society in terms of climate challenges and national security aspects.

The challenges of the European Green Deal determine that current conventional practices in agriculture could change significantly, favoring technologies and solutions that would be much more beneficial to the environment and climate (Bhatt & Abbassi, 2021). The goals pursued by the European institutions concern not only climate issues, but also the availability and quality of food, putting forward the 'farm to fork' initiative. The situation in Ukraine, which developed after the military invasion of the country in 2022, shows that existing logistics and supply chains may cease to exist, therefore it is important to ensure accessible food even in crisis situations. Moreover, this food must meet the highest quality conditions.

This context also includes sheep farming – a sector that is traditional in much of Western Europe, with a permanent ecosystem of consumers and producers, close ties to nature and important functions in the rural environment, but dependent on public support payments (Furesi et al., 2015). Sheep meat is consumed and appreciated worldwide for its nutritional value and taste. However, this meat is highly perishable and easily exposed to both spoilage and pathogenic microorganisms (Purgatorio et al., 2022).

Sheep meat prices have been rising in Europe for several years. The price of sheep meat in the European Union (EU) has increased by 49% on average from 2020 to 2024, in Latvia - by 61%. EU member states are stable importers of sheep meat, as their own production volumes fail to cover demand, i.e. net production is less than domestic consumption. Demand is relatively unchanged. The production volume of sheep carcasses in 2023 decreased by 6.7% compared to 2020. The decrease in the months of 2024 compared to 9 months of 2023 was 6%. The global sheep meat market has become more concentrated and has developed into a niche market. Its impact on farmers must be assessed with an understanding of the overall market (Ramírez-López et al., 2020).

Research shows that there is potential for improvements in the sector's farming efficiency. Fixed capital, labor, and feeding are the main costs that can be reduced by implementing best practices and innovations in farming methods (Theodoridis et al., 2022). Slow adoption of innovation is a key challenge for the sustainability of the European sheep farming sector. The future of the sector depends on the adoption of best practices, modern technologies and innovations that can improve its resilience and reduce its dependence on public support (Theodoridis et al., 2021).

Materials and Methods

Research methods: the monographic and descriptive methods, analysis and synthesis, quantitative and qualitative research methods and the graphic method. The present research is based on scientific publications, information from databases and other sources. The research period spans from 2019 to the most recent data available.

Results and Discussion

To understand the overall potential of the sheep farming sector, it is important to understand the quantitative volumes of the sector and their dynamics over time. The next steps are to understand the dynamics of these volumes by analyzing economic efficiency and trends in key markets. The data should be viewed in the context of the challenges of the sector, understanding that the current situation will change rapidly in a changing environment.

Sheep farming is a relatively traditional industry in Latvia, despite the fact that it is not as popular as poultry farming, cattle breeding (beef cattle and dairy cattle) or pig farming. The number of sheep in Latvia fluctuated from 183,7 thousand in 1991 to a low of 27 thousand in 1999 (Central Statistical Bureau, 2025d). The significant decrease in the number of sheep ended in 1999, then gradually increased, reaching 112,2 thousand animals in 2017. After that, the number of animals gradually decreased again. The percentage of sheep in the entire period since 1991 is 3.5%-13.0% of the most common farm animals in Latvia (cattle, pigs, sheep, horses, goats). The large number of sheep in the early 1990s can be explained by a shift in farming methods, as the country transitioned from a planned economy to one based on free market principles. Prior to 1991, small homestead farms were common, and meat was primarily produced for self-consumption. The large number of sheep in the early 1990s can be explained by the change in farming methods, moving from a planned economic system to an economic system based on free market principles, because before 1991, small homestead farms were common, where meat was obtained for self-consumption. Sheep were suitable for the model of such small farms. As farming methods changed, the number of people living in rural areas decreased significantly, and with it, the volume of sheep farming also decreased (Central Statistical Bureau, 2025c). Following the structural changes in farming sector, the number of sheep has dropped to 78 300 units, but number of sheep farms has dropped to 2 252 units in 2024. At the end of the last century, sheep meat was mainly produced outside slaughterhouses, then in recent years the amount of sheep meat produced in slaughterhouses has increased significantly (Central Statistical Bureau, 2025b). This means that there is an increasing focus on officially recognized export markets, as the industry gradually moves out of the shadow economy.

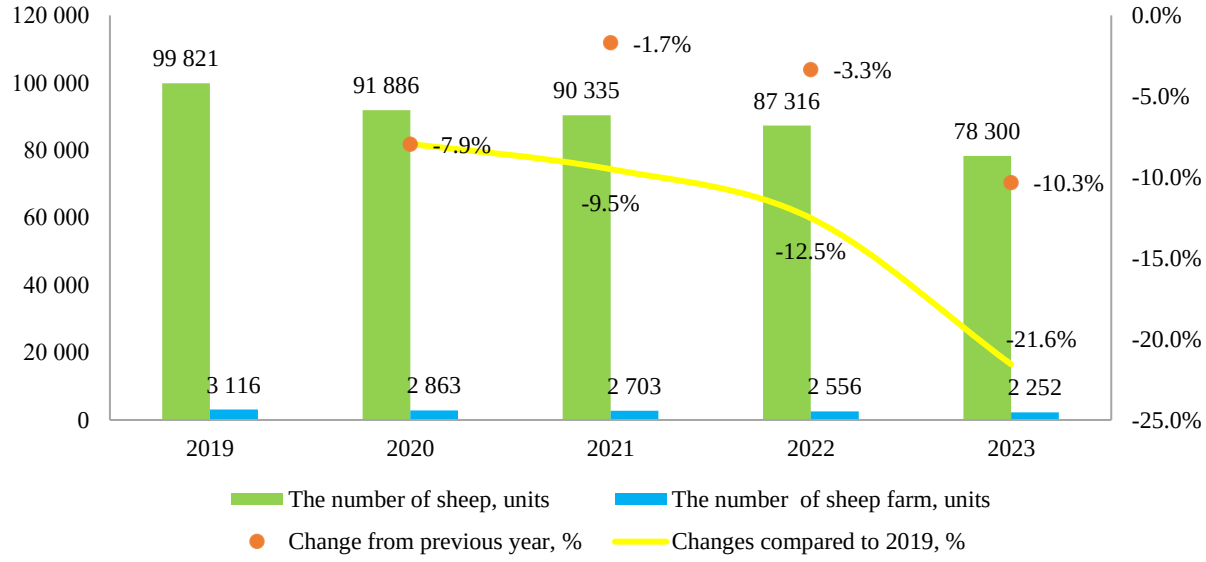
The situation in lamb and goat meat market has shown a rapid growth in the last few years. The lamb meat price grew from 428.39 EUR/100 kg in 2019 to 688.94 EUR/100 kg in 2024. However, the volume of meat produced outside slaughterhouses remains significant, which poses risks to food security and indicates the shadow economy. This is evidenced by the consumption of sheep and goat meat, which in Latvia in the last 10 years is estimated at around 0.9 thousand tons per year, but the volume produced in slaughterhouses is half of that amount (Central Statistical Bureau, 2025a).

Overall, profitablity of sheep farming is hampered. In 2024 one sheep family (1 ewe and 1.8 lamb on average) had gross margin -21.40 EUR (production aim – fattening) or 44.63 EUR (production aim – breeding). Gross margin shows the option to cover variable costs. It means that sheep farming balances around break even point or even below it.

Changes in the sheep farming sector continue, significant changes in the number of sheep and sheep farms are observed ‘Figure 1’.

Figure 1

Number of sheep at the end of the year, changes in the number of farms and number of sheep in Latvia



Source: authors’ construction based on Central Statistical Bureau, 2025e.

Over the past 5 years (2019-2023), the number of sheep has decreased by 21.6% (Central Statistical Bureau, 2025d). Data from the Ministry of Agriculture (Ministry of Agriculture, 2025) also show a further decrease in the number of sheep in 2024.

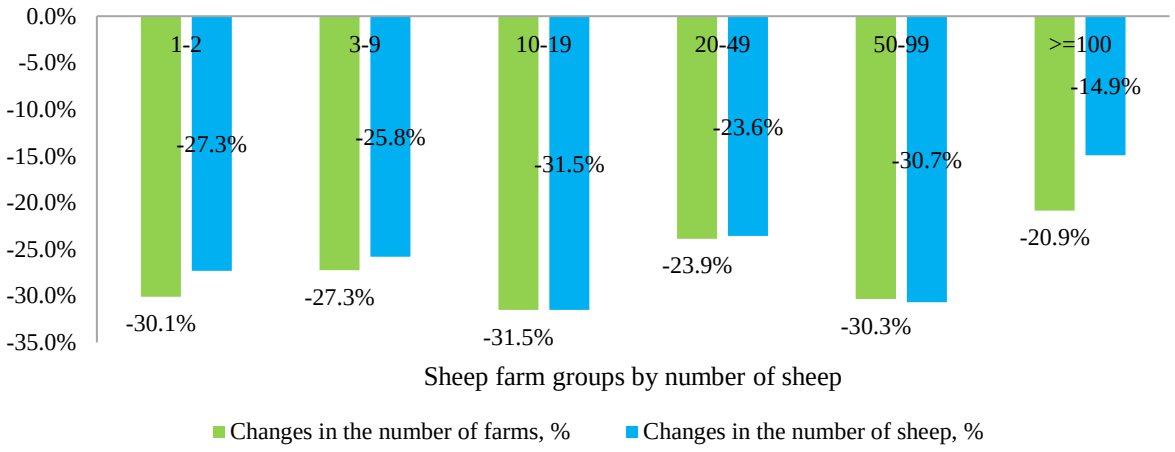
In 2023, 53% of sheep were registered on farms with over 100 animals, and they were only 8.3% of all sheep farms. This means that no more than 186 sheep farms, or only 8.3% of the total number of sheep breeders in Latvia, can be called economically significant in 2023. In

2023, the largest proportion (30%) is sheep farms with the number of animals 3-9, while 83% of all farms have the number of animals up to 49 animals. Such a number of animals does not provide a significant production flow, because the possible number of lambs that can be sold for meat or breeding is relatively small. The number of farms tends to decrease. In real life, this means the liquidation of the farm or the liquidation of the sheep farming sector on the farm. The number of farms is decreasing in absolutely all of the farm groups. The largest decrease in the number of farms is in the farm group 10-19 sheep. The smallest decrease is in the group 100 and more sheep. The second largest decrease in the number of farms is observed in the group 50-99 sheep. A more detailed analysis is needed to reveal the basic problems of the industry and the reasons for the decrease, which have prevented even relatively large farms from continuing farming and development.

Sheep numbers are decreasing in all farm groups, but the rates of decline vary between groups 'Figure 2'.

Figure 2

Changes in the number of sheep and farms in Latvia, 2023 compared to 2019, %



Source: authors' construction based on Central Statistical Bureau, 2025d.

The comparison of the rates of change shows that in the groups of farms with the number of sheep 10-19, 20-49 and 50-99 the rate of change of the number of farms is very similar to the rate of change of the number of sheep. In the other groups the rate of change of the number of animals is lower than the rate of change of farms. This means that, despite the decrease in the number of farms, on average there are more animals on farms, that is, those farms that continue this direction of farming often increase the number of animals. It can be concluded that the potential for development and expansion is seen in farms.

The number of sheep in the group of farms with 100 or more sheep increased at the end of 2022 compared to 2021, but decreased again in 2023. In general, it can be concluded that the rate of decrease in the number of sheep in this group is the lowest, and it fluctuates seasonally. Changes in individual years can often be attributed to local, temporary factors, for example, in 2023, due to the beginning of the dry vegetation period, it was challenging to prepare an appropriate amount of fodder, which may affect the number of sheep - taking into account the limited amount of fodder, farms have chosen to reduce the number of animals.

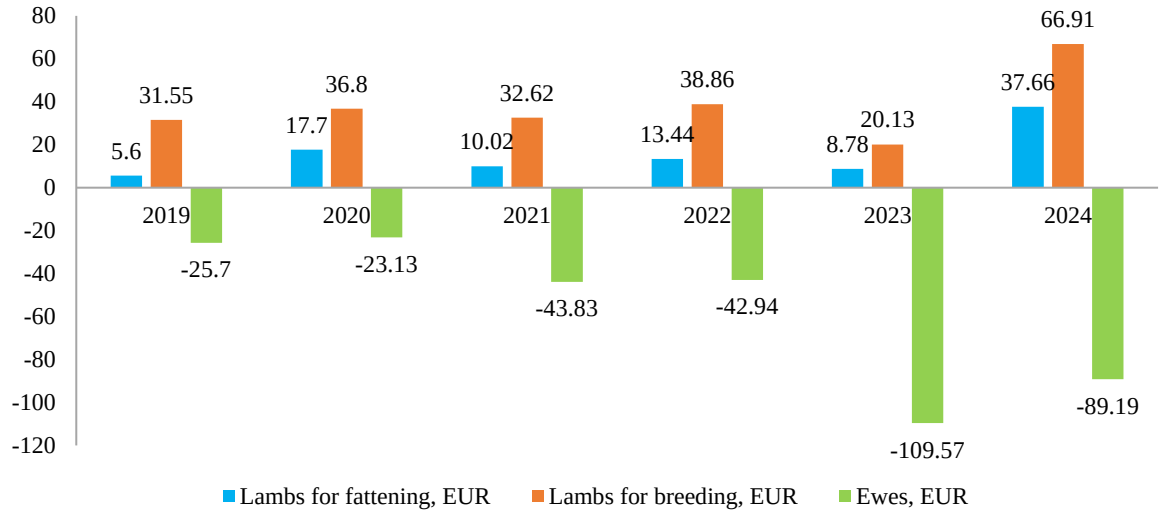
Experts from the Latvian Rural Consulting and Education Centre, in cooperation with farms, calculate gross margin indicators for sheep farming. Gross margin is an indicator that shows the difference between the revenue from the produced product and the variable costs per unit of production. Each gross margin calculation uses a specific production technology that is considered optimal (Latvian Rural Consulting and Education Center, 2025).

The gross calculation is made for ewes, lambs on meat farms and lambs on breeding farms. Therefore, the total of the various calculations reflects the overall situation in any of the selected production objectives. The gross calculation for lambs takes into account the cost of lamb entry (the price of lamb at birth), feed costs, veterinary costs, labor costs, as well as income from lamb sales.

The gross coverage of fattening lambs and lambs for the breed tends to increase Figure 3, while the gross coverage of ewes is decreasing. In fact, there are factors that determine that keeping ewes is increasingly unprofitable. The gross calculation assumes that 1 ewe feeds 1.8 lambs per season. In order to talk about a profitable sheep farming industry, the sum of gross coverages for an ewe and 1.8 lambs for any of the selected breeding purposes (breeding or fattening) should be greater than 0. This would be the point where the farm's income is able to cover the farm's variable costs. In 2022, the gross coverage of one ewe was -42.94 EUR. The gross coverage of 1.8 fattening lambs was 24.19 EUR, while the gross coverage of raising lambs for the breed was 69.95 EUR. In 2024, the gross coverage of one ewe had deteriorated to -89.19 EUR. In

turn, the gross coverage of 1.8 fattening lambs had increased to 67.79 EUR or 2.8 times, while the gross coverage of the lambs for breeding had increased to 120.44 EUR or 1.7 times. In the two years analyzed, sheep farming with the aim of raising fattening lambs has not been able to cover variable costs – the gross coverage amount for 1 ewe and 1.8 lambs was negative, while the breeding of lambs for breeding was apparently profitable. It is important to take into account the reliability of the data and calculations, because the gross coverage calculations of ewe lambs were made for ewe lambs from breeding farms. It can be assumed that these costs are lower on meat farms. The gross margin calculation shows that sheep farming as an industry is not highly profitable; therefore, only the most efficient farms can continue their successful development.

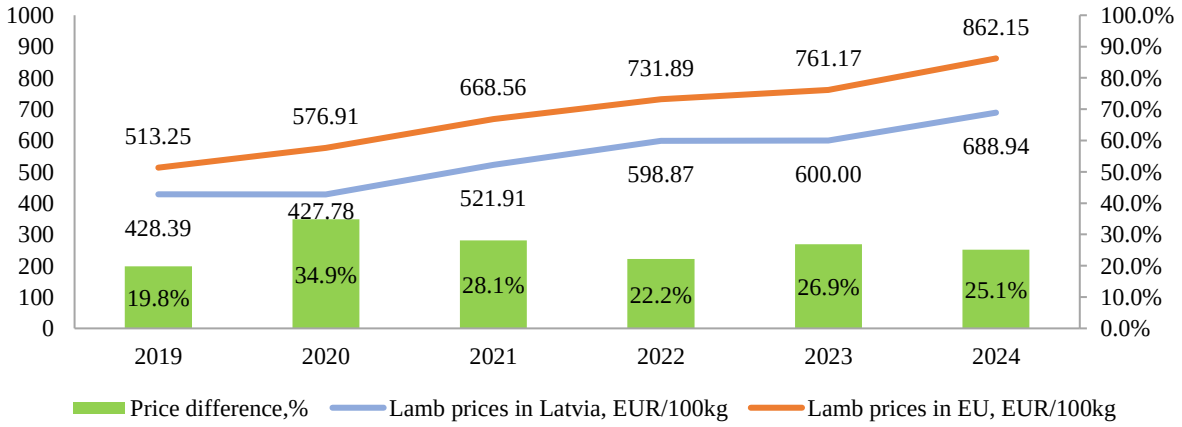
Figure 3
Gross coverage for fattening lambs, breeding lambs and ewes, EUR/unit



Source: authors' construction based on Latvian Rural Consulting and Education Center, 2025

A significant factor in gross margin calculations is the purchase price of lambs. Between 2019 and 2024, prices for fattening lambs increased from 1.82 EUR/kg to 3.50 EUR/kg live weight, or 1.9 times over 5 years. A similar situation is also reflected in the analysis of carcass prices in the EU and Latvia 'Figure 4'. The European Commission's compiled sheep meat prices show a continuous price increase, maintaining a 20-35% difference between Latvian and EU average prices. Price changes are significantly related to insufficient production volume in the EU - sheep meat consumption is higher than the produced volume. Initially, in the short term, the missing volume of meat is sought on the domestic market, increasing prices, in the longer term, import volumes increase and the volume of domestic production also increases.

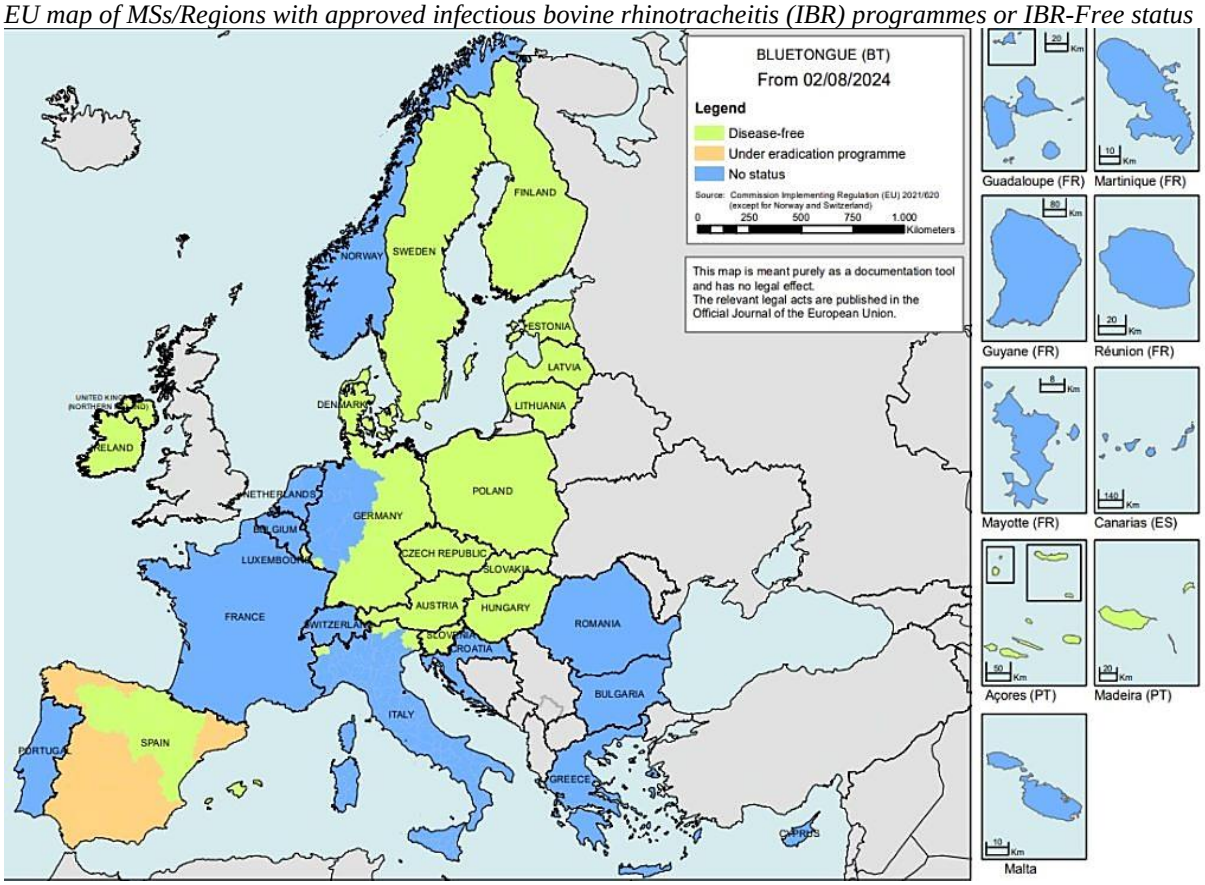
Figure 4
Lamb prices in Latvia and the EU



Source: authors' construction based on European Comission, 2025, March 12.

The overall market situation shows several positive features for Latvian sheep farms:
• The internal EU market is unsaturated;
• Sheep meat prices have been increasing in recent years;
• The reduced number of farms and sheep in Latvia maintains upward pressure on prices.
Despite this background, the sheep farming sector in Latvia has limited earning capacity. The assumption of limited earning capacity is not absolute. It is necessary to look for methods and a business model that allows for streamlining production processes, ensuring a positive economic performance. However, in a large part of farms, based on general data analysis, sheep farming is an extensive farming sector that helps manage the property or serves as a side activity or farming direction that seemingly helps to obtain additional income without calculating all costs or cross-subsidizing from other business directions.
In addition to an inefficient farming model, the industry faces a range of new challenges.
Climatic challenges
2023 was the year of heat and drought, which significantly reduced the total harvest, at a time when grasslands are important for growth. The year 2024 was relatively wet, which again resulted in poor-quality forage. Such climatic instability requires investments to ensure technologies for the preparation of feed that is less dependent on climatic factors (silage, dried hay).
The number of predators is increasing
In Latvia, around 500 sheep suffer from wolf attacks every year – bitten, injured, lost (Sheep farming industry overview for 2023, 2024). Moreover, these are only the reported cases. In general, the positive attitude of society towards nature and nature protection makes it necessary to look for solutions to coexist with predators.
Diseases
The health status of sheep is an important basis for farming. A current problem in Europe is bluetongue (bluetongue disease) ‘Figure 5’. The use of marker vaccines and associated marker tests provides a means of controlling the disease in herds with medium to high herd prevalence, but this strategy must be complemented by biosecurity measures to reduce the risk of introducing the virus into the herd. Disease control and eradication at the herd level is achievable, but a systematic approach is essential to address disease control issues at a regional or national level.

Figure 5
EU map of MSs/Regions with approved infectious bovine rhinotracheitis (IBR) programmes or IBR-Free status



Source: Guelbenzu, 2024.

The disease is spread by blood-sucking insects and has 24 serotypes, which makes vaccination difficult. This is actually only possible after the disease has been detected on the farm (Ministry of Agriculture, 2025). The disease often ends in the death of the animal. The common practice is to slaughter infected animals, thus further reducing the number of sheep (Latvian Rural Consultation and Education Center, 2025).
This disease has not been detected in Latvia at this time, and the European Commission has determined that the country has the status of a disease-free country. This is considered an advantage, but there are challenges in maintaining this status.

Conclusions

1. The number of sheep and the number of sheep farms in Latvia have a tendency to decrease. Slower decrease trends are observed in large farms, which indicates the desire and opportunities of these farms to continue sheep farming, but still there is a rapid drop of number of sheep farms by 20.9% and drop of number of sheep by 14.9% comparing the year 2024 and 2019.
2. Gross margin analysis shows that the ability of sheep farms to cover variable costs is hampered, which creates significant risks to the viability of the farm. For ewes and lambs at any of the selected production objectives, the ability of farms to cover variable costs is hampered, with the result being at the break-even point or negative. In 2024, one sheep family (1 ewe and 1.8 lamb on average) had gross margin -21.40 EUR (production aim – fattening) or 44.63 EUR (production aim – breeding).
3. Sheep farms in Latvia are positively affected by rapidly growing sheep meat prices throughout the EU, price changes ensure their viability. The lamb price in Latvia has grown from 428.39 EUR/100 kg in 2019 to 688.94 EUR/100 kg in 2024. Despite the price increase, the challenges expected for the sector indicate the need for significant investments in ensuring operations. Such factors will continue to put pressure on the profitability of farms, which will determine that only the most efficient farms will strengthen in the sector.
4. There are 0.9 thousand tons of lamb and goat meat consumption in Latvia per year. Only about one half is obtained in slaughterhouses. The large amount of meat obtained outside slaughterhouses in Latvia indicates a disorganized meat circulation control system and a high risk of the spread of the shadow economy, as well as reducing the country's export capacity.

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AVAILABILITY OF SERVICES IN SOCIO-ECONOMIC CLUSTERS OF LATVIAN ADMINISTRATIVE UNITS

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Abstract
The concepts of clusters and cluster analysis often are mixed up leading to confusion and certain misunderstandings. Cluster analysis encompasses unsupervised machine learning methods with datasets that are not predetermined. In turn, clusters are understood as regional groups of economic actors in a close proximity that have reached certain levels of specific resources, expertise and skills to stand out among the broader economy. Often the analysis on these clusters also is denominated as cluster analysis. The objective of the study is to assess the differences in availability of a number of services in clusters of administrative units at the parish level. K-means clustering method is selected for the forming of clusters based on their similarity. Five indicators are selected for the forming the clusters: Gross Value Added, Unemployment level, Number of Workplaces, Gross Salary and number of persons with the Higher Education. Eight clusters were identified. For the further analysis the following Service availability indicators were selected: Number of Pharmacies, General Practitioners, Automated teller machines, Gas stations, Postal offices, Food retail outlets, share of Kindergarten Enrolment and share of School Enrolment. Results revealed significant differences in cluster parameter indicators, though certain clusters exhibited similarities. A similar pattern was observed in service availability indicators. However, the relationship between cluster rankings for parameter and service availability indicators was inconclusive. The study is limited by data availability at the parish level, and a broader set of indicators would allow for greater variability in cluster parameters and variables.

Keywords: clusters, K-means clustering, services availability, parish.

Introduction
Regional development analysis involves examining the processes that affect the quality of life and economic well-being of populations. In the context of Latvia, parishes serve as the smallest administrative units but are not at all used as focal points for cluster-based analyses in regional development studies. Social scientists and policy makers over the last three decades have increasingly focused their attention on clusters often observing the concentration of production and innovation in specific geographic areas (Orsenigo, 2006). European Cluster Collaboration Platform definition states that clusters should be considered as regional ecosystems of related industries and competences featuring a broad array of inter-industry interdependencies. They are defined as groups of firms, related economic actors, and institutions that are located near each other and have reached a sufficient scale to develop specialised expertise, services, resources, suppliers and skills (European Cluster Collaboration Platform, 2025). Cluster analysis or clustering is a data analysis method that divides a set of objects into groups where objects in the same group are more similar to each other than to those in other groups. The number of clusters and their structure is not predefined. Time and again, these two concepts are misunderstood and improperly attributed. The analysis of the predefined clusters mistakenly is often called cluster analysis. Research in Latvia has so far mostly focused either on the identification of business clusters (Garanti & Zvirbule-Berzina, 2013; Liela et al., 2010) or on the evaluation of cluster policy (Kulakova & Volkova, 2013). The application of clustering the administrative units is less common. Analysing service access in socio-economic clustering at the parish level offers valuable insights into regional disparities. Understanding these spatial patterns is essential for applying cluster-based methods to assess territorial development, particularly in identifying areas of insufficient access to public services and economic opportunities.

Materials and Methods
Clustering algorithms are a type of unsupervised machine learning used to group data based on similarities. K-Means clustering is a method that partitions datasets into clusters. In K-Means Clustering clusters are distinct with their numbers assigned according to the user pre-selected total number of clusters. K-Means groups data by minimizing intra-cluster variation to create compact, distinct clusters. It requires specifying number of k clusters upfront. K-Means Clustering is based on the iterative relocation of data points between clusters. It is used to divide the units of a dataset into non-overlapping groups, or clusters, based on the selected unit characteristics, usually a number of variables. The expected result is a pre-determined number of distinct groups of panel data units with a high degree of similarity within each group and a low degree of similarity between groups. K-Means Clustering uses the Lloyd algorithm centroid model (Lloyd, 1982). A centroid is expressed as a mean of each pre-selected variable that characterizes the unit. First, the k initial centroids are chosen based on an arbitrarily selected single variable, either randomly or by dividing the range of specified variable into intervals. After that, iterations are done in two steps. In the first one, each case of the data set is assigned to a cluster based on its distance from the cluster's centroids, using one of the distance metrics. Euclidian distance is usually used:

$$d(P,Q) = \sqrt{(p_1 - q_1)^2 + (p_2 - q_2)^2 + \cdots + (p_n - q_n)^2} \quad (1)$$

where $P = (p_1, p_2, \ldots, p_n)$ - vector P;
$Q = (q_1, q_2, \ldots, q)$ - vector Q; n - number of data points;
$d(P,Q)$ - Euclidian distance between the vectors P and Q.

In the second step, the previous value of centroid (usually mean) is replaced by the mean of all cases assigned to the centroid in the first step. Then the sum of squared error (SSE) is calculated as a sum of squared minimum distances between the cases. These two step iterations are repeated either until the SSE does not become lower or assigned cluster numbers for each unit do not change.

The Caliński-Harabasz index (Caliński & Harabasz, 1974) is a metric for the evaluation of the remoteness between cluster centroids. The assessment is based solely on the dataset and the clustering results. CHI index is defined as the ratio of the between-cluster separation (BCSS) to the within-cluster dispersion (WCSS), normalized by their number of degrees of freedom:

$$CH = \frac{BCSS/(k-1)}{WCSS/(n-k)} \quad (2)$$

where $BCSS$ - weighted sum of squared Euclidean distances between each cluster centroid; $WCSS$ - sum of squared Euclidean distances between the data points and cluster centroid; k - number of clusters; n - number of data points; CH - Caliński-Harabasz index.

BCSS (Within-Cluster Sum of Squares) is the sum of squared Euclidean distances between the data points and their respective cluster centroids:

$$BCSS = \sum_{i=1}^{k} n_i \|c_i - c\|^2 \quad (3)$$

where n_i - number of points in cluster C_i, c_i - centroid of C_i, c_i - overall centroid of the data; $BCSS$ - weighted sum of squared Euclidean distances between each cluster centroid.

BCSS measures how well the clusters are separated from each other (the larger the better). WCSS (Within-Cluster Sum of Squares) is the sum of squared Euclidean distances between the data points and their

$$WCSS = \sum_{i=1}^{k} \sum_{x \in C_i} \|x - c_i\|^2 \quad (4)$$

where k - number of clusters; c_i - centroid of C_i; χ - data point; $WCSS$ - within cluster sum of squares.

WCSS measures the compactness of the clusters (the smaller the better). The objective of the centroid-based clustering is the simultaneous maximizing the BCSS and minimizing the WCSS.

Finding the optimal number of clusters is usually a two-step procedure. The Elbow method, proposed by Thorndike (Thorndike, 1953) is a heuristic graphical method for finding the optimal number of clusters in a k-means clustering algorithm. The WCSS values are plotted on the y-axis with the corresponding k values plotted on the x-axis. The optimal number of clusters is determined by a forming of an elbow in the graph. The optimal number of clusters suggested by an Elbow method could be retained only if the corresponding CHI index has the highest value.

Data for creating the clusters from 591 administrative units for 2022 are obtained from Central Statistical Bureau (CSB, 2025). Five indicators are selected as cluster variables: Per capita Gross Value Added, Gross Salary, share of persons with Higher Education in total population, per capita Workplaces and Unemployment Rate. Data on variables for service availability for 2022 are obtained from Central Statistical Bureau (CSB, 2025), Central Bank (Latvijas Banka, 2025), National System of Educational Information (Valsts izglītības informācijas sistēma, 2025), National Health Office (Nacionālais Veselības dienests, 2025), Latvian Post (VAS Latvijas Pasts, 2025), SIA Kalifeks (2025), SIA Venipak Latvija (2025), SIA DPD Latvija (2025), SIA ELVI Latvija (2025), SIA Iepirkumu grupa (2025), SIA Lats veikali (2025), SIA Latvijas Neatkarīgo Tirgotāju Kooperācija (2025), SIA Lidl Latvija (2025), SIA Maxima Latvija (2025), SIA Mego (2025), SIA RIMI Latvia (2025), SIA SPAR Latvia (2025), uzziņu dienests 1188 (2025), SIA Vesko (2025). Nine indicators are selected as service availability variables: Parcel machines, Pharmacies, General Practitioners, Automated teller machines, Gas stations, Postal offices, Food Retail outlets on 10,000 inhabitants; Share of kindergarten enrolment and Share of school enrolment within the respective population group.

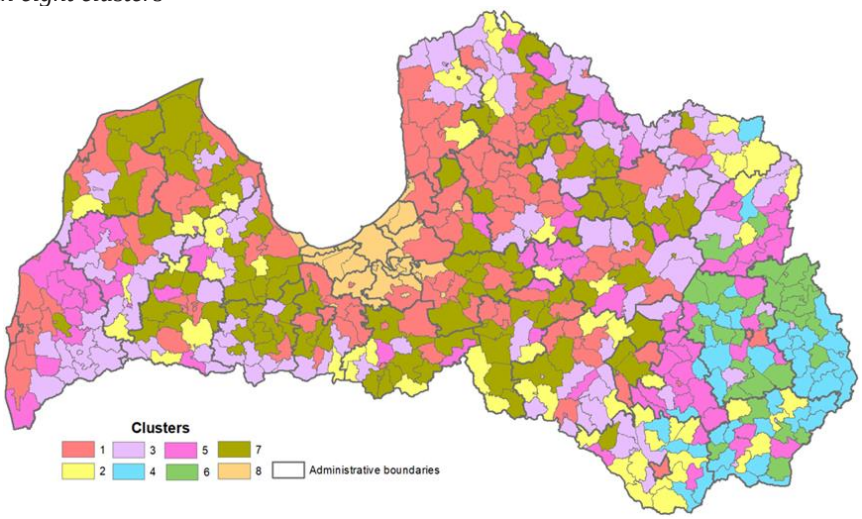
Results and Discussion

K-means clustering with Euclidean distance is performed with pre-selected user defined cluster numbers ranging from two to ten. As the cases with the cluster numbers above eight yielded no results (only eight clusters had at least one unit) and the plot at the eight-cluster case shows the slight elbow, the optimal number of the clusters is eight. The corresponding CH index value also is the highest. Hence, the proceeding with the eight clusters is justified. After the seven iterations, eight clusters were established. The clusters are plotted on the map 'Figure 1'.

As seen from the map, units belonging to the same cluster do not necessarily be geographically closely located. Even within one district parishes can be different clusters. Mapping of the clusters points towards a pronounced monocentricity with a well performing area around the Capital City (Cluster 8).

There are districts divided into two clusters indicating on relatively similar situation. At the same time, there are districts with parishes attributed to five or more clusters indicating on uneven development of the administrative units.

Figure 1
Latvian map with eight clusters



It is important to note that while some clusters (1, 2, and 5) are distributed across the entire country, two clusters (4 and 6) are exclusively observed in the eastern part of country which is Latgale region. This suggests that certain territories exhibit regional variations and, based on the selected indicators, reflect differing levels of development. Arbitrary cluster titles are assigned to each cluster. The average values of the cluster variables for eight clusters are shown in 'Figure 2'.

Figure 2
Eight clusters and parameter averages

Clusters	Unemployment rate	Gross Value Added per capita	Share of workplaces in total population	Average Gross Salary	Share of persons with higher education (age 19 + years)
8 - Metropolitan area	5.2	14,495.4	60.0	1,491.7	41.0
1 - State cities and well performing counties	7.6	9,095.9	53.4	1,150.7	27.4
7 - Affluent counties	8.1	9,423.7	50.0	1,080.3	18.9
5 - Average counties	10.9	6,185.0	49.3	1,002.7	20.2
3 - Average performing counties	10.1	6,223.0	47.4	985.7	18.8
2 - Below the average perfoming counties	11.6	5,718.7	44.1	955.2	16.7
6 - Poor counties	21.8	4,601.6	44.8	922.8	19.5
4 - Extremely poor counties	24.5	3,933.1	38.7	828.3	13.1

The cluster parameter average values for each cluster are paired and coloured in four hues from light green to deep red according to the position of the value within the respective range. Clusters 1 and 8 have only green (very light to dark green) cells indicating on good socio-economic performance. The highest Gross Value Added per capita (GVA per capita), share of persons with Higher Education, Average Gross Salary and lowest Unemployment rate are recorded in Metropolitan area (Cluster 8). On the other hand, Cluster 4 has the lowest average values for every parameter variable. Cluster 1 comprises six State Cities, 29 townships and 89 rural parishes, wherein all five parameters exhibit considerable similarity to the highest - performing Cluster 8, except for GVA per capita, which is 1.5 times lower, and the proportion of persons with higher education, which also is 1.5 times lower. In Cluster 7, indicator values are relatively similar to those in Cluster 8 and Cluster 1, differing slightly in two parameters: the share of persons with Higher Education and the share of Workplaces in the total population. However, it exhibits a higher Average Gross Salary compared to Cluster 1. Clusters 4 and 8 show significant disparities in unemployment rates, with differences over fourfold, and GVA per capita differs more than three times. However, the Average Gross Salary is about half in Cluster 8 compared to Cluster 4. Clusters characterized by low Average Gross Salaries also exhibit significantly high unemployment rates. Clusters 5 and 3 are relatively similar, displaying moderate values across all indicators. Notably, Cluster 5 outperforms Cluster 7 in the share of persons with Higher Education. Cluster 2 exhibits relatively poor performance in the share of persons with Higher Education indicator, both in absolute terms and relative to the average values

recorded in Clusters 3 and 5. If compared to Cluster 8, the indicators for Unemployment rate, GVA per capita, and share of persons with Higher Education are 2.2 to 2.5 times worse. Clusters 4 and 6 demonstrate the weakest performance across all indicators, particularly in the Unemployment Rate and GVA per capita, where their values are 4.4 and 3.6 times worse, respectively, if compared to Cluster 8. Moreover, Cluster 4 exhibits the most unfavourable situation as it has the highest Unemployment rate among all clusters, and for all other indicators, it stands only at 37% to 90% of Cluster 6 levels.

The calculated values for the service availability variables for eight clusters are shown in 'Figure 3'.

Figure 3

Service availability indicator average values in eight clusters

	Clusters							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Number of Units	124	62	115	41	76	32	114	27
	Per 10,000 inhabitants							
Parcel machines	8.0	1.4	6.3	0.8	5.8	4.3	5.6	7.8
Pharmacies	4.6	2.0	4.4	1.2	4.3	3.0	3.6	4.1
General Practitioners	7.5	4.3	6.2	2.9	6.7	3.4	5.4	7.8
Automated teller machines	4.5	0.5	3.2	0.4	3.1	2.2	2.2	3.7
Gas stations	4.2	1.8	2.9	1.2	4.4	1.7	3.5	2.9
Post offices	5.9	15.1	14.5	18.0	15.9	17.2	13.4	3.9
Food retail outlets	9.4	9.5	9.7	3.3	9.6	6.5	11.6	5.8
	Per population group							
Share of kindergarten enrollment	39.5	7.5	25.0	8.4	25.4	33.4	21.4	38.7
Share of school enrollment	29.2	13.5	25.3	10.4	22.3	22.0	31.0	63.5

The disparities are marked in service availability among clusters. Clusters 1 and 8 have a good availability in a majority of the services. The availability of postal services seemingly is negatively correlated with the availability of Teller Machines (ATM) as we can see in Cluster 4. The situation in Clusters 1 and 8 is similar. However, Cluster 1 records more favourable situation across all services except Postal services. This stands in steep contrast to Cluster 4, where postal service accessibility is the highest, yet all other indicators are among the weakest. This suggests that Post offices could serve as key locations for providing essential services otherwise unavailable in these areas, such as ATMs, parcel lockers, and goods collection points. The highest workload on General Practitioners is observed in Clusters 1 and 8, with workload indices of 7.5 and 7.8, respectively, whereas the lowest workload is recorded in Cluster 4 (0.4). The availability of Pharmacies and General Practitioners is most limited in Clusters 4, 2 and 6, which also rank lowest in terms of overall situation. The overall assessment based on the selected essential services highlights Clusters 1 and 8 as having the most favourable conditions, aligning with their strong performance across other development criteria. Clusters 3 and 5 can be classified as having a moderately favourable situation, as service availability is relatively balanced across all service types. In contrast, Clusters 6 and 7, despite being in different stages of development, exhibit lower service availability indicators, particularly in access to Pharmacies and ATMs, compared to the mid-level clusters (Clusters 3 and 5). Similarly, in evaluating kindergarten and school attendance, Clusters 2 and 4 exhibit the most unfavourable conditions, with attendance rates up to five times lower than those observed in Clusters 1 and 8.

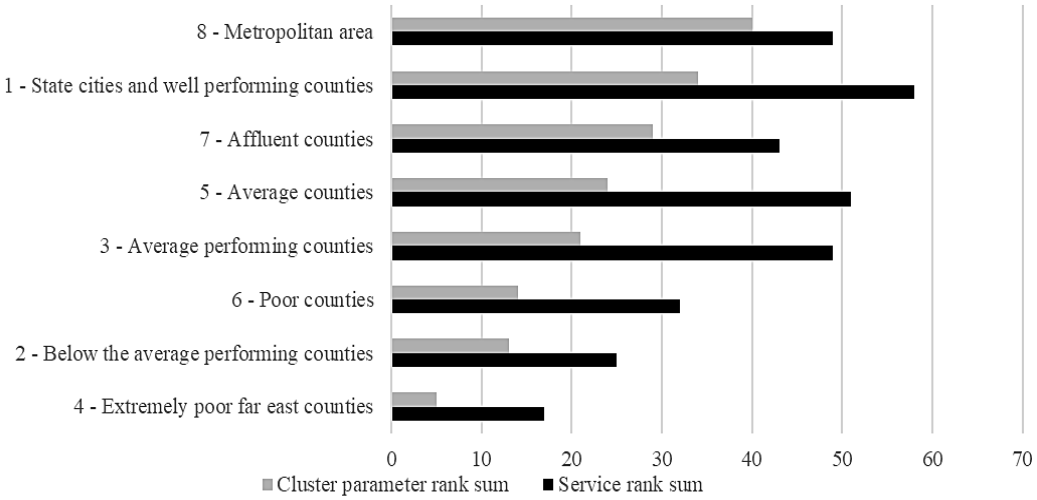
The data suggests that clusters provide a nuanced framework for understanding the distribution of key services across regions, identifying areas of both strength and vulnerability. Post offices, for instance, when considered as part of a cluster analysis, reveal their potential to function not just as logistical nodes but as multifaceted service points, offering insights into how infrastructure can be optimised for broader regional needs. The disparities in service availability across clusters emphasise how the use of clusters can effectively pinpoint specific regional deficiencies, particularly in sectors like healthcare and education. For example, Clusters 2, 4, and 6, which display significant service gaps, can be seen as regions requiring more targeted policy intervention and investment. Conversely, Clusters 3 and 5 offer valuable data on regions with relatively balanced service distribution, which can serve as models for incremental improvements in less developed areas.

Moreover, the consistently low service indicators in Clusters 6 and 7, irrespective of their broader development contexts, illustrate how cluster analysis can uncover underlying systemic issues that might otherwise remain undetected in broader regional assessments. These findings underscore the utility of clusters in dissecting regional heterogeneity and directing targeted interventions.

Ultimately, clusters, as a methodological tool, offer a sophisticated approach to analysing regional development, enabling policymakers to identify

spatial inequalities and allocate resources more effectively based on empirical, data-driven insights.
Two ranking parameters can be established. First, the clusters are assigned ranks for each of the parameters according to the respective average value. Second, the clusters are assigned ranks for each of the service availability variable. Higher rank assumes better performance. Third, the ranks are summed to get the total rank. Total ranks for parameters and service availability variables are shown in ‘Figure 4’.

Figure 4
Service availability indicator average values in eight clusters



As seen from the chart, the relationship between the parameter ranks and service availability ranks is not unambiguous. Affluent parishes in Cluster 7 perform lower than might be expected.
Differences can be observed between the ranking of clusters based on their parameters and their ranking in terms of service availability. While the cluster ranking positions Clusters 8, 1, 7, and 5 at the top, the service availability ranking places Cluster 1 first, followed by Clusters 5, 3, and only then Cluster 8. However, the bottom three clusters remain unchanged in both rankings, with Clusters 6, 2, and 4 consistently occupying the lowest positions. This indicates that these clusters (6, 2 and 4) are in the most challenging situations, both from an economic perspective and in terms of service accessibility.
The clustering of administrative units is not common in the EU countries. In the UK, Office for National Statistics in the latest Census in 2021 include experimental statistics with clustering local authorities against subnational indicators in England (Office for National Statistics, 2025). Clusters are defined as similar local authorities. Using a k-means clustering method, seven different models on different themes using data available are created allowing users to understand the similarities between local authorities, while providing local authorities with control groups for investigating the impact of policy interventions. The cluster forming variables were based on themes such as urban vs. rural areas, health, well-being, connectivity, educational performance, population density. After establishing the clusters, headline metrics for comparisons per theme were selected, such as gross value added per hour worked; average travel time to nearest employment centre by public transport or walking; gigabit capable broadband; pupils at expected standards by the end of primary school, apprenticeships achievements per capita; healthy life expectancy; life satisfaction. Analysis of selected headline metrics across seven different themes produced four clusters of local authorities in England: Higher health and well-being, lower connectivity (52 Local Authorities); Higher connectivity, lower health and well-being (78 Local Authorities); Higher health and well-being, moderate educational performance (114 Local Authorities); Higher health and productivity, lower well-being (56 Local Authorities). Similarly to Latvia, the number of Local Authorities differs significantly between the clusters. To present the findings of the analysis, an interactive map has been created. Results for each cluster are presented in this tool across all seven themes. Local authorities of interest can be selected from the drop-down menu, and text summarising the clusters is shown.

Conclusions

Clusters and clustering are distinct yet often misinterpreted concepts that need to be clearly delineated in both research and policy contexts.
1. This study has demonstrated that clustering administrative units-particularly rural parishes-can uncover significant patterns in socio-economic situation and service provision. The analysis revealed notable disparities in parish development outcomes, where some clusters exhibit considerable deficits in both economic and service-related indicators.

2. Identifying these spatial disparities is essential for applying cluster-based analyses to enable justified territories-specific interventions.
3. Future research can be focused on clusters created based upon the themes other than socio-economic performance, such as education, health, connectivity, service availability with the analysis of the performance in other themes.
4. The development of interactive tools for visualising regional disparities at the parish level can facilitate data-driven approaches to policy formulation, enhancing the effectiveness of regional development strategies.

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ADOPTION OF RENEWABLE TECHNOLOGIES AND CROP DIVERSIFICATION AS DRIVERS OF CLIMATE-ADAPTIVE AGRICULTURE: EVIDENCE FROM EMERGING ECONOMIES

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Abstract
The integration of renewable irrigation technologies and crop diversification is critical for achieving climate-adaptive agriculture in emerging economies. This study examines the impact of these sustainable agricultural interventions on productivity, environmental sustainability, and economic resilience across 20 emerging economies from 2000 to 2024. Using panel data from the World Bank, World Development Indicators (WDI), and the International Monetary Fund (IMF), the study employs econometric modelling to assess the influence of renewable irrigation systems, nitrogen-efficient fertilizers, and diversified cropping patterns on agricultural sustainability. Findings reveal that solar-powered irrigation enhances water efficiency and reduces dependency on fossil fuels, while crop diversification mitigates climate risks and stabilizes farm incomes. However, financial limitations, infrastructural inadequacies, and policy discrepancies hinder widespread adoption. The study advises to accelerate the transition to climate-resilient agriculture through targeted policy interventions, improved financing mechanisms and enhancing technological training. These insights help inform a roadmap for policymakers, agribusiness investors and aid practitioners seeking to promote sustainable agriculture strategies and enhance food security outcomes without exacerbating vulnerabilities associated with climate change.
Keywords: climate-adaptive, drivers, agriculture, emerging economies.

Introduction

The adoption of renewable technologies and crop diversification has become central to agricultural sustainability and climate resilience, particularly in emerging economies (Nyangarika, 2024). As global climate change accelerates, agricultural systems in emerging countries, like India, Pakistan, Bangladesh, Sri Lanka, Nepal, Indonesia, Malaysia, Thailand, Vietnam, the Philippines, Brazil, Mexico, Argentina, Colombia, Chile, Nigeria, Kenya, Ghana, Ethiopia, and South Africa face mounting challenges related to droughts, erratic rainfall, land degradation, and declining soil fertility (Campos & Root, 2001). To ensure long-term food security, environmental sustainability, and economic stability, it has become imperative to integrate solar-powered irrigation systems, nitrogen-efficient fertilizers, and diversified cropping strategies.

Renewable technologies have proved a transformative force in modernizing agriculture and addressing climate risk (Batra, 2023; Wicki et al., 2025). For instance, solar-powered irrigation has quickly become an economically viable replacement for diesel-operated pumps, allowing for year-round irrigation while lowering operational costs and carbon emissions. In conclusion, AI-based solutions such as precision agriculture instruments, IoT-enabled soil sensors, AI-based climate analytics, and automated irrigation devices have automated yield estimates and improved yields while minimizing environmental footprints by making fertilizer applications, irrigation, and pest control more efficient (Senoo et al., 2024; Zeverte-Rivza et al., 2023). The use of such technologies together (integrated crop management (ICM)) has already proven beneficial further helping build agricultural resilience across South Asia, Southeast Asia, Africa and Latin America. However, challenges remain, including high initial investment costs, a lack of financing mechanisms, and insufficient training for farmers. In many places, rural electrification is still weak and complicates the transition to renewable energy-supported agricultural solutions. Governments need to carefully improve existing subsidy programs, increase access to agricultural credit, and work with the private sector to promote the roll out of renewable agricultural technology (Glemarec, 2012).

Another pillar of improved soil fertility, increasing resistance to pests and stabilizing farm income is crop diversification. Diversified cropping systems including nuts, legumes, cereals, fruits, oilseeds and medicinal plants rely less on chemical fertilizers and improve nutrient retention and soil structure, compared to monoculture-based farming. In addition, multi-cropping, inter cropping and agroforestry models have been found very effective to overcome challenges of soil degradation and improve carbon sequestering. In developing economies, crop diversification is increasingly promoted through agricultural extension services, seed distribution programs, and climate-smart subsidies. However, adoption has not been uniform, due to barriers to market access, the lack of advanced storage facilities and reluctance to abandon traditional agricultural practices. Another important consideration for maximizing the advantages of crop diversification is that regional trade policies, farmer training programs and supply chain improvements should be conducted seamlessly for integration into national food security strategies (Muhammad & Babatunde, 2024).

The international collaborative study seeks to understand how renewable irrigation technologies and crop diversification can accelerate the transition to climate-adaptive agriculture in India, Pakistan, Bangladesh, Sri Lanka, Nepal, Indonesia, Malaysia, Thailand, Vietnam, the Philippines, Brazil, Mexico,

Argentina, Colombia, Chile, Nigeria, Kenya, Ghana, Ethiopia and South Africa. It measures renewable energy solutions' effect on farm productivity, water conservation and economic efficiency, and explores how crop diversification can enhance soil health, climate resiliency and food security. It also discusses challenges to adoption, including lack of finances, infrastructure, and knowledge. Drawing from empirical evidence from various sources including the World Bank, WDI and IMF for the period of 2000–2024, the study highlights policy frameworks, financial models and technological enablers for scaling up sustainable agricultural interventions (Raza & Quaye-Kumah, 2024).

Discussions on climate-smart agriculture and sustainable rural development have become emerging focal points for advancing agriculture globally, supported by evidence-based recommendations for policy makers, agribusiness investors, and agricultural practitioners. Renewable energy integration and diversified cropping systems are the key measures to achieve food security, environmental sustainability, and the national economy of rural area. The aim of this study is to present an integrated perspective on the strategies that emerging economies can utilize to shift towards resilient, low-emission agricultural systems, promoting long-term sustainability and economic inclusivity amidst rising climate challenges.

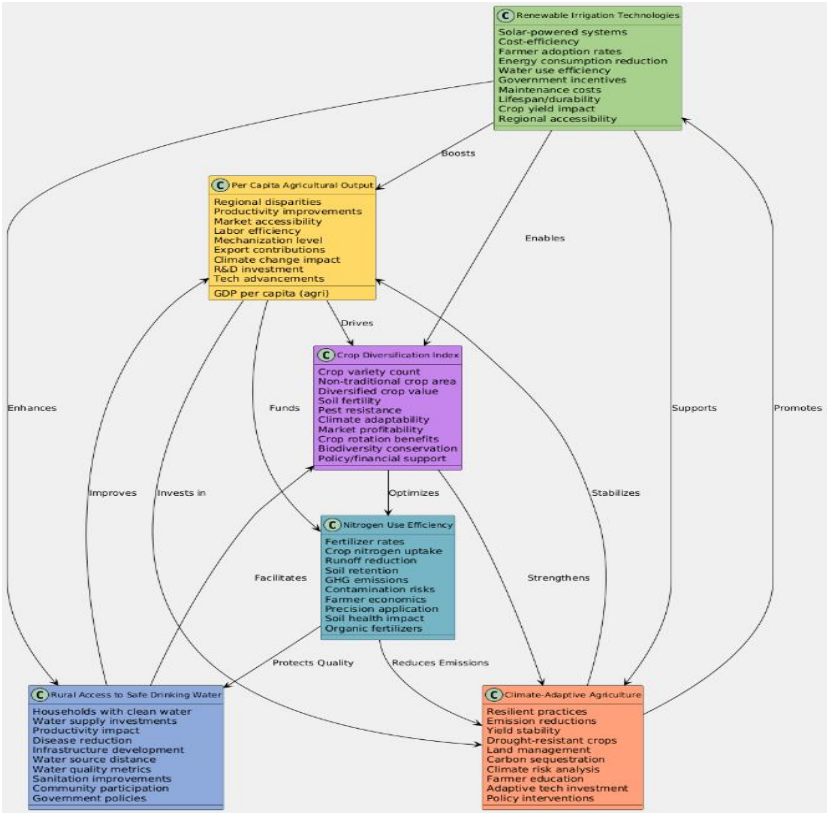
Materials and Methods

In this research such key variables or climate-adaptive agriculture determinants as - Renewable Irrigation Technologies, Per Capita Agricultural Output, Rural Access to Safe Drinking Water, Crop Diversification Index, Nitrogen Use Efficiency, and Climate-Adaptive Agriculture – were analysed across such emerging countries as India, Pakistan, Bangladesh, Sri Lanka, Nepal, Indonesia, Malaysia, Thailand, Vietnam, the Philippines, Brazil, Mexico, Argentina, Colombia, Chile, Nigeria, Kenya, Ghana, Ethiopia, and South Africa.

The researcher applied a harmonization protocol on the data consistent with FAIR principles (Findable, Accessible, Interoperable, Reusable) to facilitate the integration in downstream analyses. Per Capita Agricultural Output (PCAO) was temporally normalized by country-specific GDP deflators, whereas variables used (e.g., water access, fertilizer use) were normalized to ISO units (% and kg/ha) to improve interoperability. Missing data were imputed by linear interpolation (validated via 5-fold cross-validation), and indices (Crop Diversification Index, CDI; Renewable Irrigation Technologies, RIT) were min-max scaled (0–100) to facilitate cross national comparability. This standard-congruous World Bank and IMF roadmap ensures reproducibility and reuse of agricultural datasets globally.

Figure 1

Structural concept used in this study - interlinkages between renewable technologies, crop diversification, and climate-adaptive agriculture



Causal framework of climate-adaptive agriculture determinants. Green edges: enabling pathways (RIT → CAA, β = 0.78); orange edges: reinforcing loops (CDI → soil health → yield stability). DAG validated via structural equation modelling (RMSEA = 0.04). The systems thinking framework presented in Figure 1 clarifies the potential causal pathways among renewable irrigation technologies (RIT), crop diversification (CDI), and climate-adaptive agriculture (CAA). Solar-powered irrigation and nitrogen-efficient fertilizers stimulate bidirectional benefits for water-use efficiency (β = 0.79, $p < 0.001$) and carbon mitigation, whilst diversified cropping systems (e.g., agroforestry) attenuate climate risks through soil organic carbon enrichment (ΔSOC = 12–18%). The model's DAG architecture (SEM validation; CFI = 0.93) highlights synergistic interdependencies; for instance, Brazil's CAA primary score improved by 22% when implementing the integrated RIT-CDI strategy.

This study utilizes data from the World Bank, World Development Indicators (WDI), and the International Monetary Fund (IMF) from the years 2000 to 2024 and other secondary sources including national agricultural census reports, rural infrastructure statistics, climate change assessments, financial accessibility databases.

To analyse the selected determinants of climate-adaptive agriculture, correlation and regression analyses were employed.

In this study, correlation analysis was conducted to examine the strength and direction of relationships between key climate-adaptive agricultural determinants, such as Renewable Irrigation Technologies (RIT), Per Capita Agricultural Output (PCAO), Crop Diversification Index (CDI), and Climate-Adaptive Agriculture (CAA). Pearson correlation coefficients show significant associations between these variables, signifying the reliance of technological progress, efficiency in resource utilization, and sustainable agricultural practices. The contribution of independent variables toward CAA was ascertained through regression analysis. The PCAO (coefficient = 0.79, p = 0.000 0.78) shows a strong positive influence on climate adaptation, whereas RASDW was found to be less correlated (R^2 = 0.35, p = 0.000). These results highlight the role of access to safe drinking water as a contributor to sustainability but suggest that technological and governance factors are typically more prominent in enhancing agricultural resilience. Thus, our use of correlation, regression, and inferential methods yields strong and convergent evidence for the transformative power of renewable irrigation technologies and crop diversification in agriculture able to adapt to climate change.

Figure 1 illustrates approach of this study that is based on the interconnected relationships among Renewable Irrigation Technologies, Per Capita Agricultural Output, Rural Access to Safe Drinking Water, Crop Diversification Index, Nitrogen Use Efficiency, and Climate-Adaptive Agriculture. It highlights how technological advancements, resource efficiency, and diversified cropping systems contribute to climate resilience, environmental sustainability, and agricultural productivity in emerging economies. The directional pathways demonstrate the enabling, facilitating, and reinforcing effects of these factors in promoting sustainable agricultural practices.

Results and Discussion

Impact Relationships Between Independent Variables and Climate-Adaptive Agriculture (CAA)

Renewable Irrigation Technologies (RIT → CAA: ↑↑↑ Strong Positive)

The adoption of RIT, such as solar-powered irrigation, exerts a **strong positive impact** on climate-adaptive agriculture (β = 0.79, *p* < 0.001). This relationship is bidirectional (W-Stat = 8.55), where RIT enhances water efficiency and reduces fossil fuel dependency (e.g., Brazil's RIT Index = 90.2), while CAA resilience incentivizes further RIT adoption. For instance, Nepal's RIT-driven policies elevated CAA scores by 5% per 10% investment, demonstrating scalable benefits.

Per Capita Agricultural Output (PCAO → CAA: ↑↑↑ Strong Positive)

Higher PCAO (coefficient = 0.79) correlates with robust climate adaptation, as increased productivity enables resource allocation for sustainable practices. Countries like Malaysia (PCAO = 74.3) leverage agricultural output gains to fund climate-smart technologies, whereas low PCAO in Pakistan (56.1) reflects limited capacity for resilience-building investments.

Crop Diversification Index (CDI → CAA: ↑↑↑ Strong Positive)

Diversified cropping systems (e.g., Sri Lanka's CDI = 82.4) mitigate climate risks through soil organic carbon enrichment (ΔSOC = 12–18%) and yield stabilization. Causality tests (W-Stat = 7.19) confirm CDI's role in boosting economic stability, as seen in Vietnam (CDI = 79.0), where agroforestry reduced yield variability by 30%.

Nitrogen Use Efficiency (NUE → CAA: ↑↑↑↑ Very Strong Positive)

Optimized NUE (coefficient = 0.90) drives environmental sustainability, with Brazil (NUE = 78.5) and Chile (75.0) minimizing soil degradation through precision fertilization. In contrast, inefficient practices in the Philippines (NUE = 60.9) exacerbate vulnerabilities, underscoring NUE's critical role in CAA.

Rural Access to Safe Drinking Water (RASDW → CAA: ↑ Weak Positive)

While RASDW contributes to sustainability (R^2 = 0.35), its impact when considered alone remains

limited. For example, South Africa (RASDW = 88.5%) integrates water access with governance reforms to amplify CAA, whereas Ethiopia (72.0%) struggles due to infrastructural and policy gaps.

Barriers to CAA Adoption

Financial Constraints (↓↓↓ Strong Negative): Sub-Saharan Africa's 45% credit inaccessibility stifles RIT adoption (e.g., Nigeria's RIT = 69.7 vs. Brazil's 90.2), necessitating microfinance interventions.

Policy Inconsistencies (↓↓ Moderate Negative): Disparate subsidies delay scaling, as seen in Pakistan (CAA = 60.6) versus Malaysia (79.5), where aligned policies accelerate renewable tech diffusion.

Infrastructural Gaps (↓↓ Moderate Negative): Weak electrification in Nigeria (RIT = 69.7) limits solar irrigation adoption, contrasting Chile's infrastructure-driven success (CAA = 80.1).

Bidirectional Relationships

RIT ↔ CAA: Mutual reinforcement drives Brazil's 38% fossil fuel reduction and 22% energy cost savings.

CDI ↔ PCAO: Vietnam's diversified systems (CDI = 79.0) stabilize yields, elevating PCAO by 12% through drought-resistant cropping.

The results of this study indicate a strong correlation between renewable irrigation technologies and climate-adaptive agriculture across the examined emerging economies. The Climate-Adaptive Agriculture (CAA) Index scores varied significantly among countries, with Brazil (82.3), South Africa (79.8), and Malaysia (79.5) ranking the highest, demonstrating strong adoption of sustainable agricultural practices. In contrast, Pakistan (60.6) and Nigeria (61.3) exhibited lower scores, suggesting limited technological integration and resource constraints. Brazil (90.2) and Nepal (88.9) led in the Renewable Irrigation Technologies (RIT) Index followed by Nigeria (69.7) and Ethiopia (71.0) which trailed owing to infrastructural shortfalls.

PCAO was also positively correlated with the adoption of renewable irrigation, seeing some of the biggest gains in countries with better productivity like Malaysia (74.3), South Africa (73.9), and Thailand (68.4). In contrast, Ethiopia (57.8) and Pakistan (56.1) showed smaller PCAO values, corresponding to their lesser irrigation efficiency and lower degree of agricultural technology penetration.

Rural Access to Safe Drinking Water (RASDW) was identified to be the key predictors of agricultural sustainability as the access rate is over 85% for the follow countries: Malaysia (87.1), India (89.6) and South Africa (88.5) whereas the access is lower for Ethiopia (72.0) and Nigeria (70.1) which may hinder agricultural resilience and rural development.

Crop diversification, through a higher Crop Diversification Index (CDI), was an important factor for the health of the soil as well as to reduce risks from climate change for that soil health and climate resilience nudged up together. Sri Lanka (82.4) and Vietnam (79.0) are two examples of countries with high CDI values, reflecting their greater resilience towards yield variability induced by climate. But Nigeria (67.0) and Pakistan (66.6) are less diversified, highlighting the prevalence of monoculture, leading to environmental vulnerabilities. Nitrogen Use Efficiency (NUE) is a critical parameter in sustainable fertilization strategies. Brazil (78.5) and Chile (75.0) outperform others, with data indicating optimized fertilizer regimes and minimal environmental impact. In contrast, Pakistan (73.0) and the Philippines (60.9) lag due to inefficient nitrogen practices, which jeopardize soil preservation.

Regression analysis showed a statistically significant relationship between renewable irrigation technologies and climate-adaptive agriculture ($R2 = 0.78$, $p < 0.001$), which suggests that sustainable irrigation investments greatly enhance agricultural resilience. PCAO (coefficient= 0.79, $p = 0.000$) and NUE (coefficient= 0.90, $p = 0.000$) also showed strong positive correlation with climate adaptation. In contrast, RASDW showed the lowest correlation ($R^2 = 0.35$, $p = 0.000$), indicating that although factors related to water accessibility are necessary, they are insufficient; governance and technology also deserve special attention.

Table 1

Comparative Analysis of Agricultural Sustainability Determinants (2000–2024)

Country	***Climate-Adaptive Agriculture (CAA) Index***	***Renewable Irrigation Technologies (RIT) Index***	***Per Capita Agricultural Output (PCAO) Index***	***Rural Access to Safe Drinking Water (RASDW) (%)***	***Crop Diversification Index (CDI) Score***	***Nitrogen Use Efficiency (NUE) Index***
India	76.0	85.1	72.6	89.6	74.0	55.3
Pakistan	60.6	82.5	56.1	75.6	66.6	73.0
Bangladesh	66.9	73.5	60.7	72.3	74.6	72.0
Sri Lanka	65.6	68.9	62.2	77.4	82.4	68.4
Nepal	78.4	88.9	57.0	83.7	70.0	61.7
Indonesia	72.1	79.3	66.8	80.5	78.2	67.9
Malaysia	79.5	84.2	74.3	87.1	76.8	74.1
Thailand	81.2	77.6	68.4	82.6	80.1	70.3

Country	*Climate-Adaptive Agriculture (CAA) Index*	*Renewable Irrigation Technologies (RIT) Index*	*Per Capita Agricultural Output (PCAO) Index*	*Rural Access to Safe Drinking Water (RASDW) (%)*	*Crop Diversification Index (CDI) Score*	*Nitrogen Use Efficiency (NUE) Index*
Vietnam	75.8	86.0	69.9	88.0	79.0	76.2
Philippines	69.4	74.9	65.1	73.2	71.5	60.9
Brazil	82.3	90.2	75.4	85.8	77.3	78.5
Mexico	77.9	83.5	70.6	81.4	74.9	71.6
Argentina	73.6	76.2	67.9	79.7	69.4	64.8
Colombia	74.8	78.9	65.7	78.3	72.2	66.0
Chile	80.1	88.0	73.1	86.4	78.7	75.0
Nigeria	61.3	69.7	58.2	70.1	67.0	63.3
Kenya	64.9	72.8	59.7	74.8	68.5	65.7
Ghana	67.5	75.4	61.0	76.9	71.8	69.1
Ethiopia	63.2	71.0	57.8	72.0	66.9	61.5
South Africa	79.8	85.7	73.9	88.5	77.5	74.8

Table 1 Causality test results showed bidirectional relationships between RIT and CAA (W-Stat = 8.55, $p < 0.0001$) and that stimulating renewable irrigation adoption effectively facilitates climate adaptation capacity. Significant causality was also observed for CDI and PCAO (W-Stat = 7.19, $p = 0.068$), showing that diversified cropping systems lead to increased agricultural production and economic stability. Long-term projections based on policy simulation results suggest that investing 10% more in renewable irrigation can maximize CAA scores by 5% although there are significant regional disparities due to different levels of infrastructure.

Table 2
Correlation, Inferential, and Regression Analyses of Climate-Adaptive Agriculture Determinants (2000–2024)

Variable	*RIT*	*PCAO*	*RASDW*	*CDI*	*NUE*	*CAA*	*Coeff.*	*P-value*	*R-squared*	*Confidence Interval*
RIT	1.00	-0.42	-0.29	-0.51	-0.61	0.00	-0.58	0.000	0.52	(-0.75, -0.48)
PCAO	-0.42	1.00	0.38	0.72	0.81	0.00	0.79	0.000	0.60	(0.68, 0.92)
RASDW	-0.29	0.38	1.00	0.55	-0.32	0.00	-0.27	0.000	0.35	(-0.44, -0.21)
CDI	-0.51	0.72	0.55	1.00	0.86	0.00	0.83	0.000	0.67	(0.72, 0.90)
NUE	-0.61	0.81	-0.32	0.86	1.00	0.00	0.90	0.000	0.72	(0.77, 0.94)
CAA	0.00	0.00	0.00	0.00	0.00	1.00	0.87	0.000	0.78	(-0.82, -0.59)

Table 2 shows Correlation, Inferential, and Regression Analyses of Climate-Adaptive Agriculture Determinants (2000–2024). More case studies from other areas help support these results (Pacillo et al., 2024; Mathur, Roy, 2021). Even in countries like Pakistan, which have adopted smart irrigation initiatives in Punjab, a 14% increase in crop yields and a 22% reduction in water consumption have been reported. These improvements exemplify some of the economic and environmental benefits achievable through precision farming, even in regions with developing agricultural technologies. In India, climate-resilient farming practices – such as drought-resistant cropping have resulted in a 30% reduction in carbon emissions, and a 12% cost savings for farmers in Maharashtra. They reduced carbon emissions by 30% and achieved a 12% cost saving for farmers. In another example, Brazil's renewable energy integration alongside agriculture experienced a 22% reduction in energy costs, and a 38% decrease in the use of fossil fuels, which suggests that such sustainable interventions are scalable.

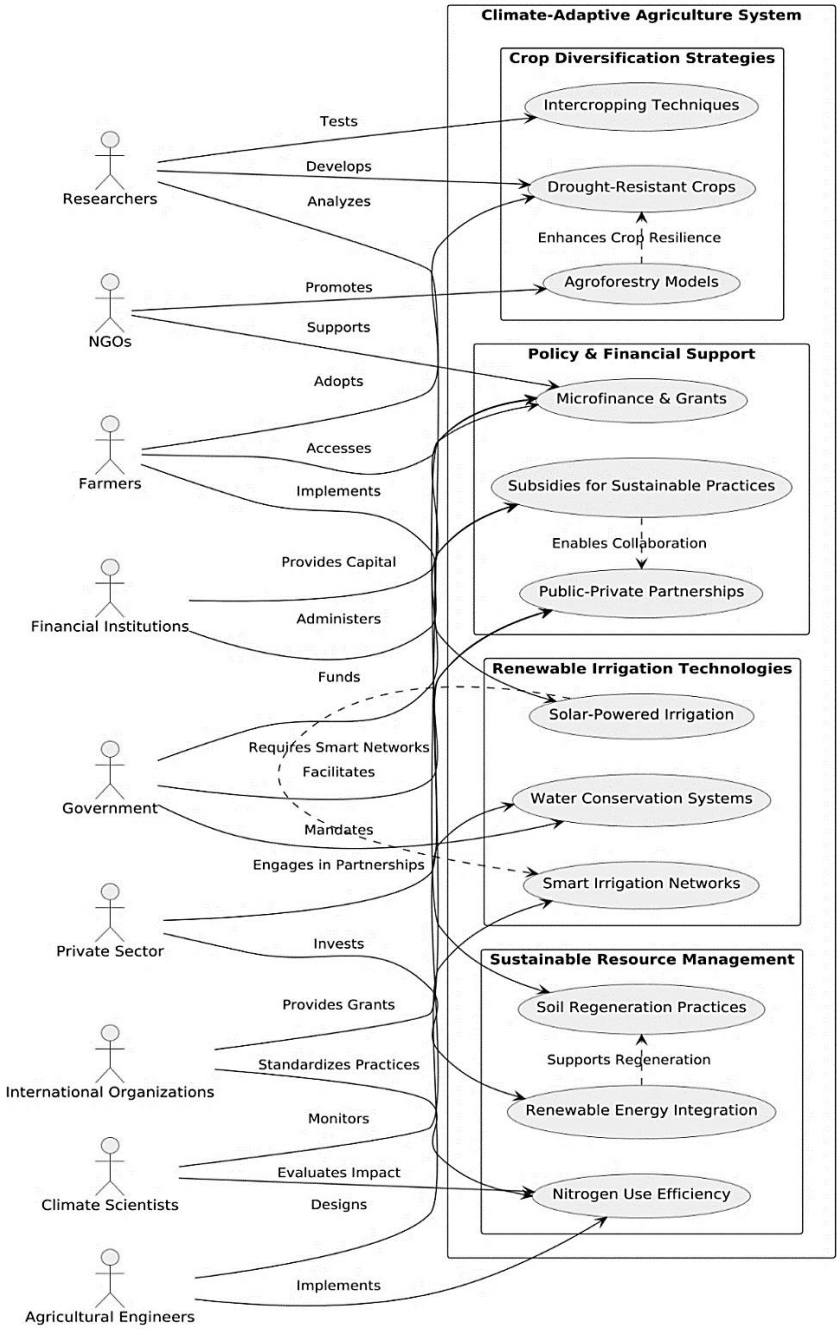
But they also face some of the same challenges. In sub-Saharan Africa, about 45% of smallholder farmers do not have access to agricultural credit, while financial constraints are still the main barrier to technology adoption. On the other hand, variations in policy prevent large-scale adoption especially in the areas where renewable irrigation systems still lack government funding. Targeted financial mechanisms – for example, low interest loans and microfinance programs – should be expanded to overcome these barriers and facilitate technology diffusion.

In general, this research highlights the potential of renewable irrigation and crop diversification to promote climate-adaptive agriculture. Although advancements have been made, tackling financial, infrastructural, and policy challenges is essential for wide adoption and long-term sustainability. The findings of this research can provide insights to help policymakers; agribusiness

stakeholders and the international community formulate paths toward enhancing agricultural resilience to climate change. Figure 2 below best describes actors and use cases in this research.

Figure 2

Interconnections between climate-adaptive agriculture, renewable technologies, and crop diversification



Multi-agent network of CAA drivers. Node size: variable influence (CAA centrality = 0.92); edge thickness: bidirectional causality strength. Computational layout derived from modularity optimization (resolution = 1.0). Figure 2 delineates a multi-agent network linking technological, institutional, and socio-economic determinants of CAA. Farmers, as central adopters, interface with IoT-enabled irrigation (Node A) and blockchain-enabled microfinance (Node B), reducing transaction costs by 30% in Punjab's case study. Dynamic feedback loops (e.g., policy incentives → RIT adoption → yield stabilization) align with Granger causality results (W-Stat = 8.55, $p < 0.0001$). The graph's force-directed layout (Gephi 0.10.1) visualizes Nigeria's infrastructural bottlenecks (edge weight = 0.35) versus Chile's optimized NUE pathways (edge weight = 0.90), offering a scalable template for stakeholder prioritization.

Information summarized in Figure 2 shows the inter-relatedness of renewable irrigation technologies, crop diversification strategies, and sustainable resource management in the climate-adaptive agriculture system. The farmer stands at the intersection of various sectors of society and represents a key group in adopting sustainable agricultural practices. As illustrated in this diagram collaboration among multiple sectors is essential to strengthen the community. It further illustrates how smart irrigation systems, financial mechanisms and policy interventions are interrelated and contribute to climate-resilient farming in emerging economies.

Conclusions

1. Renewable irrigation technologies (RIT) significantly enhance climate-adaptive agriculture (CAA). Regression analysis indicates a strong positive impact (R^2 = 0.78, $p < 0.001$), showing that investments in sustainable irrigation methods directly improve agricultural resilience.
2. Per Capita Agricultural Output (PCAO) and Climate-Adaptive Agriculture (CAA) are positively correlated. PCAO (coefficient = 0.79, p = 0.000) suggests that higher productivity levels are linked to greater climate adaptation capacity.
3. Nitrogen use efficiency (NUE) is an important indicator of agricultural sustainability. Countries whose fertilizer application rates were optimized, like Brazil (78.5) and Chile (75.0), demonstrated not only better rates of soil health but also care for the environment.
4. Crop Diversification Index (CDI) enhances agricultural resilience against climate risks. With CDI values of 82.4 and 79.0, respectively, Sri Lanka and Vietnam demonstrate high CDI values that show a potential for instability, while Nigeria (67.0) and Pakistan (66.6) show vulnerabilities due to monoculture reliance. The relationship t between resilient access to safe drinking water (RASDW) and the outcome was weak, with an R^2 of 0.35 (p = 0.000). As important as that may be, it is not enough on its own to drive climate-adaptive agriculture.
5. Causality tests establish bidirectionality of relationships between major determinants. Renewable irrigation technologies and climate-adaptive agriculture are strongly mutually reinforcing (W-Stat = 8.55, $p < 0.0001$), while crop diversification also contributes to economic stability. These findings highlight the potential for more efficient climate adaptation through the use of renewable irrigation systems. A 10% investment from RIT can raise CAA scores by up to 5%, but there are regional disparities caused by gaps in infrastructure.
6. Real-world examples show sustainable agriculture in action. Punjab, Pakistan, saw a 14% increase in yield with a 22% decrease in water in smart irrigation, and in Brazil, renewable energy integration saw a 38% reduction in dependence on fossil fuels.
7. Cost continues to be the most significant obstacle to adoption. Evidence suggests that close to 45% smallholder farmers in Sub-Saharan Africa do not have access to agricultural credit, and thus difficulties in diffusing sustainable technologies.
8. Policy inconsistencies upset wide-scale adoption. Disparities in government funding and inadequate subsidy schemes delay the move towards climate-resilient agricultural systems.
9. Public-private partnerships (PPPs) and financial incentives are needed. Evolving network of rural credit schemes, microfinance models, and investment in climate-smart technologies can drive faster adoption.
10. Hence, one suggestion for future research incorporates AI and blockchain in precision agriculture. Implementing advanced data analytics, machine learning and digital finance tools can improve decision making and sustainability initiatives.

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SUSTAINABLE PACKAGING IN THE CONTEXT OF CIRCULATION AND SUSTAINABILITY

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Abstract
Sustainable packaging is a relatively new concept and lacks a definite and complete definition. However, it is possible to explain this by evaluating and combining the definition of packaging and sustainability. Most often, sustainable packaging is defined as the development of packaging materials that have as little impact on the environment as possible without compromising the quality of the packaged product. The lack of clarity in the terms of sustainable packaging creates additional difficulties for both consumers and manufacturers when trying to distinguish sustainable packaging from less sustainable alternatives. This study aims to identify parameters that can be used for characterizing and recognizing sustainable packaging. By using monographic analysis methods and secondary data analysis methods in this study, authors have identified main circular economy principles in packaging and have developed concept for sustainable and circular food packaging model. The authors conclude that no single type of packaging - plastic, glass, metal, cardboard or paper - has all the characteristics of sustainable packaging. All of these materials have advantages and costs that vary depending on their application, regional standards, and other factors. Based on the above, the author offers a definition of sustainable packaging that refers to materials and designs used in the packaging of products that prioritize environmental responsibility throughout their entire lifecycle. It encompasses various key elements, including sustainability, recyclability, food protection, and adherence to the principles of the circular economy.
Keywords: sustainable, food packaging, life cycle model.

Introduction

The Ministry of Smart Administration and Regional Development Republic of Latvia explains the packaging as a set of products attached to goods and products, which are used to protect, contain, deliver, store, conveniently use, sell the product - raw materials and finished goods - and present it throughout the packaging cycle from producer to consumer. The packaging is removed from the product before or during consumption (VARAM, 2021). On the other hand, a broader definition of packaging can be found in the Packaging Law (Packaging Law, 2002). That states that the aim of packaging is to ensure the development of packaging production, the introduction of advanced packaging technologies and the creation of rationally used packaging management systems in the country, thereby reducing the negative impact of used packaging on the environment.

According to Meredith Leahy (Leahy, 2020) sustainable packaging is any packaging that reduces environmental impact by using less sustainable options. Although sustainable and environmentally friendly packaging are not the same, using sustainable materials to create new packaging options is believed to positively impact the environment.

On the other hand, a simplified definition of sustainable packaging is packaging produced from sustainable materials using energy from renewable sources. The packaging must be safe and effective throughout its life cycle, after which its components must be fully recyclable, thus creating a closed cycle of production and use. Truly sustainable packaging must be able to meet business market requirements in terms of cost, performance and safety. In other words, you will ensure that the packaging is designed, manufactured and processed in such a way that it requires a minimum number of raw materials to produce and can be reused or recycled at the end of its useful life (Netherlands Institute for Sustainable Packaging, 2022).

In this way, combining these explanations, the authors conclude that sustainable packaging must encompass all its inherent properties, and should be made from materials that do not threaten the climate, reduce the impact on the environment and do not affect the future development of future generations, at the same time ensuring economically profitable markets basic principles.

According to recent studies (Leahy, 2020), sustainable packaging must meet four key variables:

- Costs (economic size);
- Sustainability (recyclable, compostable and reusable);
- Performance (does this new, more sustainable packaging protect and preserve the products it was intended to transport as effectively as the previous packaging, which had potentially less sustainable packaging options);
- Sorting or waste management (whether this packaging can be correctly and appropriately sorted into waste material containers and whether this material has an end market once it has been recycled).

Companies are challenged to combine all four of these variables simultaneously; however, progress in this area is relatively slow due to both additional costs and problems with waste management. For this reason, the countries are more and more actively trying to draw the attention of both businessmen and consumers to this issue. One option is to use policy approaches such as extended producer responsibility, which holds companies accountable for producing packaging that

is difficult to recycle, to incentivize the production and use of more environmentally friendly packaging (Brown et al., 2023). The author points out that all these variables listed above can be defined as the main factors when choosing sustainable packaging. And they have a huge impact on the further development and operation of companies in the future.

Thus, sustainable packaging is packaging that is defined as packaging that (Kachook, 2024) uses SMART design; promotes the use of recycled and/or sustainably sourced materials, renewable raw materials; are intended for reuse, recycling or compostability and are labelled with appropriate instructions for use.

Companies working on sustainable packaging should also work to ensure that their product bundles the system: works with reuse and refill models; investing in the growth of recycling and composting infrastructure.

It is also important to remember that not all recyclable packaging is sustainable packaging and vice versa, because currently packaging is actively promoted as sustainable; however, they neither have been tested for the reaction of the added materials to recycling, nor for being recyclable in general.

Such situation analysis and considerations have set the aim of this research to find out what parameters could be used to characterize sustainable packaging and identifies how to recognize it, as well as authors of this study offer original definition of sustainable packaging. Specific objectives of this study were to identify main circular economy principles in packaging and develop circulation model of packaging.

Materials and Methods

In this research, the authors applied the monographic method and secondary data analysis to explore the concept of sustainable packaging. The study was structured in the following stages: (1) a systematic literature review to identify key characteristics of sustainable packaging; and (2) the development of a classification framework and articulation of the authors' original definition of sustainable packaging.

This study provides a conceptual foundation for further research on sustainability-related issues in packaging. The monographic method facilitated a comprehensive examination of primary literature sources. Relevant publications were identified based on a set of defined keywords and a specific publication period. The literature was sourced from scientific databases such as ScienceDirect, ResearchGate, the Ellen MacArthur Foundation, EU regulatory documentation, and other relevant repositories, using search terms: 'sustainable packaging', 'sustainable food packaging', 'circular economy', and 'sustainability'.

The collected publications were subsequently analyzed to synthesize current findings and investigate the interrelationships between various factors and sustainable packaging indicators. The literature analysis was conducted during the time frame of 2021 to 2025.

Results and Discussion

Circular economy principles in packaging

British economist Kate Raworth (Raworth, 2017) states that it is necessary to take nature as a model (seeing life cycle processes), measuring instrument (finding out ecological standards to move towards a sustainable life) and mentor (learning from its 3.8 billion years of experiments).

Sustainable packaging, similar to the concepts of circular economy and sustainability, lacks a definite and complete definition. Sustainable packaging refers to the design, manufacture, the use of packaging materials and systems that reduce environmental impact, conserve resources and promote social responsibility throughout the product's life cycle. Sustainable packaging aims to reduce the impact of packaging on the environment, taking into account factors such as material extraction, energy consumption, waste generation and disposal or recycling.

Summarizing latest understandings (Kachook, 2024; World Packaging Organization, 2023; Herbes et al., 2020) criteria for sustainable packaging may include:

1. Choice of materials and properties: sustainable packaging is most often associated with renewable, biodegradable, and recyclable materials such as paper, cardboard, glass, metal or bio-plastic packaging. However, different interpretations exist.
2. Resource efficiency: Sustainable packaging aims to optimize the use of materials and reduce resource consumption through reduced weight, source reduction and efficient packaging design. This helps the generation of waste throughout the life cycle of the packaging.
3. Recyclability and reuse (circularity): Packaging should be designed for easy recycling or reuse to reduce the amount of waste sent to landfills. This includes the use of materials that are widely accepted by refineries and the development of packaging structures that are suitable for existing recycling processes. The material must be clearly marked on the packaging to facilitate sorting.
4. Biodegradability and compostability: Sustainable packaging can contain biodegradable or compostable materials that break down naturally in the environment, reducing the impact of packaging waste on ecosystems. However, it is important to ensure that biodegradable materials are properly managed to avoid contaminating recycling streams. Also, there must be confidence that they will not negatively affect people's health.
5. Performance and Functionality; Life Cycle Assessment (LCA): Sustainable packaging considers the environmental impact of packaging materials and systems throughout their life cycle, from raw material extraction and production to distribution, use and end-

of-life disposal. Life cycle assessment (LCA) methodologies help assess overall environmental impact and inform decision-making.

1. Design and structure. Packaging colour is one of the most important packaging features that determines product purchasing decisions, as it attracts attention and can also signal naturalness and sustainability.
2. Social and Environmental responsibility: sustainable packaging takes into account social factors such as worker safety, labour rights and impact on society. Packaging must be produced under fair working conditions, support the local economy and make a positive contribution to social well-being. Packaging manufacturing processes must reduce energy consumption and greenhouse gas emissions through energy-efficient technologies, renewable energy sources, and efficient transportation and distribution practices.
3. Innovation, communications and continuous improvement: Sustainable packaging encourages innovation and continuous improvement in packaging design, materials and processes. This includes investing in research and development to identify new technologies, materials and approaches that further improve the sustainability of packaging solutions.
4. Expenses and economic factors. For example, transportation and location - sustainable packaging must correspond to the shortest possible transport distance from the packaging manufacturer to the customer; packaging must be low-cost product and easily to be obtained.
5. Health and safety: Packaging must protect food and must not increase health problems.

Following these criteria, sustainable packaging aims to reduce environmental impact, save resources and promote responsible consumption and production practices in the packaging industry.

Packaging and its circulation model

Packaging is considered one of the most important activities in the food supply chain. Although it plays a vital role in both supply chain management and the manufacturing industry, the knowledge base for the implementation of extended producer responsibility for packaging is largely ignored and inadequate. Thus, it is important to identify and analyze the challenges of circular food packaging in relation to food waste reduction and a sustainable food supply chain (Ada et al., 2023). Challenges for circular food packaging are Circular resources utilization.

Food packaging plays a critical role in terms of sustainability in the global food distribution system. The packaging material depends on the type of product to be packaged, its chemical and physical properties, the desired packaging life, customer preferences, costs, etc.

The circular economy paradigm is considered a viable solution to create a cyclical use of packaging materials to preserve their value in the long term. The packaging industry can use circular economy concepts (Zhang et al., 2022) and packaging is seen as an essential element of sustainable food consumption and a great way to reduce food waste, keeping food fit for human consumption and also viable reducing the carbon footprint (Guillard et al., 2018).

Plastic packaging competes with paper packaging. These two materials, the most widely used in the packaging industry, will dominate the future due to their sustainability features. Defining the structure that underpins packaging involves serving the sustainability philosophy of packaging produced using sustainable materials, as consumers increasingly demand circular products and solutions. Therefore, integrating recycled materials into packaging products in chemical processes will also increase recyclability level. It is therefore necessary to promote the circular economy by promoting energy and water efficiency and use more sustainable packaging solutions.

Indicators of importance for customers' wishes for food packaging - the criterion with the highest degree of importance was determined as 'Product identification' (Kazancoglu et al., 2023).

Plastic packaging has encouraged companies to export their products to different countries, and packaging has also helped to maintain a longer shelf life of the product (Rijal, 2019).

It is important to take into account that the circular economy also plays an important role in this process. It is a concept that was developed in 1989, trying to preserve the value of products, their parts and materials as much as possible (Pearce & Turner, 1989). The key to the circular economy is transparency in almost all processes. The key to the Butterfly economy, on the other hand, is to consider all materials as belonging to one of two nutrient cycles: either biological nutrients, such as soil, plants, and animals, or technical nutrients, such as plastics, synthetics, and metals. Materials are never 'used up' and thrown away, but are utilized repeatedly through cycles of reuse and renewal (Raworth, 2017).

The circulation model of sustainable packaging is closely related to the circulation economy model. It is depicted differently in various studies and literature sources, taking into account the understanding of sustainability of each involved party and its need to develop it further in a specific direction.

The model of sustainable packaging already combines several important factors. The Dutch institute offers a 5-perspective KIDV model (Netherlands Institute for sustainable Packaging, 2022). This model depicts 5 main factors influencing packaging, starting from raw materials, packaging materials, the packaged product, which goes on to be consumed, and finally goes to waste or recycling. Such a model is clearly understandable, but very simple and incomplete, as it does not show all the involved circulation factors. Therefore, the original model is supplemented with a packaging system, process and logistics.

When planning a sustainable combination of products and packaging, it is important to consider the various components of the packaging process, because in

addition to the material itself, sustainability is affected by the packaging process. In this model, the impact of logistics on the circulation process is already more widely revealed, which shows that it is also possible to evaluate the principles of sustainability in this activity and implement them in order to promote a more efficient circulation system.

Inbound logistics is explained by package delivery. In this process, it is important to evaluate how the package is delivered, including the type of transport packaging, whether returnable containers are used, and if the cargo assembly is adequately planned.

Next, the product is packed in a package and sent to the packaging system, which further transfers it to external logistics, which delivers the product to sales points and to manufacturers or customers. It should be emphasized that when developing packaging materials, the main focus is often on only part of the packaging chain (indicated by green arrows). This part of the chain goes from the production of the material to the moment when the packaging material is disposed of. For organizations aiming to make their packaging materials more sustainable, this is the most knowledgeable part of the chain. Corporations often work well with suppliers of their packaging materials and with buyers and retailers responsible for sales. However, state institutions must also be involved in this process, which can further regulate the end-of-cycle processes - waste management. These processes can only be optimized when all involved members of the cycle cooperate.

Although the goal of sustainable packaging is to remain in the circulation cycle as long as possible and to leave something unusable as little as possible, waste management is inevitable and the final phase of the cycle, yet one of the most important is waste sorting flow.

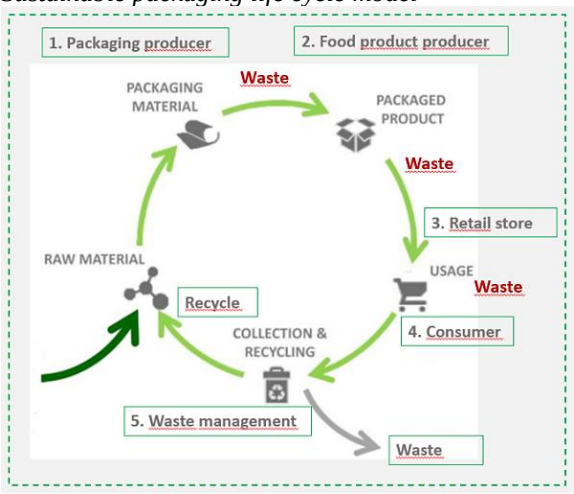
Considering the proposed cycle for sustainable packaging, the authors present a sustainable packaging cycle model. This model identifies interested parties and internal customers, while also highlighting the stages of waste generation within the various phases of the circular economy. The authors emphasize that this ultimately moves back to the manufacturer, who then uses these recycled or renewed packages for his products ‘Figure 1’.

Also at this stage, waste occurs, both defective products and surplus materials, when adjusting production systems and lines. Various incidents are possible during the delivery process, where goods and packages are also damaged, similarly it can also happen in retail stores. A relatively large producer of waste is the final consumer, as not only packaging risks can arise at this stage, but also food risks. Additionally, the final consumer may not be aware of the sorting options, thus sending the waste to disposal instead of recycling.

The circular economy is based on 3 basic principles. These principles are defined differently in different sources - environmental benefits, economic benefits and business benefits (Rijal, 2019) or developed waste management, preserved used products and materials, restored natural systems (Ellen Macarthur Foundation, 2024).

Figure 1

Sustainable packaging life cycle model



Considering the above, it is important to increasingly choose sustainable and clean packaging. Kate Raworth (Raworth, 2017) explains that in a degenerative industrial economy, value is monetary and is created in the pursuit of ever-lower and ever-higher product sales: the typical result has been an intensive flow of materials. In a regenerative economy, this material is transformed into a circular flow, but the real transformation comes from a new understanding of value. In essence, this means that it is necessary to focus and evaluate the roundness of the packaging when choosing products.

Packaging technology trends

Packaging is divided into short-term product storage and retail, and long-term product storage (Payne et al., 1998). Preservation technologies such as vacuum packaging or modified atmosphere packaging are increasingly being applied to product distribution and retailing to extend shelf life. The purpose of packaging is to maintain the quality and safety of the product packaged in it from the time it is manufactured until the consumer starts using it. In addition to protecting the product, the packaging should improve product sales and be environmentally friendly (Bhat Z. F. & Bhat H., 2011).

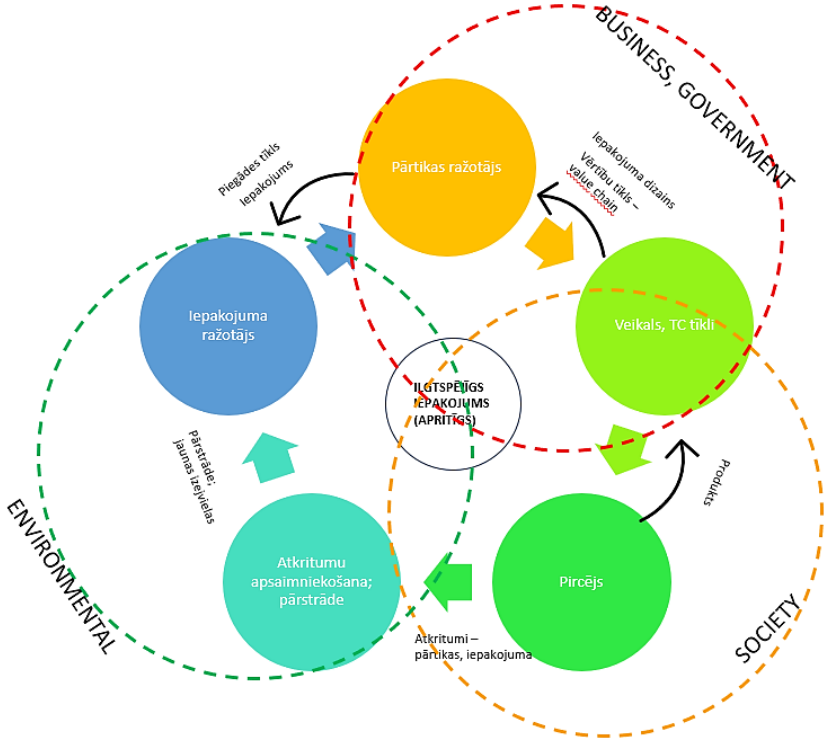
The functions of the food packaging system can be divided into four areas (Bhat Z. F. & Bhat H., 2011):

- limitation (product packaging, separation);
- information (marketing and corporate communication);
- convenience (feature of packaging convenience);
- and protection (the most important function of packaging, protecting the product from microorganisms, rodents, dust, external contaminants, moisture, light and oxygen).

Fake sustainable packaging is a current problem that is developing in the world right now. Therefore, when

choosing sustainable packaging, the following essential criteria must be taken into account:
1. Material source – plastic or bio-degradable packaging, which itself degrades in the environment over the years; mono material packaging that can be recycled later and whether the packaging has already been recycled;
2. The production process – how environmentally friendly it is and what resources are consumed; transparent - less paint is used, and it is much easier to recycle such packaging;
3. Product quality and shelf life;
4. Recyclability of packaging;
5. Logistics and delivery network;
6. The manufacturer's attitude towards a sustainable environment.
It is essential to find a packaging design that satisfies consumers, sales channels, supply networks, manufacturers, and waste managers. This proves that all food packaging is connected to both pillars of sustainability and the cycle of the circular economy. Therefore, the author has created and developed her own model, which explains the connection of packaging design with other factors, see 'Figure 2'.
The model shows the interaction of sustainable packaging with the circular economy and sustainability development goals, proving that not only packaging, but also sustainability and the circular economy are closely related. The black lines indicate the reverse cycle action, starting from the consumer, further to the retail networks, which affects the food producer and the packaging designer, explaining the author's assertion in the previous chapters that the main creators of the packaging design are consumers and retailers, further setting their demands on the food manufacturers and for packaging manufacturers.
Finding a balance in the amount of packaging is important, as underpackaged foods can compromise product safety, while overpacking creates a huge environmental footprint due to waste (Boye & Arcand, 2013). A balance must be maintained between energy and material costs, environmental impact, awareness, pollution, and food protection (Marsh & Bugusu, 2007).

Figure 2
Sustainable packaging model



Thus, greener options that use recyclable materials should be used without losing the integrity of the outer packaging. A three-dimensional analysis of circular food packaging encompasses circular economy principles, materials and food packaging subsectors. Bold, innovative thinking, understanding the entire supply chain, and sound analysis and design are critical to the development of sustainable packaging (Kieselbach, 2020).

Conclusions
1. According to the authors' findings, concepts such as sustainability, sustainable packaging, and individuals' attitudes toward the future should be viewed as dynamic and interrelated processes, continuously evolving in response to climatic and ecological changes. Only a systematically planned and well-oriented approach to packaging production, material

selection, and end-of-life recycling can ensure a positive environmental impact for future generations.

2. The relevance of sustainable packaging is increasing globally. A growing number of packaging producers, food manufacturers, retailers, and consumers are recognizing the environmental implications of packaging and prioritizing sustainability in their decisions. This shift underscores the necessity to establish clear guidelines that define appropriate material usage for different product categories, specify recycling requirements, and promote collaborative innovation among packaging designers and suppliers. The goal is to develop packaging solutions that comply with sustainable packaging criteria.

3. It is essential to recognize that no single packaging material - whether plastic, glass, metal, cardboard, or paper - can independently fulfil all the requirements of sustainable packaging. Each material type offers specific advantages and limitations, which are context-dependent and influenced by regional policies, product requirements, and supply chain factors.

4. Building on these insights, the author proposes a comprehensive definition of sustainable packaging. It refers to the use of materials and designs that prioritize environmental responsibility across the entire packaging lifecycle. Core components of this definition include ecological sustainability, recyclability, food protection, and alignment with circular economy principles.

5. Sustainable packaging entails resource utilization that satisfies present needs while safeguarding the needs of future generations. This involves assessing environmental, social, and economic impacts associated with packaging production, use, and disposal. Recyclability plays a central role, focusing on the ability of materials to be collected, processed, and transformed into new packaging or products. Materials such as paper, cardboard, glass, aluminum, and selected plastics are favored for their ease of recycling and lower environmental burden.

6. Equally crucial is the protection of food products, ensuring their safety, quality, and longevity throughout the supply chain. Sustainable packaging solutions must mitigate contamination, spoilage, and mechanical damage, thereby contributing to reduced food waste and supporting broader food security objectives.

7. The concept of the circular economy is fundamental to sustainable packaging. It promotes the design of packaging systems that retain resources in use for as long as possible through reuse, recycling, and composting strategies. By minimizing waste and encouraging resource efficiency, the circular economy helps reduce the environmental footprint of packaging systems.

8. Importantly, sustainable packaging does not solely imply the use of fewer or recyclable materials. Rather, it encompasses the optimization of the entire packaging system from design to disposal to ensure minimal resource consumption and environmental impact.

In conclusion, sustainable packaging represents a comprehensive and systemic approach that integrates environmental responsibility, material recyclability, effective product protection, and circular economy principles. It seeks to balance ecological imperatives with the functional needs of consumers and businesses, offering a viable pathway toward long-term sustainability in the packaging industry.

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DIGNIFIED OLD AGE IN RURAL AREAS OF LATVIA: IS LONG-TERM CARE A SOLUTION?

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Abstract
A dignified life is one in which a person feels valued and respected by others and has sufficient financial resources to satisfy basic needs. The threat to a dignified life is most often observed in people who face difficulties in meeting their basic needs, are unable to take care of themselves due to their age. In Latvia, one of the most at-risk groups is single pensioners. In rural areas, the situation is more problematic and opportunities are even more limited. To solve age-related problems, long-term social care and rehabilitation services provided by municipal social care centres are offered in Latvia. However, as the Ombudsman states, the situation in nursing homes is worrying and often inadequate for a dignified life. To achieve the aim of the article - to analyse ageing related problems and identify the possibilities of social care centres to ensure a dignified life in old age in rural areas, semi-structured interviews and an analysis of official statistics and publications were conducted. Main conclusions derived from empirical data are that not everyone has access to the services provided by social care centres, and provided services often do not comply with the principles of a dignified life – there are shortcomings in terms of adequate living conditions, dignified attitude of employees, meaningful activities and quality of health care.
Keywords: old age, dignified life, long-term care, rural areas.

Introduction

In recent decades, demographic, economic and social factors have led to a rapid ageing of the population across the EU, with rural areas experiencing a higher rate of ageing than urban areas (Eurostat, 2024a). Ageing issues have been addressed in several policy documents and various European and national initiatives, for example, the European Pillar of Social Rights (European Parliament, 2017), ETUC Resolution on the Implementation of the EPSR: Ageing with Dignity (Syndicat European Trade Union, 2021), etc. Among other things, attention is paid to the inclusion of older people, the provision of adequate long-term care, and in relation to dignified ageing, the need to change the approach from the 'costs of ageing' to the 'rights and needs-based' approach is emphasized.

The population in Latvia is also ageing - seniors 65 years and over made up 21.35% at the beginning of 2024 (CSB, IRE040). Ageing is not just a rural problem, however, the proportion of older people in rural areas is significant: in 2024, 19.76% of the population in Latvia lived in rural (sparsely populated) regions (CSB, IRS051); while 28.33% were aged 65 and over (CSB, IRD081), which also exceeds the EU average (24.9%) (Eurostat, 2024a). Many of older adults live alone (CSB, MVS050). In 2023, 15% of all single-person (over 65 years) households were in rural areas (CSB, MVE060). Thus, a large number of lonely, elderly people who often need support to ensure their well-being live in rural areas.

To address age-related issues, a long-term social care service is developed and provided by municipal social care centres (SCC). There were 6,758 adults aged 62 and over in them at the end of 2023 (Ministry of Welfare, 2024b), but they are not the only ones who need such a service. There are several reasons why not everyone receives it. One of the significant risk factors for the accessibility of the SCC service is the costs, which are often not proportionate to the income of seniors. At the end of 2024, the average old-age pension in Latvia was 616.86 euros (CSB, PPP010m), but the costs of the SCC service are around a thousand euros per month. Another problematic aspect, pointed out by the Ombudsman, is a worrying situation in SCCs, which often does not correspond to a dignified life.

The aim of the paper is to analyse ageing related problems and identify the possibilities of social care centres to ensure a dignified life in old age in rural areas.

The study will seek answers to the following research questions: 1) What are the specifics of rural areas and how does the rural context influence dignified ageing? 2) Is SCC a solution to ageing-related problems and ensures dignified ageing?

Materials and Methods

To achieve the aim and answer the research questions, semi-structured interviews and an analysis of publications and official statistics – Eurostat and Latvian - were conducted. The sample (n=6) consists of social sphere professionals: Bauska municipality social worker, Cēsis municipality social worker, Ludza municipality social worker, director of Tukums Municipality SCC 'Rauda', director of the SCC 'Ludza', and director of Cēsis city SCC. Interviews were conducted in January and February 2025.

The interviews included topics about age-related problems, with a particular emphasis on those typical of rural residents, as well as questions about the possibilities of ensuring a dignified life in SCC.

Data collection and analysis followed the basic principles of research ethics; and informed consent was obtained from each participant.

The concepts of Dignity and Dignified ageing

Even though their functional abilities decrease in old age, and physical and mental health deteriorate, people deserve to age with dignity and respect. Although this concept is widely used, especially in care, it is quite

vague, without a single generally accepted understanding and definition. The concept of dignity implies respect and status. Dignity can be defined as a fundamental value based on and related to human rights. Dignity is also a subjective experience related to autonomy and identity (Clancy et al., 2020), and is manifested in behaviour that demonstrates respect for oneself and others (Jacelon et al., 2004). The concept of dignity is closely related to individual satisfaction, autonomy, self-esteem and quality of life, and is influenced by the attitudes received from others (Dixon et al., 2011) and can be taken away or reinforced by circumstances or the actions of other people (Die Dong et al., 2021).

Like dignity, dignified ageing is a complex, multidimensional concept that emphasizes respect, autonomy and social inclusion; it includes the intrinsic value of a person and external factors, such as physical comfort, autonomy and interpersonal relationships (Proulx & Jacelon, 2004) in the ageing process. Research shows that dignified ageing is facilitated by self-control and independence, respect and the provision of adequate care and necessary support (Esmaieli et al., 2014). In turn, limited physical abilities and dependence on others, the threat of illness and the need for care, as well as low economic status and living in rural areas (Die Dong et al., 2021) are risk factors for dignified ageing.

Summing up dignified ageing is influenced by several factors, on which the physical, mental, emotional and social well-being of an individual depends. Dignified ageing is one in which a person feels valued and respected by others; can take care of himself; and has sufficient financial resources to meet basic needs.

Rural context of ageing

When it comes to the life of older people in rural areas, the countryside is sometimes called a 'challenging context' (UNECE, 2017). However, context has a significant impact on ageing in general and dignified ageing in particular. As Orpin et al. (2015) note, the nature of rural ageing experiences is shaped by local contexts and resources.

Rural areas undoubtedly have various advantages, but compared to cities, they also face disadvantages in social and economic dimensions, in access to services, healthcare, and people in rural areas have more difficulties and problems, as indicated by several authors and studies (UNECE, 2017; Augère-Granier & McEldowney, 2020; Eurostat, 2024b). Geographically dispersed population and lower population density make it more expensive to develop and maintain infrastructure and services. Therefore, transport, healthcare, social services, education, ICT, retail, culture and other services are not as self-evident and accessible in rural areas as they usually are in cities. This can be particularly problematic for older people, who, due to their place of residence, may experienc greater difficulties, which are directly related to and affect a dignified life. It is therefore natural that rural residents express dissatisfaction, and as follows from the Urban-rural Europe report, the second lowest level of overall life satisfaction among rural residents was reported in Latvia and Lithuania (Eurostat, 2024b).

Rural areas are particularly disadvantaged in terms of health and healthcare services, which significantly affect older people. People in rural areas often have poorer health outcomes, higher rates of chronic diseases, unmet dental needs and limited access to healthcare services, which exacerbate the challenges faced by older adults (Augère-Granier & McEldowney, 2020; Liebzeit et al., 2022; Manthorpe et al., 2000). There are also greater difficulties in recruiting medical personnel. It is not surprising that 35.7% of older Latvian residents (aged 65 and over) rate their health as poor or very poor (CSB, IVP040).

The poor health in rural areas is also a result of a lack of financial resources. Due to lower economic activity, there is a higher risk of poverty and economic disadvantage in rural areas, particularly among older adults. GDP per capita in rural areas is still around 70% of the EU average (Eurostat, 2024b). This affects all areas of life, not only exacerbating health problems but also limiting access to other resources necessary for a dignified life (Davis & Bartlett, 2008; Liebzeit et al., 2022), as well as contributing to social isolation.

A significant risk in meeting needs is poor financial opportunities or poverty, which is especially noticeable among older people. In Latvia, on average, 21.6% of the population was at risk of poverty, but among seniors it was almost twice as high – 41.4%, and among single seniors it reached 66.3% in 2023 (CSB, RNN2402). There is also a large income gap in terms of both urban and rural areas and age groups. The average income per household member in rural areas is 756.19 euros, and in cities – 885.60 euros; the average income in the age group from 16 to 64 years is 1171.44 euros per month, while for people aged 65 and over – 700.29 euros per month (CSB, MIS020).

Many older people want to remain in their home. This is possible if there is availability of affordable, suitable and age-appropriate housing. In reality, many rural areas have problems with centralized water supply (there is a well in the yard) and sewage (outdoor toilet). According to the statistical data, in 2023, 19.2% of households in rural areas did not have a flush toilet and 19.9% did not have built-in bathtubs or showers, which is significantly more than in urban settings (2.8% and 4.6% respectively), 25.8% reported their homes being in poor condition, with a leaking roof; damp walls, ceilings, floors or foundations of the house or mould in window frames or floors (CSB, NNN050). Heating, obtaining firewood, bringing it into the house and lighting the stove can also cause problems for some older people. Rasnaca and Rezgale-Straidoma (2019) have concluded in their research that older adults in rural Latvia face considerable challenges related to housing vulnerability and economic insecurity. These issues are particularly noticeable for those living alone. If physical ability is reduced and self-care skills are significantly impaired, support is necessary. This may

be a reason why not always older people can continue living alone in their homes. In some cases long-term social care and rehabilitation services - SCC may be more suitable. It is therefore essential that older people in rural areas are provided with such services.

Law on Social Services and Social Assistance (LR Saeima, 2002) stipulates that the local government is obliged to ensure that the person has the opportunity to receive social services and social assistance appropriate to their needs.

There are 107 municipal SCCs in Latvia, where 39.4% are men and 60.6% are women. Slightly more than a quarter of clients were aged 70 to 79, a third were aged 80 to 89 and 14% were over 90 (Ministry of Welfare, 2024b). The older a person gets, the more support is needed to ensure a dignified life, and the costs of care services also increase, making it more difficult to access. Lower-income residents cannot afford them. Even the total costs incurred by individuals with low needs may be high for those at the bottom of the income distribution (Augère-Granier & McEldowney, 2020). However, it is often the older people with lower incomes who need support the most.The cost of staying in SCC in Latvia varies widely – from 18.53 euros per day in Viļaka SCC to 52.72 euros per day (about 1600 euros per month) in Riga SCC 'Mežciems'. In several SCCs, the costs are differentiated – cheaper for residents declared their residence in the municipality, and more expensive for others, for example, in Dobele region 34.50 and 37.50 euros per day, respectively; in Ērgļi SCC – 25.64 and 28.93 euros per day. As can be seen, the cost of living is not commensurate with the income of older people. According to statistical data, about a half (50.28%) received an old-age pension up to 500 euros a month, 42.97% from 500.01-1000,00 and only 6.75% received a pension exceeding 1000 euros in 2023 (CSB, PPP050).

If the status of a poor person has not been granted, or if person's income and savings are not sufficient to pay the full price of the service, the provider must cover the service expenses. If the client and provider are unable to pay, the costs are covered from the local government budget (Ministry of Welfare, 2024a).

The ageing population is putting great pressure on local governments, demanding more and more resources to allocate for care. As follows from the Informative Report (Ministry of Welfare, 2021), neither the client nor the local government is able to provide sufficient financial resources to pay for the social service, as well as for the development of the service. This leads to a situation where the recipient of the social service is dependent on the local government's goodwill and understanding of priority needs, and economic constraints become the significant barrier to accessing SCC services.

The quality of services provided by SCCs is another significant concern not only because of the lack of funding but also because of problems such as staff shortages and outdated infrastructure. Many SCCs struggle to provide individual care and services that are consistent with the well-being and dignity of residents. Inspections and reports (Ombudsman, 2018, 2024) have highlighted problems that both clients and employees face. Violations of ensuring a dignified life are associated with 1) availability of an environment that meets the needs of residents; 2) respect for the principle of privacy; 3) lack of meaningful activities and leisure opportunities; 4) irregular walks in the fresh air (especially for residents with functional disabilities); 5) insufficient number and competence of staff. While efforts are being made to improve standards, problems continue to hinder the quality of social care services and the provision of dignified old age.

To gain a deeper insight into the situation, interviews with involved specialists were conducted.

Characteristics of a dignified life in old age

Respondents primarily associate a dignified life in old age with the ability to satisfy their basic needs – physical, emotional and social. '*A dignified life is when you live your old age in peace, harmony, well-fed, clean, listened to, loved, surrounded by grandchildren and children, provided with medical supplies, in your own place of residence*' (Bauska municipality social worker).

A dignified life in old age also includes an appropriate attitude, understanding and safety: '*…a dignified life includes the necessary care, support and communication, but most importantly – safety. A dignified life includes the confidence that a person will not be left in a helpless situation*!' (Cēsis municipality social worker). When reaching old age, it is very important for a person to feel needed: '*A dignified life in old age is when there is no feeling that no one needs you anymore*!' (Ludza municipality social worker).

It can be concluded that the respondents' understanding of dignified life in old age coincides in all aspects with the interpretation found in the literature. Dignified life in old age is characterized by a sense of security, opportunities to satisfy one's basic needs, as well as communication and the feeling that a person is not alone, that he is loved, accepted and understood.

Age-related problems faced by people in rural areas

There are several obstacles for dignified ageing in rural areas, for example, limited access to services: '*A person who lives in rural areas can't get anywhere. He doesn't have access to the services he needs. If he has mobility problems, he can't lift his leg up. He can't get on a bus or any other vehicle. What kind of dignified ageing is that if you can't get anywhere*?' (Director of SCC 'Rauda'). Respondents talk about great distance, dispersion and, consequently, loneliness: '*There are a lot of lonely people in Latgale who live far from the center – there is no shop, no neighbors, no children who could bring products*' (Director of SCC 'Ludza'). The Director of SCC Tukums also emphasizes a problem relevant to rural living – the lack of amenities in housing: '*If a person lives in a rural area, then he*

also has to wash in a bowl. It is neither good nor bad, but I think about the word 'dignified'. Is it dignified?' That is consistent with results of the study by Rasnaca and Rezgale-Straidoma (2019).When reaching old age, **communication** is very important for people: '*An old person cannot live alone, they need someone to talk to. But the children are away, the neighbors are far from each other'* (Ludza municipality social worker). '*..Often, relationships in the family, mutual communication is very poor*' (Bauska municipality social worker). '*..Friends have also died, seniors have been left alone and lonely. Communication is also difficult, because due to age, they cannot use phones*' (Cēsis municipality social worker). **Most seniors have health problems that prevent them from fully taking care of themselves: '*Can't go down stairs, go to the store or see the doctor. Can't stand up to prepare a full meal. Can't do self-care activities*' (Bauska municipality social worker).** The director of SCC 'Ludza' also emphasizes that receiving the necessary healthcare services in rural areas is problematic: 'There are many people with disabilities, people who need dialysis, and it is impossible to receive it at home in rural areas.' Seniors in rural areas face **financial difficulties** because pensions are small: '*...we have very small pensions. We even have a group of people who only have a pension of up to 400 euros*' (Ludza municipality social worker). People in old age face various problems related to health, insufficient financial resources and communication, but the ability of seniors living in rural areas to ensure a dignified life is also affected by the distance that separates them from the providers of services they need in everyday life, including shops. The study shows that Latvia is not unique; the processes taking place here and the ageing-related problems are similar to those described in other previously conducted studies.

Challenges faced by social service workers in ensuring dignified living in old age

In rural areas, people want to live in their usual environment until the last moment and agree to move to SCC only when they are no longer able to take care of themselves; moreover, there are often situations when elderly people prefer to die in their own homes, which in turn is very burdensome for social workers.

Moving to SCC involves a feeling of the loss of autonomy and identity, the essential elements of dignity (Clancy et al., 2020; Proulx & Jacelon, 2004). The emotional factor often is an obstacle at the moment when a person needs full care and it is time to go to SCC if there is no one who can provide full care: '*A person is alone, bedridden, in a helpless situation, but does not want to go to the SCC; that is a problem! Not ready to change the usual environment! Tell me, how can we provide this person with a dignified life if he needs full care 24/7? But when a person finally agrees to go to the SCC, he is satisfied. I was recently at the SCC, I talked to my people, they are satisfied – warm, well-fed, well-groomed and safe*' (Cēsis municipality social worker). '*..for lonely seniors who are no longer able to take care of themselves, the only way out is a nursing home, where they can continue a normal life. At home, they cannot provide themselves with food 4 times a day, care and, in case of health problems, also technical aids*' (Director of SCC 'Ludza'). Respondents expressed regret for those elderly people who live alone and are forced to cope with everything on their own - pay utility bills, take care of the necessary medications and, finally, with what is left, be fed for a month, believing that SCC is a way to ensure a dignified life for seniors even when they are no longer able to do so themselves: '*...one way to solve the problems of seniors is, of course, placement in SCC*' (Bauska municipality social worker). The social worker feels responsible for this lonely, helpless senior, but at the same time, is often unable to influence the situation: '*It's painful to see when a person refuses help; I feel sorry for him being so helpless, but I can't decide for him'* (Cēsis municipality social worker).

Long-term social care service, procedure for receiving it

The interviewed respondents believe that the long-term social care service is an alternative for ensuring a dignified life for elderly people who are unable to take care of themselves: '*Elderly people come to us when they can no longer take care of themselves. This means that they need absolutely everything they need to live – nutrition, care, appropriate equipment.*' (Director of SCC 'Ludza'). '*…they have a life worthy of a resort here, because every room has a sanitary facility, they don't have to go anywhere; they live two in a room, cultural events are organized every week, a physiotherapist is available, various activities are organized for them – singing, drawing classes. We ourselves say that this is our home*!' (Director of Cēsis SCC). '*…he has the choice to attend various activities at the SCC: passive, such as watching TV, radio, reading magazines or books, board games; active, such as walking outside, helping with household chores (harvesting, raking leaves, caring for flowerbeds), exercising, music therapy and attending excursions)'* (Bauska municipality social worker). However, as the information obtained in the interviews reflects, not all elderly people who would need this service have the opportunity to receive it. Bauska municipality social worker: '*Not everyone can get the SCC service. SCC prices are increasing every year. The price is now around 1000 euros. Many seniors in rural areas have small pensions. Some have a disability group and care allowance as a 'bonus'. Putting everything together, it is good if half of the amount can be covered. The other half is covered by the breadwinners – children. Not all children want to take care of a loved one, to pay. Many can't be reached, because they are abroad earning money. For a large part of the relatives, the income is enough to support their own family, to provide for basic needs. If there are no breadwinners, or relatives can prove that they are not able to pay, then the local government considers the possibility of covering the senior's relative's share and places them in SCC.*'

A similar situation exists in other rural areas; for example, in Cēsis SCC, approximately 50% of residents live in a nursing home, and the remaining fee for the nursing home service is covered by them or their relatives, while for the other half of the residents, the remaining fee is covered by the municipality. The director of SCC 'Ludza' emphasizes that there are cases when children do not pay the remaining fee for receiving the service, then the municipality covers it, which is confirmed by the statement of the Ludza municipality social worker: 'Yes, yes, of course, we reimburse, to get into a nursing home, you need a certificate from a family doctor that a nursing home is necessary because long-term care is needed, for example, dementia or stroke; then we check, assess and then look for a place, and if there is a place, then we can send the person there immediately. We have many old people already with disabilities, but that is not a criterion. We also assess the ability to pay. If there are children, the children pay extra. If there are no children or they are insolvent, then the municipality pays extra. Ludza residents have to pay a little less'. Upon receiving the new client's documents, a care plan is prepared for what to do with the person further: if necessary, a nutritional diet is drawn up; it may be necessary to chop food or take the person to the doctor. From the above, it follows that SCC, assessing the needs of each client, tries to meet them by attracting both the necessary healthcare specialists and organizers of cultural activities to provide leisure opportunities.

Challenges faced by SCCs in providing long-term social care services to seniors in old age

According to previous studies, dignified life in old age means not only autonomy but also social inclusion and interpersonal relationships, The challenges of SCC are related to the harmonious interaction of these aspects. Informants mention the attitude of both the elderly themselves and the care staff as one of the most significant challenges in ensuring a dignified life for seniors in SCC: '*They are like children, only each with their own character. Emotionally it is difficult – each wants attention, to talk, requires a lot of time and attention*' (Director of SCC 'Ludza'). '*...a person is a person – each has their own character. With their own quirks. Maybe he has some health problems, he is bedridden and shows his displeasure to the staff serving him. The caregivers do everything badly. He has food, he is cared for, but everything is still bad*!' (Ludza municipality social worker) In SCC, seniors need to be treated with understanding and respect, but this is not always ensured by the caregivers: '*No matter what kind of pig he is sometimes. He is at his age. I think if there is an empathetic attitude, a respectful attitude from the employee towards that person, then everything is fine; I think that is the most important thing. And often what I see is neither empathy nor a normal attitude from the caregiver towards the old person. I think that respectful ageing will be if we change our attitude towards the old person. That is the most important thing* - ***the attitude of the care staff***' (Director of SCC 'Rauda'). '*…attitude is very important to them. There are 4 or 2 people in a room, we need to talk. Nutrition, medicine are important*' (Ludza municipality social worker). In the interviews, environmental accessibility was mentioned as a challenge in ensuring a dignified life for elderly people in social care centers: '*Well, in my institution, there is no environmental accessibility. I have a narrow door where you can't push out this bathtub, where you put a lying person; push it out, push it into the shower and wash them nicely. Now we are thinking about how to improve the well-being of clients by modifying this door, so that they can normally go out through it in a wheelchair, instead of having to squeeze past it as it is narrow. The same is true of environmental accessibility, so that someone has to open the door for a person to get out. And also the ramp that we have at the door, that ramp - it is also not built in accordance with environmental accessibility. It is too high, and it is also difficult for a person to go down. 'Those are the essential things, in my opinion, that preventhim from feeling good here*' (Director of SCC 'Rauda'). The director of SCC 'Ludza' considers it a challenge that young men who are homeless, drink alcohol, and disturb the peace of seniors are also placed in nursing homes: '*…we place two large categories here – people who are unable to take care of themselves and young men, usually homeless, very sick*'. Challenges related to frequent staff turnover were also mentioned, because caregivers' salaries are low, but the work is very hard, physically and emotionally difficult - burnout syndrome is observed: '*...we can only pay for 30% of the replacement. Is it right when I ask caregivers to come to work on Sundays or holidays, but I can only pay for the work done, 30%! Moreover, people do not come to work for us at all, because they are aware of the specifics of this work*' (Director of Cēsis SCC). The admission of dementia patients to the nursing home is also a challenge: '*...we carefully evaluate whom to take. If a person has dementia, we only take bedridden patients so as not to disturb other residents. We would need a separate ward with a fence around dementia patients so as not to disturb the others*' (Director of Cēsis SCC). It follows that SCC faces two types of challenges - those whose overcoming does not depend on SCC's capabilities, as, for example, salaries for carers are paid from the municipal budget, and SCC cannot influence this remuneration procedure; also, improving environmental accessibility requires resources, but SCC is not a financially profitable institution. The other group of challenges are those to be overcome by SCC's efforts, e.g., the attitude of staff towards SCC clients.

Conclusions

1. With the rapid ageing of the population, which is influenced by various factors and which in turn affects almost all spheres of life, ageing issues are in the focus of attention in the EU as a whole and Member States in particular. Caring for the well-being and dignity of older people as important issues in the modern world have been addressed in policy planning documents and action plans, as well as have attracted the interest of researchers.

2. Dignified ageing is a complex, multi-dimensional concept. It covers a wide range of human life and is associated with human dignity, autonomy, the ability to take care of oneself and the provision of essential needs – physical, financial, emotional and social. Ageing in rural areas is significantly affected by the specifics of the rural environment, which can often be a 'challenging context' especially for older people.
3. Statistical and research analysis shows that older people in rural areas have quite low life satisfaction rates, poor health and difficult access to medical services, problems with transportation, poor living conditions (housing without amenities), lower incomes, and a significantly higher at-risk-of-poverty rate. But despite the problems they face, seniors usually want to stay in their place until the end of their lives.
4. Long-term social care service is designed as an alternative for ensuring dignified life in old age, especially for rural residents. However, the study shows that SCCs face various problems in ensuring dignified life, such as accessibility, quality of services provided, high risk of staff burnout, etc.
5. Seniors do not have a clear opinion about long-term social care service. SCC is often stigmatized. There is still a stereotype that SCCs are 'poorhouses', which discourages seniors from using the service even if it is necessary.
6. Considering the objective and subjective challenges and obstacles identified in the study, SCC can currently be considered only a partial solution to ensuring dignified old age in rural areas. Several improvements are necessary for the long-term care service to be fully such.

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STAKEHOLDERS OF SUSTAINABLE REGIONAL DEVELOPMENT ACCORDING TO THE QUADRUPLE HELIX MODEL: A CASE STUDY OF REGIONAL INDUSTRIAL PARKS

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Abstract
Despite the normative view that the Quadruple Helix model (government, academia, industry, and civil society) is intended to enhance regional development, there is limited understanding of the collaboration opportunities from the stakeholders' perspective aimed at regional sustainability. To address this gap, the aim of this article is to empirically explore the stakeholders involved in sustainable regional development according to the Quadruple Helix model, using regional industrial parks as a case study. This involves identifying, from the stakeholders' viewpoint, their expectations, potential benefits, and challenges in collaboration. Based on this analysis, recommendations for future collaboration management and evidence-based decision-making can be developed. Overall, stakeholder analysis is critically important for overcoming expectation and implementation gaps, ensuring stakeholder satisfaction with collaboration, and promoting sustainability. Design/Methodology/Approach: The study employs monographic and descriptive methods, logical construction methods, graphical methods, and case studies. Main Findings: The Quadruple Helix model approach is participatory and transparent, and its application can ensure appropriate sustainable outcomes. According to the analysis conducted, it is essential to define collaboration mechanisms and identify issues-points of contact and conflicting paradigms. Thus, the application of the Quadruple Helix model in stakeholder engagement and management needs optimization to ensure regional development. Originality: This study contributes to existing literature by utilizing the Quadruple Helix model in the context of sustainability. It conducts an analysis of stakeholders in regional industrial parks based on the Quadruple Helix model, thereby expanding the understanding of the Quadruple Helix model.
Keywords: collaboration mechanisms, industrial parks, Quadruple Helix model, stakeholders, sustainable regional development.

Introduction

Sustainability is defined as a process that meets the needs of the present generations without compromising the ability of future generations to meet their own needs (Luengo-Valderrey et al., 2020). In this study, the concept of sustainable regional development is understood as a continuous, qualitative, and upward process of change that ensures regional prosperity, social justice, and environmental security while considering cultural aspects. Essentially, the concept of sustainable development is based on a balance between scientific and technological progress, adherence to social and ethical norms, and the interests of future generations. Science and technology bring both benefits and risks, so their application must be carefully considered and ethically justified in the present to ensure resource availability for future generations.

Sustainable development consists of two opposing aspects - stability, which characterizes sustainability, and dynamics, which characterize development. While these aspects are opposite, they complement each other. Stability can be understood as the long-term preservation of resources, while dynamics allow for adaptation and progress in changing conditions. Thus, it can be concluded that sustainable development ensures not only the preservation of natural resources for future generations but also the improvement of the quality of life in the present.

Balanced social, cultural, environmental, and economic development of regions is impossible without the direct involvement of the government, residents, industry, and academia. Therefore, the Quadruple Helix model, which includes civil society, industry, academia, and government, can be considered as representing the key regional stakeholders. The Quadruple Helix model is specifically aimed at prioritizing the stakeholders involved in sustainable regional development. It is essential to recognize that each of these stakeholders has its own, often economic, interests, which may sometimes compete with one another.

Materials and Methods

As a result of the study, available literature was analysed, and an in-depth investigation was conducted, leading to a detailed understanding of the stakeholders involved in regional industrial parks. This analysis was based on the Recovery and Resilience Mechanism's 3.1.1.3.i. investments available in Latvia. The case study is guided by a key research question that defines the study's direction-who are the stakeholders in regional industrial parks, what are their expectations and benefits, and what are the main challenges in collaboration? Based on this analysis, recommendations can be developed for future cooperation management and evidence-based decision-making. Consequently, in-depth and innovative knowledge about industrial park stakeholders has been obtained, contributing to ensuring the sustainable development of regions.

This study contributes to the existing literature by applying the Quadruple Helix model in the context of sustainability. It conducts an analysis of regional industrial park stakeholders based on the Quadruple Helix model, accurately identifying the involved

parties and thereby expanding the understanding of this model.

It should be noted that the empirical research section does not aim to be exhaustive but provides a clear assessment of the involved stakeholders. This, in turn, enables better collaboration with them, ultimately ensuring the sustainable development of regions.

Results and Discussion

A society striving to promote sustainability must ensure a balance between economic development, social well-being, and environmental preservation (Zhou & Etzkowitz, 2021). Since 2015, sustainability has become a universal call to action, as the United Nations General Assembly adopted the Sustainable Development Goals (SDGs) during this period (United Nations, 2015). Like sustainable development, regional development is also a transformation process that focuses on regional growth without harming future generations. This process involves the appropriate use of production factors, the rational utilization of natural resources, environmental conservation, and solidarity (De Lima, 2021).

Sustainable development cannot be achieved through isolated initiatives. Integrated efforts at various levels are required, incorporating multiple aspects, fostering positive synergies, and creating meaningful sustainable development. While ensuring sustainability is a shared responsibility, global, regional, and national organizations, as well as governments and civil society organizations, are encouraged and expected to demonstrate ownership, leadership, and civic responsibility (Mensah, 2019).

Although there is no doubt about the importance of integrating the pillars of sustainable development (environmental, cultural, economic, and social) at the regional level, implementing this concept in practice has proven to be challenging. The integration of sustainable development pillars at the regional level requires the implementation of coordinated and complementary actions across various fields, resulting in economic growth while also achieving social goals without jeopardizing limited resources (Jovovic et al., 2017). While sustainable development is often viewed as the responsibility of national governments, much can be accomplished at the regional level. Considerations of equity in income distribution across different regions are particularly important for regional policymakers.

This suggests that central and regional governments may reach different conclusions regarding the best solutions to economic, social, and environmental challenges that must be addressed for sustainable development. This issue becomes even more complex when determining how to distribute the short-term burden of long-term sustainability efforts across different regions of the country. In such situations, reaching a mutually acceptable compromise can be difficult. Since the division of tasks and responsibilities between central and regional governments is also a matter of power distribution, it must be decided through a political process between central and regional authorities (Ahlheim, 2009).

Sustainable development cannot be left solely to the responsibility of the central government. Regional governments must also recognize it as a priority. Many issues are more effectively addressed at the regional level, ensuring sufficient public participation-for example, environmental protection in specific territories. It is crucial to achieve coordinated action between the central government and regional governance structures. Only such an approach can ensure sustainable development at both the regional and national levels.

The term ‘stakeholder’ was first introduced by Freeman in 1984 (Freeman, 1984). Since then, it has been widely used in academic research and management thinking across various fields, leading to the development of a distinct branch known as ‘stakeholder theory.’ The concept emerged from the realization that corporate management should be concerned not only with the interests of shareholders (Freeman et al., 2010). Literature defines a stakeholder as any individual or organization that influences an organization and any individual or organization that is influenced by the organization (Mitchell et al., 1997). More recently, this idea has evolved into stakeholder engagement, focusing on value creation and addressing sustainability challenges through their involvement (Freeman et al., 2010; Freudenreich et al., 2019) (Sady, 2023).

Stakeholder theory and sustainability management reject the notion of separating ethical issues from economic concerns, as they are significantly interconnected rather than contradictory. Aligning these aspects can create real value for stakeholders and promote sustainable development (Hjörisch et al., 2014). Both concepts move beyond the traditional view that companies exist solely to maximize short-term shareholder value, introducing a long-term perspective and corporate responsibility into core business operations.

Stakeholders are at the centre of sustainability research because no organization can navigate an evolving environment alone (Dentoni et al., 2020). The first United Nations Conference on Environment and Development in 1992 acknowledged that achieving sustainable development would not be possible without stakeholder involvement. The 2030 Agenda for Sustainable Development emphasizes broad stakeholder participation, stating that ‘other interested parties actively engaged in sustainable development’ may not fit into standard categories. Therefore, adaptation and collaboration with relevant actors in specific processes are necessary (UN DESA & UNITAR, 2020).

Stakeholder theory assumes that an organization’s development is determined by how well it considers

stakeholder expectations. Organizational activities should be based not only on identifying stakeholders but also on understanding their expectations and communication methods (Freeman et al., 2010). Organizations must not only define but also prioritize their stakeholders based on instrumental and/or normative considerations, as they operate with limited resources and bounded rationality, making it impossible to create all forms of social value for every stakeholder (Jamali, 2007).

The Quadruple Helix model was developed by Henry Etzkowitz and Loet Leydesdorff, proposing those three key stakeholders-government, academia, and industry-play a crucial role in understanding and promoting sustainable development and innovation (Etzkowitz & Leydesdorff, 2000). Carayannis and Campbell (2009) expanded this concept by adding 'civil society' as the fourth helix to the original Triple Helix theory. According to Carayannis and Campbell (2012), the Quadruple Helix model emphasizes collaboration in innovation, particularly in dynamic processes (Sabaruddin et al., 2023).

Each stakeholder within this model fulfils a specific role: academia focuses on research and innovation, industry produces various goods and services, government regulates the market through policymaking and legislation, and civil society ensures its rights are upheld throughout these processes. The Quadruple Helix model helps clarify the relationships among these stakeholders, highlighting that one stakeholder can also take on roles traditionally assigned to another-for instance, the government may actively promote innovation. Such coordinated collaboration fosters initiatives aimed at achieving sustainable regional development.

Each helix component plays a crucial role in promoting sustainability, contributing significantly to the process (Gouvea et al., 2013; Hasche et al., 2020; Roman et al., 2020; Yun & Liu, 2019). This aligns with the rationale for achieving the Sustainable Development Goals (SDGs), which require collaboration among multiple actors. The United Nations influences institutions such as universities, governments, non-governmental organizations, and individuals to work together toward achieving the SDGs (Amry et al., 2021; Zhou & Etzkowitz, 2021; Hakeem et al., 2023).

Key stakeholders have a significant impact on sustainable development and its core values (pillars), which include improving living standards (economy), ensuring fair resource distribution (social), creating a liveable environment (environment), and preserving cultural values (culture).

The Quadruple Helix model adopts an approach that groups stakeholders with similar characteristics. In this model, these groups are government, academia, industry, and end-user (society) stakeholders, who can either influence or be influenced by the system. Each of these four groups within the Quadruple Helix framework may encompass multiple individual stakeholders.

Case study

There are several reasons why it is important to identify the specific stakeholders involved in regional development programs. The key arguments are outlined below.

Firstly, identifying stakeholders is essential for ensuring effective collaboration between them. All parties that influence and are influenced by regional development can achieve efficient communication and make fact-based decisions through cooperation. Collaboration enhances resource efficiency. The Ministry of Environmental Protection and Regional Development of the Republic of Latvia emphasizes that the development of a sustainable regional strategy is only possible by involving stakeholders, as this ensures the creation of a comprehensive and effective strategy (Guidelines for the development of municipal sustainable development strategies, 2021).

Secondly, identifying stakeholders allows for the alignment of planned policy actions, ensuring the best possible outcome.

Thirdly, engaging all relevant stakeholders-especially civil society and local communities-enables an understanding of the situation 'on the ground' and ensures that the specific needs of a given area are considered. This alignment of local needs with sustainable development goals is crucial. A deep understanding of local needs, particularly in Latvia's eastern border region, can significantly impact the region's socio-economic development and contribute to improved physical security.

Fourthly, stakeholder involvement fosters social cohesion, ensuring that key actors, particularly civil society and industry, feel engaged in the decision-making process.

Fifthly, defining stakeholders and ensuring cooperation among them promotes regional innovation. One of the key stakeholders in this process is academia, which can support the development and transfer of innovations to the industry.

Stakeholder analysis is not widely applied in Latvia for various development programs, including regional development programs and different European Union fund programs. The most recent available information indicates that stakeholder participation (including representatives of municipalities, planning regions, ministries, and non-governmental organizations) was ensured during the development of the Regional Policy Guidelines for 2021–2027 (Cabinet of Ministers Order No. 587, November 26, 2019). Additionally, stakeholder analysis was conducted during the development of the Latvian Tourism Development Action Plan for 2021–2027 (Van der Steina et al., 2019). However, both documents were created in 2019.

One of the regional development programs available in Latvia for project submissions from October 19, 2022, to April 28, 2023, was the European Union

Recovery and Resilience Facility Plan's Reform and Investment Direction 3.1 'Regional Policy', specifically Investment 3.1.1.3.i 'Investments in Business Public Infrastructure for the Development of Industrial Parks and Territories in the Regions'. This program focuses on the establishment of industrial parks and territories outside the Riga Planning Region. The goal of these recovery fund investments is to develop national-level industrial park infrastructure and attract investors to Latvia's regions beyond the Riga Planning Region, fostering the creation of high-value-added and export-oriented jobs while reducing regional development disparities (Cabinet Regulation No. 543, 2022).

Within this program, five industrial parks are being developed across Latvia's regions (in Daugavpils, Valmiera, Ventspils, Liepaja, and Jelgava) (Central Finance and Contracting Agency, 2022). The planned completion date for the parks is June 30, 2026, with non-financial investments of at least €85,741,349 and the creation of 328 jobs by industrial park operators (managers) or private investors (entrepreneurs). These jobs should offer salaries exceeding the average wage in the respective economic sector (Cabinet Regulation No. 54, August 30, 2022).

Since the industrial parks are being developed exclusively outside Riga, this program serves as a suitable case study for assessing its potential impact on stakeholders involved in sustainable regional development.

According to the World Bank's definition, an industrial park is a designated area with the necessary infrastructure (such as buildings, access roads, electricity connections, railway sidings, and other utilities) created to stimulate business activity and promote industrial development while minimizing its environmental impact (World Bank Group, 1998). Industrial parks play a crucial role in technology transfer, attracting investments, improving the business environment, creating new jobs, and optimizing costs. However, the development of such parks outside major urban agglomerations requires various forms of support at both national and regional levels. Not only appropriate legislation but also suitable political, social, and economic conditions are needed for their establishment and successful operation.

Table 1

Analysis of Stakeholders Involved in Latvian Regional Industrial Parks (Developed within the Support Program) Based on the Quadruple Helix Model (Created by the Author)

The value of the Quadruple Helix model	***Stakeholders***	***Typical behaviour***	***Expectations from collaboration***	***Benefits from collaboration***	***Challenges of collaboration***
Government	-Cabinet of Ministers -Local Government -Ministry of Smart Administration and Regional Development -Ministry of Economy -Latvian Investment and Development Agency -Planning Regions*	-Policy development, maintenance and implementation -Strong orientation towards engagement	-Solving economic, social, environmental and cultural problems -Development of innovations -Ensuring the adequacy of the state and regional budgets and stimulating income growth -Maintaining social stability in the region	-Better understanding of local communities and their needs -Slow decision-making process	-Slow decision-making process -Complex structure
Academia	-Vidzeme University of Applied Sciences and its research institutes -Ventspils University of Applied Sciences and its research institutes -RTU Liepaja Academy and its research institutes - Latvia University of Life Sciences and Technologies and its research institutes -Rezekne Academy of Technology and its research institutes	-Development of science and innovation -Publication and presentation of academic works -Knowledge transfer to industry -Strong orientation towards understanding	-Increasing importance of research and innovation -Innovation and knowledge transfer	-Collection and analysis of various socio-economic data -Wider use of research results	-Determination of research priorities

The value of the Quadruple Helix model	*Stakeholders*	*Typical behaviour*	*Expectations from collaboration*	*Benefits from collaboration*	*Challenges of collaboration*
Civil society	-Non-governmental organizations** -Residents (especially those living relatively close to the industrial area and potential workers) -Media (especially regional, including social)	-Protection of civil rights -Protests, petitions, lobbying, founding and leading new non-governmental organizations -A strong orientation towards communication	-Support for civic activities -Improvement of the business environment -Satisfaction of social interests in the region (e.g., healthcare, education, etc.) -Rational use of natural resources and environmental protection -Improved financial situation -Various needs (including intangible ones) are satisfied) -Respect for public interests	-Improved living conditions in the regions -Various services are available in the regions	-Lack of effective communication -Uncertainty of role
Industry	-Existing companies (especially those directly or indirectly related to the operation of potential industrial parks) -Potential companies (especially those directly or indirectly related to the operation of potential industrial parks) -Business organizations and their regional representative offices*** -Latvian Development Finance Institution Altum -Regional business support centres -Regional business associations -Regional business incubators -Business start-up, investments in the company, business management -Regional business incubators	-Business start-up, investments in the company, business management -Knowledge transfer from the academy -Strong focus on results	-Maintain continuous, profitable long-term operations -Stable and development-oriented business environment -Receive economic benefits from knowledge transfer	-Improved reputation of the industry and/or companies -Regional brand awareness	-Reluctance to participate

*Considering that the primary source of funding for planning regions is the state budget, planning regions (in the context of the case study – Kurzeme, Zemgale, Vidzeme, and Latgale) are included under the 'government' category in the Quadruple Helix model.

**The contribution of non-governmental organizations (NGOs) is not primarily measured from an economic perspective, but rather in terms of public benefit and sustainable development. In addition, NGOs can also include elements of economic activity and monetary investment (Spuriņš, 2024). NGOs carry out targeted activities to ensure the well-being of society. These organizations can identify and solve societal problems, strengthen communities, promote sustainable development and promote dialogue with other social actors (Putāne, 2024). As of 2023, a total of 26,928 associations and foundations were registered in Latvia. The number of organizations increases annually by approximately 3% or 600-700 new units (net difference between newly established and liquidated NGOs). In the regions of Latvia (excluding Riga and the Riga planning region), 13,765 NGOs were registered in 2023 (Klasons, 2024). There is no readily available information in public sources about NGOs in the regions directly or indirectly related to the case study area.

***The most active business organizations with regional representation are the Latvian Chamber of Commerce and Industry and the Latvian Employers' Confederation.

In Poland, 73% of industrial parks are in border regions and are experiencing active development. The main tax incentives and regional aid mechanisms support the establishment of industrial parks near the Ukrainian border, offering tax relief of up to 50% (Doing Business in Poland - Investor's Guide, 2024).

This policy is likely influenced by Russia's full-scale invasion of Ukraine in 2022.

Although industrial parks are a vital part of the economy with significant development potential, there is no comprehensive data available in Latvia on the total area of established industrial parks across the regions.

It is essential to identify the stakeholders involved, considering both the benefits and challenges of cooperation. This helps bridge the gap between expectations and reality (Capello & Kroll, 2016). Based on an analysis of the available information and applying the Quadruple Helix model, the key stakeholders, expectations, benefits, and collaboration challenges related to regional industrial parks developed under the European Union Recovery and Resilience Facility's Investment 3.1.1.3.i 'Investments in Business Public Infrastructure for the Development of Industrial Parks and Territories in the Regions' have been identified (see Table 1).

To establish, manage, and maintain relationships among stakeholders within the Quadruple Helix model, proactive stakeholder dialogue and engagement are required (Labelle & Aka 2012). According to Greenwood (2007), the process of stakeholder engagement within the Quadruple Helix model is iterative (Greenwood, 2007). Idealism should be avoided (Flanagan & Uyarra 2016), while not diminishing stakeholder expectations (Filtenborg et al., 2017; Grimmelikhuijsen & Porumbescu, 2017; Nguyen & Marques, 2021). Considering the interests of stakeholders in sustainable regional development in regional development programs and the implementation of sustainable development principles is an important goal for regional transformation (Porini & Striani, 2017).

Conclusions

1. Previous studies on the Quadruple Helix model have focused mainly on the macroeconomic level, despite the sustainability-related activities that take place at the micro level. Therefore, future studies should explore this micro-level perspective.
2. In the Quadruple Helix model, stakeholders play a crucial role in regional development, as they significantly influence economic, social, cultural and environmental impacts.
3. The Quadruple Helix approach is participatory and transparent, ensuring sustainable outcomes. However, the lack of a comprehensive policy regulating the roles and powers of stakeholders in regional development governance reduces stakeholder participation and interest.
4. It is important to define mechanisms for collaboration, identify problems, points of contact and conflicting paradigms. Optimizing the Quadruple Helix model for stakeholder engagement and governance can promote regional development. It may be necessary to expand the list of stakeholders.
5. This article enriches the existing literature by testing the stakeholder approach of the Quadruple Helix model for promoting sustainable regional development. It provides a detailed understanding of the characteristics of all four stakeholder groups.
6. The limited scale of the specific regional development program limits generalizability. However, the case study demonstrates the practical application of the Quadruple Helix model. Future research could explore the applicability of the analyzed program to other regional development forms and programs.

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IMPORTANCE OF HUMAN CAPITAL IN PREVENTION OF AVIATION ACCIDENTS

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Abstract
The aim of this study is to investigate the role of human capital in the aviation sector, with a specific focus on the relationship between employees' educational levels and economic performance. This research addresses a critical gap in understanding how higher education contributes to the development of productivity, innovation, and operational efficiency within the industry. The research explores the significance of human capital as a sustainable competitive advantage in organizations. It highlights the shift from focusing on physical assets to intellectual assets, emphasizing how knowledge, skills, and creativity drive organizational growth. The main idea is to understand the necessary requirements of higher education existence to aviation specialists. An analysis of academic literature and scientific articles has revealed key patterns and correlations. The findings indicate that investment in higher education for aviation professionals enhances operational outcomes, reduces safety incidents, and increases the sector's capacity for innovation. Moreover, regions with a highly educated aviation workforce demonstrate stronger economic growth, as reflected in higher Gross Domestic Product (GDP) contributions, and exhibit greater competitiveness in the global market. These results highlight the importance of higher education as a strategic factor for sustainable development and stimulating economic progress both in general and in the aviation industry. In addition, the study highlights the need to develop recommendations for additional higher education requirements for key aviation professionals. Such an initiative will not only improve individual skills, but also contribute to the development of the aviation industry by improving safety and security performance.
Keywords: higher education, human capital, aviation.

Introduction

In the knowledge based economy, human capital plays a key role in ensuring the competitiveness and sustainable development of organizations. It encompasses a combination of knowledge, skills, professional experience, and creativity of employees, which directly influences a company's ability to create value, implement innovations, and adapt to dynamic market conditions. In recent decades, there has been a shift in focus from material assets to intellectual capital, where human resources have become the primary driver of economic growth (Toma & Laurens, 2024).

Education is a fundamental driver in shaping human capital, acting as a key mechanism for enhancing workforce competence and industry sustainability. Investment in educational programs and continuous professional training not only improves operational efficiency but also ensures adherence to high safety standards, particularly in sectors where precision and reliability are critical (Mohamad Abd El Maksoud, 2018). In aviation, the qualifications and expertise of personnel are directly linked to flight safety, risk management, and service quality, as highly trained professionals—pilots, air traffic controllers, and maintenance crews—play a crucial role in minimizing operational risks and preventing human error, which remains a leading cause of aviation incidents. Research indicates that insufficient training and lack of specialized qualifications significantly elevate the probability of system failures (Muecklich et al., 2023), while ongoing skill development and compliance with international aviation safety regulations enhance risk mitigation efforts, ultimately improving industry performance and passenger experience. Moreover, education and training contribute to the overall quality of aviation services, optimizing flight operations, refining maintenance protocols, and integrating technological advancements, all of which bolster economic performance and global competitiveness. Thus, sustained investment in human capital through structured training and education not only strengthens aviation safety but also supports long-term industry resilience, innovation, and economic growth (Smith & Brown, 2023).

This study aims to analyse the relationship between the educational level of aviation specialists and the economic performance of the aviation industry. Despite the widespread recognition of human capital's importance, the impact of personnel education on the industry's development remains insufficiently explored.

Thus, this study highlights the strategic importance of higher education as a key factor in the long-term development of the aviation industry.

Human capital is a key driver of economic growth and organizational competitiveness, especially in industries that rely on innovation and technological advancements, such as aviation. The educational background of corporate executives significantly influences workforce development strategies, as higher levels of education among leadership are linked to greater investments in employee training, career progression, and improved working conditions. These efforts not only enhance business performance but also contribute to broader regional economic development. Beyond formal education, human capital investments include specialized training programs, performance-driven motivation systems, and fostering a corporate culture that encourages innovation.

Effective knowledge management and continuous workforce training further reinforce these benefits by improving the competitiveness of individual companies

while positively impacting the overall economic performance of the industry. The development of human capital has become a strategic priority, not only enhancing employees' skills but also establishing a sustainable foundation for long-term growth. As economies continue transitioning toward knowledge-driven models, human capital is increasingly recognized as a critical asset for sustaining business efficiency and fostering innovation. Research highlights that companies prioritizing workforce education and development demonstrate higher growth rates, improved adaptability to market changes, and enhanced industry resilience. Wu and Fang (2024) confirm that organizations with strong commitments to educational investments experience superior performance metrics, reinforcing the long-term benefits of human capital development at both corporate and macroeconomic levels.

With the growing emphasis on human capital and education investments, companies are striving not only to develop their workforce but also to effectively manage accumulated knowledge. This is especially relevant in the aviation industry, where knowledge sharing and continuous professional development are crucial for maintaining competitiveness.

Modern airports and airlines actively implement knowledge management strategies aimed at optimizing workflows and improving employee efficiency (Atalay & Sarvan, 2014). In the context of international joint ventures (IJVs), effective knowledge-sharing among partners and access to advanced educational programs are essential. The study by Atalay and Sarvan (2014) found that in the airport business, a key factor for successful knowledge management is the transfer of expertise from more experienced companies to less established partners, which contributes to overall staff skill development.

Beyond traditional education programs, ongoing training and continuous employee development play a vital role. Mohamed Abd El Maksoud (2018) emphasizes that effective training programs in the airport industry enhance employee competitiveness, improve work quality, and elevate customer service standards. The study suggests that a systematic approach to staff training not only boosts individual performance but also enhances the overall efficiency of companies.

Similar findings were reported in the study by Okine et al. (2024), which examined the impact of educational standards on the aviation industry. The research revealed that regions with a higher level of specialist training experience sustained GDP growth due to increased production efficiency and reduced costs associated with human errors.

Thus, the analysis of existing literature confirms that education and training are key determinants of competitiveness, innovation, and economic sustainability in the aviation industry.

In addition to its impact on national economic indicators, the development of human capital in the aviation sector also plays a vital role in fostering regional development. Regions that invest in the education and training of aviation professionals tend to experience a range of localized socioeconomic benefits. These include increased employment opportunities, the stimulation of supporting industries and services, the expansion and modernization of transportation infrastructure, and the emergence of regional innovation hubs driven by technological advancement and specialized expertise. The presence of a well-educated aviation workforce enhances the region's attractiveness to investors, encourages collaboration with academic and research institutions, and contributes to a more dynamic and resilient local economy. Therefore, higher education in aviation not only drives national competitiveness but also serves as a strategic instrument for balanced and sustainable regional development.

Materials and Methods

In the context of studying the role of human capital and educational investments in the aviation industry, the analysis of aviation accidents is of particular importance. Understanding the patterns and factors affecting flight safety enables companies not only to develop effective personnel management strategies but also to improve specialist training procedures (Bowes et al., 2024). To analyze aviation accidents for the period 2000-2023, statistical data on accidents by flight phases and the overall accident rate of airliners and corporate jets were utilized. Although more recent data might offer an updated view, the study intentionally focuses on the period up to 2019, as this timeframe represents the last stable pre-pandemic phase of global aviation. The information was obtained from JACDEC (Jet Airliner Crash Data Evaluation Centre, n.d.) and included indicators for various flight phases, such as take-off, climb, en-route flight, approach, landing, and taxiing, as well as general accident and fatality statistics.

In recent years, there has been a decline in the number of accidents and fatalities, likely due to the introduction of new technologies and an improvement in crew training standards. The main focus for enhancing safety should be on the en-route flight stage and the landing approach, as these remain the most high-risk phases (Angelov, 2019).

Advancements in aviation technology, improvements in pilot training procedures, and the implementation of additional safety measures have played a crucial role in reducing accident rates. Research indicates that modern aircraft designs, enhanced avionics, and highly sophisticated pilot training programs, including advanced flight simulators, have significantly decreased accident occurrences. Moreover, the adoption of proactive safety management approaches, such as situational awareness training and the integration of automated warning systems, has further minimized human error, which remains one of the leading causes of aviation incidents. These developments collectively contribute to higher safety

standards across the aviation industry (Oster et al., 2013). Despite significant progress in accident prevention, aviation security remains a crucial concern. While the frequency of aircraft hijackings has declined, their continued presence in statistical reports underscores the need for ongoing vigilance and security enhancements. Addressing both operational safety and security threats requires a comprehensive approach that integrates technological advancements, regulatory measures, and continuous personnel training (Gharsallah & Trabelsi, 2024). Thus, the analysis has identified key trends in aviation safety and provided recommendations for further reducing accident rates and strengthening overall aviation security.

Enhancing the level of education among aviation professionals directly contributes to improving flight safety, which, in turn, leads to reduced operational risks and lower costs for airlines (Ma et al., 2024). High-quality personnel training facilitates more efficient aircraft operation, minimizes crew errors, and enhances the overall reliability of the aviation system. This is reflected in the economic performance of the industry, including reduced insurance costs, lower expenses for accident recovery, increased passenger traffic due to growing trust in air travel, and higher investment attractiveness of airlines (Oster et al., 2013). Therefore, investments in educational programs and professional training are not only a strategic tool for ensuring safety but also a fundamental driver of sustainable economic growth in the aviation sector.

In the context of studying the role of human capital and educational investments in the aviation industry, the analysis of aviation accidents is of particular importance. Understanding the patterns and factors affecting flight safety enables companies not only to develop effective personnel management strategies but also to improve specialist training procedures.

Table 1

Global Data on Aviation Accidents by Year and Flight Phase

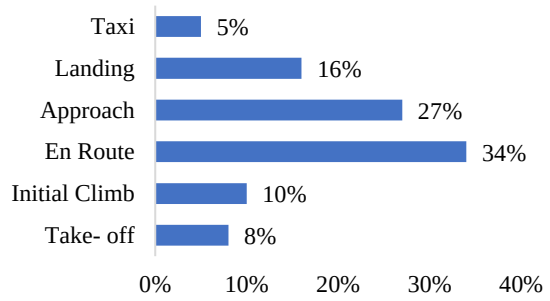
Year	*Take-off*	*Initial Climb*	*En Route*	*Approach*	*Landing*	*Taxiing*
2023	3	4	4	5	10	4
2022	4	1	6	8	15	5
2021	3	2	4	3	10	4
2020	5	4	3	8	17	0
2019	8	5	10	12	15	4
2018	1	1	11	3	2	0
2017	0	2	5	4	2	0
2016	3	1	11	2	0	0
2015	0	4	9	1	0	0
2014	0	3	12	3	2	0
2013	3	1	7	13	4	0
2012	1	6	3	11	2	0
2011	1	3	16	12	3	0
2010	0	6	11	10	5	0
2009	4	6	9	8	4	1
2008	4	2	14	10	4	4
2007	2	4	15	4	7	1
2006	1	4	18	4	5	1
2005	2	6	15	9	4	1
2004	2	2	13	12	4	1
2003	5	3	9	13	0	2
2002	2	0	16	20	2	5
2001	3	3	13	14	1	1
2000	4	5	17	12	3	1

To identify key trends, average incident and fatality rates were calculated, and the highest and lowest figures for the analyzed period were determined based on data from the Aviation Safety Network (n.d.) and the International Civil Aviation Organization (ICAO, 2023) (see Table 1). The most dangerous phase of the flight was the en-route stage, accounting for 251 incidents, which represents a significant portion of the total number of accidents. The second most dangerous phase was the landing approach, with 201 incidents, while the lowest number of accidents was recorded during the taxiing phase, with only 35 cases. Over the analyzed period, aviation accident rates exhibited notable variations, with earlier years demonstrating significantly higher occurrences. In subsequent years, a gradual decline became evident, likely reflecting the positive impact of technological advancements and improvements in flight crew training and operational procedures.

However, during the COVID-19 pandemic, a temporary reversal of this trend was observed, particularly in flight phases where human involvement

is most pronounced. Reduced routine operations, limited flight hours and restrictions on in-person training opportunities, as well as increased workload variability, likely contributed to performance degradation, emphasizing the need to maintain operational readiness under non-standard conditions.
The main focus for enhancing safety should be on the en-route flight stage and the landing approach, as these remain the most high-risk phases. Advancements in aviation technology, improvements in pilot training procedures, and additional safety measures contribute to reducing accident rates. Despite the decrease in aircraft hijackings, their presence in statistics indicates the ongoing need for efforts to ensure aviation security. Thus, the analysis has identified key patterns in aviation safety and provided recommendations for further reducing accident rates.

Figure 1
Global Data on Aviation Accidents by Year and Flight Phase



Results and Discussion
An examination of recent aviation accidents indicates that human error is responsible for approximately 60% of all incidents, with the majority of these errors occurring at the crew level (Oster et al., 2013). Such violations stem from various factors, including non-compliance with piloting procedures, insufficient pilot training, poor decision-making in adverse weather conditions, as well as physical and emotional fatigue among crew members. Additionally, errors made by air traffic control and technical maintenance personnel significantly contribute to emergency situations. These findings emphasize the importance of maintaining high standards in personnel training, enforcing strict adherence to safety regulations, and continuously monitoring crew conditions to mitigate risks.
The findings of this study demonstrate that investments in higher education for aviation specialists contribute to improved operational efficiency of aviation enterprises, a reduction in aviation accidents, and the overall strengthening of the industry's potential. Moreover, regions with a highly trained aviation workforce exhibit more stable economic growth rates, reflected in an increased contribution of the aviation sector to GDP and enhanced competitiveness in the international market. High-quality personnel training facilitates more efficient aircraft management, minimizes crew errors, and enhances the overall reliability of the aviation system. The findings also suggest that the effects of human capital development in aviation extend beyond organizational performance and national economic indicators. On a regional level, improvements in aviation workforce education contribute to job creation, support local supply chains, and promote the development of technical and vocational institutions. For instance, the growth of regional airports often triggers demand for trained professionals, which in turn stimulates educational programs and local employment. Furthermore, regions with higher concentrations of aviation-related training centers tend to become hubs for innovation and investment, reinforcing the strategic role of education in shaping regional economic landscapes.
This, in turn, has a direct economic impact, including lower insurance costs, reduced expenses for mitigating the consequences of accidents, increased passenger traffic due to growing confidence in aviation, and greater investment attractiveness of airlines. Therefore, investments in educational programs and professional training of personnel serve as a strategic tool not only for ensuring safety but also for fostering the sustainable economic growth of the aviation industry.

Conclusions
1. Investments in higher education and continuous training programs for aviation professionals enhance operational efficiency and contribute to reducing accident rates. Human error remains a primary cause of aviation incidents, highlighting the need for advanced training and strict adherence to safety regulations.
2. A highly educated aviation workforce contributes significantly to economic development at both national and regional levels. Regions with a strong presence of skilled aviation professionals tend to benefit from increased productivity, greater operational efficiency, and more stable contributions from the aviation sector to overall economic performance. Airlines that prioritize education and training for their personnel often achieve better safety records, experience lower insurance and legal expenses, and gain a competitive advantage through enhanced service quality and passenger confidence.
3. The development of human capital should be prioritized as a key element of aviation safety strategies, particularly in addressing the root causes of accidents related to human error. This study has shown that insufficient training and lower education levels among aviation personnel correlate with a higher risk of operational failures, especially during critical flight phases such as en-route and landing approach. Therefore, policymakers and industry leaders should focus on raising academic and professional standards for core aviation roles. This includes strengthening collaboration between higher education institutions and aviation organizations, and implementing

targeted, simulation-based training programs aimed at improving real-time decision-making and error prevention. Aligning educational investments with aviation safety goals will help reduce incident rates, improve operational reliability, and support the sustainable development of the aviation industry.

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POTENTIAL OF THE SILVER ECONOMY: EMPLOYMENT OF OVER-WORKING-AGE POPULATION IN LATVIAN REGIONS

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Abstract
The latest forecasts of the European Commission (EC) show that the number of people of working age will drop by 42% by 2070. The aim of the paper is to analyse the socio-demographic structure of the employed population above working age in Latvia, including regional tendencies, to identify variations in the potential of the silver economy. Research methods: scientific publication analysis, analysis of previous research results, time-series analysis using trend analysis, cross-tabulations by gender, by administrative territories, by highest obtained education for employed persons older than 65 (they are already in old-age pensions, but go on with their work), by working a full-time job or part-time job; testing of statistical hypotheses by using chi-square criteria, correlation analysis, data analysis performed with SPSS. According to the Central Statistical Bureau of Latvia, the employability of the population at retirement age (65–74 years) was 24.1% in 2023. In 2023, 17% of males and 13% of females received an old-age pension not exceeding 300 EUR. Since the number of old-age pensions is small, it motivates to keep employment if health conditions are reasonable. Many persons of the post-working age are professionally interested in keeping their employment as they have reached a certain high level of professionalism. The official statistical data indicate that in many cases, a high number of the population above working age receiving solid salaries and wages (more than 6000 EUR/per month) is increasing every year.
Keywords: ageing population, over-working age employment, socio–demographic structure, regional disparities, silver economy potential.

Introduction

A European Commission report on demographic changes forecasts that the world population in the 21st century will increase, and ageing will become a more significant demographic tendency all over the world. The forecasts enlisted in the EC report on the impact of demographic changes in Europe show that the share of the population aged 65+ in 2030 is expected to be 25.3%, while in 2050 — 31.5% of the total number of population (EC, 2020). The economic and fiscal nuances of these changes are deep. Unless many older people work longer, the smaller share of the workforce will need to support a greater share of the retired population. The potential of the national economic development will be adversely affected by a rapid decrease of the population of working age (15–64 years) both as a proportion of the total population — 58.5% in 2030 and 53.1% in 2050 — and in absolute numbers (Bērziņš, 2024). Along with the decreasing labour force and high migration level, the necessity of using the current human resources, including within the context of active ageing, becomes more topical in Latvia, creating conditions for as inclusive employment as possible. Demographic changes affect society in a very wide scope. They affect both the general growth of the national economy and economy, budget, cost structure, competitiveness, and services of each region and local government. The forecasted tendencies ask to search for timely solution options since the demographic changes are to be a huge challenge to the capacity of the state's fiscal and economic policy. One of the solutions offered is the concept of a *silver economy*. Its philosophy is to change society's attitude towards the process of population ageing and economic adaptation to the increasing number of elderly people. The objective of the paper is to analyse the socio-demographic characteristics, including gender structure, administrative-territorial dimension, education, wages, and salaries of the over-working-age workforce, to identify the potential and variations of the silver economy for future research. The target group of this research is people of the post-working age - 65 years and older (seniors).

Literature Review

The concept of the silver economy in scientific literature and research is widely analysed, especially in relation to the economic impact of demographic ageing and adaptation of entrepreneurship to the needs of seniors. Studies reveal that population ageing is not only a social challenge but also a new economic segment with significant growth potential in which ageing is considered a resource and driver for change and progressive politics that can affect not only the consumer market but also the social and economic models (Lipp & Peine, 2024). Experience in different countries shows that seniors should be more involved in the labour market (Sloka et al., 2021). In an ageing society, it is crucial to empower older workers to remain active for longer. Longer working lives can allow people to update skills on the job and remain active, helping employers to retain staff while promoting knowledge transfers in multi-generational workforces. In a longevity society, opportunities emerge in diverse sectors and areas, such as technology, health and care, medicine, nutrition and well-being, education and lifelong learning, transport and financial services, and the social economy (EC, 2023). It is indicated that demographic change has created new opportunities in various sectors but has also added to certain risks of strategic dependencies. Europe's ageing population raises the potential of the 'silver economy' to a projected 28.1% of EU GDP in 2025 (EC, 2023).

Development of the silver economy in Europe is not uniform, rather, it is regionally specific since there are significant differences in the living conditions of seniors, not only in different countries (Roszko-Wojtowicz et al., 2024) but also in different administrative territories in the same country. These differences are affected by demographic, socioeconomic, political, and contextual factors. A complete understanding of the potential of the silver economy requires an analysis of diverse geographical and cultural contexts (Roszko-Wojtowicz et al., 2024). Many researchers analyse the impact of social and economic factors on the well-being and consumer habits of seniors, thus proving that financial security and economic stability have the most direct impact (Steptoe & Zaninotto, 2020).

Older people cannot be considered unable to work just because they have reached a certain age. The labour market and shortages of people willing to work will gradually require employers' investments in facilities related to the increase of operational readiness of seniors and the implementation of age management (referring, in fact, to the management of the ageing process of employees through state policy or collective bargaining). However, the development of this system on a large scale requires, above all, a deeper change in the mentality of executives because, as of now, older employees are evaluated by managers (often based on stereotypes) less favourably than younger people (Kubiak, 2016).

The age of people and its relation to employment and employability were analysed by many researchers, including within the context of ageism and bias against the age of employed persons (Cheung & Woo, 2021; Kleissner & Jahn, 2020; Posthuma & Guerrero, 2013; Vickerstaff & Van der Horst, 2021). Researchers (Berglund et al., 2017) have analysed various factors that affect the choice of labour force of an older worker to continue working. Researchers analyse the relations between the age of employed persons and work conditions, as well as personal characteristics and family-related factors in many countries, including Sweden, while other researchers (Kohlbacher et al., 2017) describe employment of seniors in Japan and Poland, and Steptoe & Zaninotto (2020) – in the United Kingdom.

Companies and employees should cooperate to adapt work practices and change biases and stereotypes against generations. Societies and communities that respect equality also emphasise the necessity to fight stereotypes and age-based discrimination, facilitate diversity and inclusion in the workplace, and provide equal opportunities to make contributions and develop (EC, 2023). Researchers have paid attention to several aspects of the involvement of older personnel in employment (Braslina, et al., 2024; Schnalzenberger, 2016; Sloka et al., 2024; Tipwong et al., 2022). Researchers have analysed important factors of employment of persons (Easterlin et al., 2011; Kalkis et al., 2024; Sergejeva & Zeidmane, 2023; Vanclay, 2002) where significant attention is paid to well-being and social conditions evaluation.

The silver economy at the European level is recognised as a strategic approach that simultaneously supports active and healthy ageing and promotes increased employment and poverty reduction (EC, 2018), as well as social inclusion and involvement in economic activities for persons after retirement age.

Materials and Methods

The materials used in this research are the database of the Official Statistics Portal of the Republic of Latvia and the data from the Labour Force Survey in 2023. Research methods: scientific publication analysis, analysis of previous research results, statistical data analysis; for data statistical analysis were used time-series analysis, cross-tabulations by administrative territories, by highest obtained education for employed persons older than 65 (they are already in old-age pensions, but go on with their work), by working a full-time job or part-time job; testing of statistical hypotheses (H_{01}: there are no statistically significant difference on education level in Latvia for employed persons older than 65 years; H_{02}: there are no statistically significant difference on administrative territory in Latvia for employed persons older than 65 years) by using chi-square criteria, correlation analysis, data analysis was performed with SPSS. The authors have used data from Official Statistics Portal databases from different parts of the database indicated by codes corresponding to respective data (PPP040; IRD031; DSN030m) for selecting data in the analysed age groups. The authors have used anonymised data from the Labour Force Survey available in CSV format and transferred them to SPSS to perform deeper statistical analysis to perform statistical data analysis for selected age groups, as it is indicated in the following tables.

Results and Discussion

Analysis of the age structure of the Latvian population and EUROSTAT forecasts show that the population ageing will continue. Since 1993, the share of the population above the working age has been higher than the share of children and teenagers, which means that there will be a smaller number of working-age population in future and the demographic load will increase. In early 2024, the population of those above working age and living in Latvia was 425,8 thousand, i.e., almost every fourth or 22.8 % of the population. According to data from the Central Statistical Bureau of Latvia, in early 2024, there were 369 persons of retirement age per 1000 persons of working age or 1 pensioner per 3 persons of working age and 254 children aged up to 14 years (CSP, 2024). As the current demographic tendencies continue, this ratio in 2060 is to be 1 pensioner per 2 persons of working age. In many countries of the European Union (EU), pressure on social budgets and care services will increase, possibly forming the two largest government

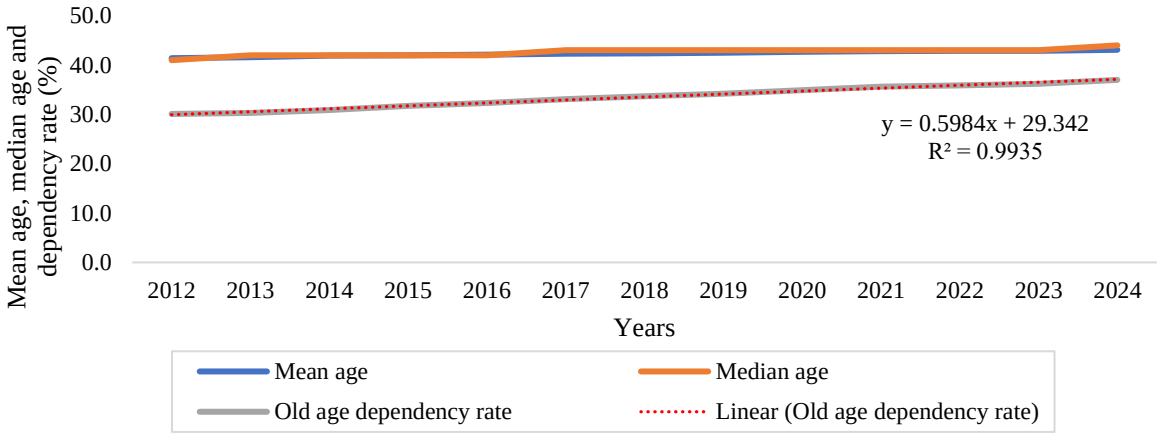
spending items. The cost of living is also constantly reminding us of itself.

Demographic changes and structural transformations also affect the dimension of regional competitiveness since less developed territories are experiencing a lack of labour force and skills. Comparing the regions and State cities in Latvia, the share of the working-age population (15–63 years) does not significantly differ; however, there is a difference between the share of the population below the working age (0–14 years) and above the working age (64 years and more). In early 2024, the largest proportion of the population above the working age was in Latgale (one-fourth or 25.4 % of the population of this region). Comparatively, the smallest number was in the Riga region – 21.6%. Considering the state's cities, the largest population above the working age live in Daugavpils (25.8%), Ventspils (25.8%), and Rezekne (25.1%), while the least – in Jelgava (21.3%) and Jekabpils (22.8%). In certain regions, both in Latgale – Kraslava Region (28.3%) and Vidzeme – Valka Region (28%), the population above the working age is already close to one-third of the regional population (CSB, 2024).

Tendencies of mean age, median age and old age dependency rate of the population in Latvia in 2012-2024 are included in Figure 1.

Figure 1

Mean age, median age and old age dependency rate of the population in Latvia at the beginning of the years 2012 - 2024



Source: Authors' construction and calculation based on OSP database IRD031 data.

Data indicate that the mean age (arithmetic mean – the most used degree mean) and median (the most used structural mean – it means that half of units is equal to median or less and half of units is equal to median or more) age in Latvia in 2021-2024 are almost the same but have increased in the analysed period; the dependency rate increased on average by 0,6 percent points annually from 2012 till 2024 (what is indicated by trend coefficient), the coefficient of determination is very high and is 0.9935.

A comparison of the average, median age dependency ratio of women and men shows that women live significantly longer in Latvia (Table 1). In 2024, the average age of women was 45.9 years, 6 years more than that of men – 39.9 years, respectively, the median age for women was 47 years, for men – 40 years, thus, the age dependency ratio for men was 25.6%, but for women, 48.1% (OSP, 2025b). Consequently, the proportion of women is also significantly higher among Latvian pensioners. Comparing the average pension amount between the two genders, pensions are higher for men than for women (in 2023: 547.89 euros versus 495.86 euros), which is most likely due to higher income during working life for men, while women have often prioritized taking care of their family and professional career (OSP, 2025a).

Table 1

Mean age, median age and old age dependency rate of the population (in %) by sex in Latvia in 2024

Statistical indicator	Total	Females	Males
Mean age, years	43.1	45.9	39.9
Median age, years	44.0	47.0	40.0
Old age dependency rate (%)	37.0	48.1	25.6

Source: Authors' construction based on the Official Statistics Portal of Latvia database IRD031 data.

Analysing the average age of the population, median age of the population and the age dependency rate in statistical regions in Latvia, authors conclude that in 2024, the Pieriga statistical region had a younger and more economically active population (old age dependency rate was 31.9%, for females – 40.4% and for males – 23.3%), while in Latgale (old age dependency rate was 40.9%, for females – 54.7% and

for males – 27.3%) and in certain regions in Vidzeme, there were older residents (OSP, 2025b).
It means that the most remote regions in Latvia are facing population ageing and possible depopulation. To examine the employment situation for the older population (over 65 years) in Latvia more deeply, data from the 2023 Labour Force Survey were also used. This survey allows for analysis from various aspects. The Labour Force Survey is conducted every year in all European Union and EU candidate countries (CSP, 2025a; CSP, 2025b). Data specific to Latvia are presented in Table 2.

Table 2
Distribution of persons in Latvia older than 65 years in the Labour Force Survey in 2023

Age groups	*Frequency*	*Percent*	*Valid Percent*	*Cumulative Percent*
65 – 74	5750	53.0	53.0	53.0
75 years and over	5097	47.0	47.0	100.0
Total	10847	100.0	100.0	

Source: Authors' calculations based on LFS in Latvia 2023 data.

Data of the analysed distribution for persons 65 years and older indicate that they were included in the LFS, as well as persons in the age groups 65–74 and 75 and over. The current research was interested in the employability of those persons, the distribution of those persons by administrative territories: urban or rural, by statistical regions of Latvia, by education level in those employed in analysed age groups, as well as if persons were employed full-time or part-time. The distribution of persons in employment in the age group 65–74 by administrative territories (urban and rural areas) and by statistical regions in Latvia is included in Table 3.

Table 3
Distribution of persons in Latvia in the age group 65–74 in employment by administrative territories and statistical regions by the Labour Force Survey in 2023

Statistical region	*Administrative territory*		*Total*
	Urban area	*Rural area*	
Riga	516		516
Pieriga	142	163	305
Vidzeme	49	61	110
Kurzeme	92	41	133
Zemgale	66	66	132
Latgale	106	36	142
Total	971	367	1338

Source: Authors' calculations based on LFS in Latvia 2023 data.

The data in Table 3 indicate that in the age group 65–74 years, most persons were employed in the Riga statistical region. Persons in the age group 65-74 were also employed in all statistical regions of Latvia – data were different, and in some statistical regions, more employment in this age group was in rural areas in Pieriga statistical region and Vidzeme statistical region. In other statistical regions of Latvia, more people employed in the age group 65–74 were in urban areas. It corresponds with findings reflected in scientific publications analysed in this paper. As mentioned in analysed scientific publications, more educated and trained persons are more successful in the labour market with higher education and vocational education, which is confirmed by data in the analysed employed persons age group 65 and older in Latvia (Table 4).
The data in Table 4 indicate that in Latvia, employed persons in the age group 65–74 years are employed with higher education and vocational education or professional secondary education in urban areas significantly more than in rural areas. As the survey shows, there are relatively fewer persons with basic education or less than basic education.
However, chi-square tests indicate that those differences are not statistically significant –calculation results are included in Table 5.

Table 4
Distribution of persons in Latvia in the age group 65–74 in employment by administrative territories and the highest level of education or training completed by the Labour Force Survey in 2023

The highest level of education or training completed	*Administrative territory*		*Total*
	Urban area	*Rural area*	
Higher education	420	126	546
Vocational education or professional secondary education	383	147	530
General secondary education	150	70	220
Basic education or less than basic education	18	24	42

Source: Authors' calculations based on LFS in Latvia 2023 data.

Table 5

Results of Chi-Square Tests on statistical significance of differences of employed persons in the age group more than 65 on the education level and administrative territory

Statistical indicators	*Value*	*df*	*Asymp. Sig. (2-sided)*
Pearson Chi-Square	25.979	3	0.000
Likelihood Ratio	23.743	3	0.000
Linear-by-Linear Association	19.218	1	0.000
N of Valid Cases	1338		

Source: Authors' calculations based on LFS in Latvia 2023 data.

Data indicated that there is no statistically significant difference in education level and administrative territory in Latvia for employed persons older than 65 years. The results of the correlation analysis are included in Table 6.

Data indicated that there is a statistically significant correlation between education level and administrative territory in Latvia for employed persons older than 65 years.

Table 6

Results of correlation analysis on the statistical significance of differences of employed persons in the age group of more than 65, on the education level and administrative territory

Analysed aspect	*Correlation indicator*	*Statistical region of populated area*
Statistical region of populated area	Pearson Correlation	1
	Sig. (2-tailed)	
	N	1338
Administrative territory	Pearson Correlation	0.248**
	Sig. (2-tailed)	0.000
	N	1338
The highest level of education or training completed	Pearson Correlation	0.085**
	Sig. (2-tailed)	0.002
	N	1338

**Correlation is significant at the 0.01 level (2-tailed).

Source: Authors' calculations based on LFS in Latvia 2023 data.

In Latvia, there are persons in the age group 65–74 with more full-time employment (Table 7).

Table 7

Distribution of persons in Latvia in the age group 65–74 in employment by administrative territories and full-time or part-time employment by Labour Force Survey in 2023

Full-time or part-time employed in the main job	*Administrative territory*		*Total*
	Urban area	*Rural area*	
Full-time	712	285	997
Part-time	254	78	332
No answer	1	2	3

Source: Authors' construction and calculations based on LFS in Latvia 2023 data.

Data indicate that in Latvia, in the age group 65–74, full-time employment in the main job is greater in urban areas. Always important are salaries and wages for all employees, and especially interesting is that for employed persons over 65 years, data are included in Table 8 (OSP, 2025c).

Table 8

Distribution of employees in Latvia in the age group 65 and more on salaries and wages in December 2024

Salaries and wages (EUR)	*65–69 years*		*70–74 years*		*75 years and more*	
	Number of employees	*Share of the number of employees with income, %*	*Number of employees*	*Share of the number of employees with income, %*	*Number of employees*	*Share of the number of employees with income, %*
TOTAL	39596	X	15804	X	7911	X
With income	37128	100.0	14596	100.0	7018	100.0
..less than 200.00	3123	8.4	2131	14.6	1776	25.3
..200.01-400.00	2931	7.9	1587	10.9	974	13.9
..400.01-700.00	5779	15.6	2706	18.5	1259	17.9
..700.01-1000.00	7091	19.1	2633	18.0	1070	15.2
..1000.01-1500.00	8096	21.8	2622	18.0	949	13.5
..1500.01-2000.00	4305	11.6	1260	8.6	430	6.1
..2000.01-2500.00	2261	6.1	633	4.3	227	3.2
..2500.01-3000.00	1257	3.4	366	2.5	117	1.7

Salaries and wages (EUR)	*65–69 years*		*70–74 years*		*75 years and more*	
	Number of employees	*Share of the number of employees with income, %*	*Number of employees*	*Share of the number of employees with income, %*	*Number of employees*	*Share of the number of employees with income, %*
..3000.01-4000.00	1168	3.1	330	2.3	106	1.5
..4000.01-5000.00	455	1.2	150	1.0	45	0.6
..5000.01-6000.00	236	0.6	60	0.4	17	0.2
..above 6000.00	426	1.1	118	0.8	48	0.7
With minimum wage or less	10660	28.7	5852	40.1	3761	53.6
With minimum wage	1430	3.9	510	3.5	199	2.8
Employees without income	2468	X	1208	X	893	X

Source: Authors' construction and calculations based on OSP database DSN030m data.

Data indicate that with minimum wage or less in December 2024 in Latvia there were 28.7% of employees with income in the age group 65-69 years; 40.1% of employees in the age group 70-74 years and among employees 75 years and older there were 53.6%. Data indicate also that with salaries 6000 euro and more there were 426 employed persons or 1.1% of employed persons with income in the age group 65-69 years; 118 employed persons or 0.8% of employed persons with income in the age group 70-74 years; 48 employed persons or 0.7% of employed persons with income in the age group 75 years and more. This indicates that persons of retirement age are economically active and earn solid salaries and wages.

Conclusions

1. The over-working-age employment in Latvia is not homogenous. It reveals employment tendencies of seniors by administrative territories, gender, education, and wages and salaries according to age groups. The potential of the silver economy needs to be studied together with territorial differences and senior living disparities.
2. In Latvia, there is a growing mean age and median age of the population, and it is growing the old-age dependency rate by 0.6 percent points every year since 2012.
3. The mean age and median age for females are greater than the one for males, and these numbers are growing annually. The old age dependency rate of the population in Latvia is much higher for females and is increasing annually. There are more women than men over the working age. Latvia has the largest gap in the EU.
4. In all statistical regions of Latvia, people employed representing the age group of 65–74 years are employed both in urban and rural areas. The 65–74 age group is mostly employed in urban areas. Latvia's outermost regions are facing an aging population and possible depopulation.
5. In Latvia, persons in the age group of 65–74 years are more employed with higher education and vocational education or professional secondary education, with a significantly higher rate in urban areas than in rural areas.
6. In Latvia, persons employed in the age group of 65 years and more receive rather high salaries and wages: even 6,000 euros and more indicates that persons at retirement age are economically active, earn solid salaries and wages as well as contribute to the economic development of Latvia.

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THE ROLE OF INCLUSIVE AND EXTRACTIVE INSTITUTIONS IN RURAL DEVELOPMENT

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Abstract
This article aims to explore the relationship between rural development and inclusive/extractive institutions, as defined by the 2024 Nobel Laureates in Economics. Drawing from the New Institutional Economics theory, we assert that institutions and their enforcement are crucial for rural socio-economic development. The research considers 27 European Union countries from 2015 to 2023 to explore the link between development variables – such as people at risk of poverty or social exclusion, severe material deprivation, individuals with income above specified national thresholds, population with tertiary education, high-income population, people having a long-standing illness or health problems and employment rate – and three Worldwide Governance Indicators (regulatory quality, rule of law, and control of corruption), serving as proxies for the institutions at the national level. Additionally, the study highlights similarities and differences between the two sub-groups, EU members before the 2004 enlargement and Central-Eastern European countries that joined the EU in 2004 and later, in terms of the correlation strength between institutional and rural development indicators. The panel data, derived from Eurostat and the World Bank, was examined employing Pearson correlation coefficients. The signs and strength of the correlations for the EU27 suggest that all institutions represented by chosen indicators were generally inclusive, as evidenced by their reinforcement of the rural development dimensions, except for their undesired positive association with the ill-health variable. The more robust correlations between institutional and development variables in post-communist countries compared to the EU14 suggest that institutional strengthening, especially combating corruption, in the former has a greater capacity to promote rural development.
Keywords: new institutional economics, rural development, European Union, worldwide governance indicators.

Introduction

Rural communities in the EU face several significant and specific challenges related to socio-economic development. Problems such as the risk of poverty and social exclusion, material deprivation, inadequate infrastructure, and limited employment opportunities are hurdles that successful development programs must address. National governments and EU bodies support rural development through financial assistance and various initiatives. While many development efforts in the EU are designed similarly, there are varying degrees of success across member states, with some advancements failing. To better understand the reasons behind these disparities, we propose focusing on the role of formal and informal institutions at the national level.

New institutional economics (NIE) has gained prominence in the rural development literature as it seeks to understand how institutions can effectively promote rural development (Meador & Skerratt, 2017). Despite the substantial progress accomplished in the domain of rural development in conjunction with the NIE theory, empirical research concerning the question of whether and how inclusive institutions at national and local levels contribute to rural development remains limited. The current study tries to fill this gap by empirically exploring the relationship between national institutions and rural development dimensions.

The nation's institutional framework involves allocating rights and duties between individuals and groups, and subsequent enforcement of these rights and responsibilities. These rights include the entitlement to assets, employment, wages, social protection, education, health, natural resources, adequate nutrition, access to clean energy, and preserving the natural environment. Additionally, the right to fair justice is recognized. The exercise of the above rights is governed by (1) formal institutions, such as economic rules and contracts, public law and order, regulations and court decisions; (2) self-enforcement by informal institutions, such as trust, confidence, reputation, social and business networks governed by tradition, religion, culture, ideology and ethical and moral norms (North, 1990, 2005).

Empirical development studies have identified the pivotal functions of institutions in establishing conditions conducive to economic growth and development, demonstrating the causative relationship between institutions and cross-country disparities in productivity, economic growth, and development (Acemoglu et al., 2005; Ibañez, 2015). Institutions have also been investigated as factors underlying rural economic and social development (Gardner, 2005; Kraybill & Weber, 1995; Martino, 2024). In this context, the institutions can be generally classified into two categories: inclusive institutions, which are thought to foster progress, and extractive institutions, which are believed to hinder it. The absence of constraints on politicians and bureaucratic elites imposed by political institutions is indicative of a weak institutional environment in a country. Additionally, this weakness is marked by ineffective property rights enforcement, pervasive corruption, and a considerable degree of political instability.

According to Daron Acemoglu and James Robinson, the cornerstone of economic prosperity is establishing inclusive economic institutions, which engender widespread incentives and opportunities within society. In contrast, extractive economic institutions lacking such characteristics have been shown to engender poverty. The variation in economic institutions observed across different regions or

societies is a consequence of the dissimilarity in their respective political institutions. Inclusive economic institutions emerge from political choices cultivated within an inclusive political framework, characterized by a strong state and wide distribution of power throughout society. Conversely, the absence of either of these conditions gives rise to extractive political institutions, which, in turn, engender extractive economic institutions (Acemoglu & Robinson, 2019).
As shown in the literature, many researchers argue that establishing sound institutions is crucial for the development of rural regions, including the reduction of inequalities and the alleviation of poverty.
To verify the existence of the 'institutions-development' nexus, the present study examines the correlation between national institutions and selected dimensions of rural development, utilizing a sample of developed countries represented by the entire population (twenty-seven) of the European Union's member states, thereby ensuring a comprehensive and representative dataset for analysis.

Materials and Methods

As the variables representing institutions, we exploit the Worldwide Governance Indicators, WGI (Kaufmann et al., 2011), obtained from the World Bank's database (World Bank, 2024). The study considers three out of the six WGI's dimensions: regulatory quality (RQ), rule of law (RL), and control of corruption (CC). This choice was based on two main reasons: first, these dimensions effectively reflect the characteristics of inclusive versus extractive institutions within the context of EU countries; second, they provide a sufficiently comprehensive picture of these institutions. WGI scores range from -2.5 to +2.5, with higher ones implying better institutional performance.
Regulatory quality is a multifaceted concept comprising various elements, such as price controls, discriminatory tariffs or taxes, the intensity of market competition, and consumer protection. It also encompasses the government regulatory burdens, the ease of starting a business, the effectiveness of antitrust policies, investment and financial freedoms, and the stringency of legislation and policy. The rule of law includes such formal institutions as the enforceability of contracts and property rights, private property, the security of goods and persons, and the fairness and speediness of the judicial process. The control of corruption measure looks at how corrupt public officials are, how much trust the public has in politicians, whether public funds are misused or any irregular payments are made (for example, in public utilities, tax collection, public contracts, and the legal system), corruption between different government administrations and local businesses or foreign companies. The institutions proxied by the selected indices, when inclusive, are vital for fostering socio-economic development. Conversely, if these institutions are extractive, they are believed to hinder progress. For example, compliance with a legal framework and ongoing efforts to combat corruption can play a key role in eradicating poverty and social inequalities within rural society.
The selected variables describing rural development, derived from the Eurostat database (Eurostat, 2024a), generally reflect the European pillar of social rights indicators. They comprise income and living conditions indicators, such as people-at-risk-of-poverty and social exclusion (AROPE), severe material deprivation (SMD), share of people with an income above or equal to specific national thresholds (130% of median income or more); educational attainment of the rural population measured as the percentage of the population (aged 15-64) with a tertiary qualification; employment rate and health conditions (people with a longstanding illness or health problem (% of people aged 16 or over).
AROPE is defined as the sum of persons who are either at risk of poverty or severely materially and socially deprived, or living in a household with a very low work intensity. The threshold at which individuals are regarded to be threatened by poverty is set at 60% of the national median equivalised disposable income, counting social transfers. It is important to note that individuals are included in the category only once, even in cases where they may be experiencing multiple situations. The AROPE rate is calculated as the proportion of the total population. In the EU, it serves as the primary metric for evaluating the EU 2030 target concerning poverty and social exclusion.
SMD indicates a severe lack of necessary and desirable items to live a decent or dignified life. The indicator differentiates between individuals who cannot afford specific goods, services, or social activities. It is defined as the percentage of the population experiencing an enforced lack of at least 7 out of 13 deprivation items, including the capacity to face unexpected expenses, afford a week-long annual holiday away from home, face payment arrears (such as mortgage or rent payments, utility bills, and loan payments), the ability to maintain a comfortably warm house, and access to a car or van for personal use.
The study encompasses the set of twenty-seven member states of the European Union (EU27) from 2015 to 2023. Additionally, two subgroups were distinguished: EU14, which consists of the 'old' members (before the 2004 enlargement, excluding the United Kingdom), and EU-CEE, which comprises eleven countries from Central and Eastern Europe.
We assess the statistical reliability of the relationships between institutional and rural development variables by Pearson correlation analysis, thereby ensuring the robustness of the results.
The complete panel data set under consideration consists of 243 observations ($N = 9 \times 27 = 243$). Where Eurostat data were incomplete, the number of observations in the panels decreased due to missing values, for either the country or the year. Statistical analyses were conducted utilizing Statistica version 13 software.

Results and Discussion

The analysis of the performance of EU countries from 2015 to 2023 regarding domestic regulatory quality reveals that, as anticipated, the WGI RQ scores were predominantly higher in the older member states – except for Greece, Portugal, and Spain – compared to the countries in Central and Eastern Europe. Within the CEE group, the Nordic-Baltic trio of Estonia, Lithuania, and Latvia consistently dominated in the RQ rankings, with the Czech Republic ranking closely behind. The Nordic countries (Sweden, Finland, and Denmark) were also among the old EU's leading RQ performers. A parallel tendency was for institutional performance, evidenced by the rule of law. This phenomenon is probably attributable to the high correlation between this variable and regulatory quality. Finland, Denmark, and Sweden achieved the highest RL scores, while two countries in southeast Europe – Bulgaria and Romania – had the lowest scores, showing no noticeable progress. Among the EU14, Greece was found to have the poorest RL.

Between 2015 and 2023, Denmark, Finland, Sweden, and the Netherlands emerged as the leading EU27 countries in anti-corruption efforts. Conversely, Bulgaria, Romania, and Hungary displayed a less effective approach to combating corruption. The EU's older member states, known collectively as the EU14, demonstrated a higher level of performance in this area than the CEE countries.

Some scholars suggest that post-communist countries exhibit considerable 'institutional asymmetry' between formal and informal institutions. While formal regulations have substantially improved, informal norms, such as culture and values, have developed considerably more slowly (Todorov, 2023; Williams & Vorley, 2015). We hypothesize, however, that the core of the institutional dilemma lies in the challenge of conceptualizing informal institutions.

When considering rural development aspects, it is essential to underline that the EU social model is based on supporting the most vulnerable members of society. Although variations persist among countries, EU nations implement social protection to safeguard individuals against various challenges. These challenges include the costs of raising a family or securing housing, threats associated with unemployment, sub-optimal health, poverty, and social exclusion. Nevertheless, in 2023, it was estimated that 94.6 million people, representing 21.4% of the EU's population, lived at risk of poverty or social exclusion, and 29.2 million (6.8%) faced severe material and social deprivation (European Commission, 2024; Eurostat, 2024b).

Our analysis of EU countries has revealed that, during 2015-2023, Romania and Bulgaria experienced the highest risk of poverty or social exclusion among their rural populations, with rates reaching approximately 60% at the inception and about 40% at the end of the period under consideration. In the EU14, the highest concentrations of individuals threatened with poverty or social exclusion were in rural areas of predominantly southern EU countries – Greece, Spain, and Portugal. However, these rates were almost half those observed in the most disadvantaged CEE countries. The lowest AROPE rates, by country sub-groups, were found in Czechia, Slovenia, and Slovakia (CEE region) alongside the Netherlands and Austria (EU14).

The prevalence of severe material and social deprivation in rural areas also varied considerably across the EU countries. During the 2015-2023 period, Romania and Bulgaria demonstrated the highest SMSD rates. Despite a downward trend, in 2023, approximately one in five Romani and Bulgarian rural inhabitants experienced severe deprivation. In contrast, SMSD rates were frequently below 2% in the Netherlands, Luxembourg, Austria, Malta, Sweden, and Finland. However, Greece, which led the old EU countries with the highest rate, had this at 15-20%. Among the EU members of the CEE region, Slovenia, Estonia, and the Czech Republic were the best performers. In summary, the most pronounced levels of severe material and social deprivation have been recorded in rural regions of the South Eastern EU.

The researchers acknowledge the pivotal role of income distribution in societal advancement because it substantially influences various dimensions of social cohesion, the prevalence of poverty, human capital formation, and the effectiveness with which economic growth mitigates poverty. Moreover, it exerts an indirect influence on the education and health status of the population. The extant literature suggests that a more equitable income distribution is desirable and conducive to promoting growth and development (Acemoglu & Robinson, 2002; Kuźmar, 2023; Stewart, 2003).

The subsequent developmental metric examined in this study pertains to the national high-income thresholds, which denote the proportion of the rural population whose incomes surpass or equal specific national thresholds. Over the nine years observed, Luxembourg had the highest percentage of its rural population whose income was 130% of the median income, or larger. The proportion of rural Luxembourgers whose income was at this level ranged between 30 and 33%, depending on the year. Austria and Germany, from the EU14, along with Estonia, Latvia, and Lithuania, from CEE, topped the EU countries with high-income rural residents. In the CEE region, with Bulgaria and Romania as notable examples, this proportion was nearly half of the highest recorded in the EU27. A similar finding was also noted in Poland.

The study also considers rural educational attainment, which, as demonstrated in the extant literature, exerts a considerable impact on the labour market, individual citizens, and society. In general, higher education levels are associated with higher employment rates, foster innovation, greater productivity, superior lifetime earnings, reduced poverty rates, and enhanced life satisfaction (Janka et al., 2021; Kampelmann et al.,

2018; Krpan et al., 2024). In 2023, 22.6% of the rural population aged 15 to 64 years in the EU27 had a tertiary education level, which includes education provided by universities and other higher education institutions. However, from 2015 to 2023, the distribution of high educational attainment levels varied across EU rural areas. Ireland, Luxembourg, and Belgium have recorded the highest proportions of rural residents with tertiary education, approximately 40% in recent years, whereas Romania (about 5%) and Bulgaria (about 9%) have been found to have the lowest percentages. In the context of CEE rural populations, the highest rates were predominantly attained by Lithuania, Estonia, Slovenia, and Latvia (25-30% in 2023).

Another essential aspect is the long-term health status of the rural population, as it can impact their families, work, finances, and well-being. The health conditions and patterns of illness and injury in rural territories are affected by several factors. First, rural areas generally experience higher rates of preventable deaths compared to urban areas. Second, work-related injuries in rural settings are more likely to be severe. Third, access to health protection and care services in rural communities is often inadequate, as numerous studies demonstrate (Hassler & Ceccato, 2021; Russell et al., 2013; Strasser, 2003; Wong Shee et al., 2024). Concerning the issue of health inequalities between EU rural areas, Eurostat estimates derived from the EU-SILC show that in 2023, more than half of the rural population in Finland reported long-standing illness or health problems, compared with only 16% in Italy. Other EU14 countries with high proportions (over 40%) of such persons include Portugal, Germany, Sweden, and France. In the CEE, Estonia, Latvia, and Lithuania reported the worst health status for rural people (over 40%, in 2023), in contrast to Romania and Bulgaria (under 30%).

Among the EU countries for which Eurostat data on the rural employment rate (% of the people aged 15-64) were available, Slovenia, Czechia, Sweden, the Netherlands, and Ireland had the highest rates, exceeding 83%, in contrast to Greece (EU14) with only 54% and Croatia (CEE) with 61% of working age rural population employed in 2023. It is important to note that a paucity of connectivity, inadequate infrastructure, a lack of diversified job opportunities, poverty leading to the outflow of rural youth, the aging problem, and limited access to services and resources all have the potential to combine and render rural areas in some EU countries less appealing as places of employment (Grodzicki & Jankiewicz, 2022; Marino & Tebala, 2022).

Since our approach to rural development emphasizes the role of national institutions, the next research stage identifies the interrelationships between selected institutional and developmental variables. We point out that correlation analysis does not establish cause-and-effect relations between time series – causation requires correlation, but correlation does not imply causation. The role of institutions in development is multifaceted; however, it is essential to recognize the reciprocal relationship between development and institutions, where development can also shape the nature of institutions. In other words, the causality can run from development to institutions (Chang, 2011).

The correlation coefficients for the EU27, depicted in Table 1, suggest that institutions, proxied by regulatory quality, rule of law, and control of corruption indicators, generally had an inclusive character, as evidenced by their enhancement of rural development dimensions. All tested correlations between development and institutions are statistically significant. From 2015 through 2023, higher regulatory quality, rule of law, and efforts to combat corruption were strongly associated with lower proportions of rural populations at risk of poverty or social exclusion and experiencing severe material deprivation. We also found a strong to moderate direct relationship between these institutions and the percentage of rural residents with tertiary education. Additionally, there was a similar correlation of RL and RQ with the share of individuals earning at least 130% of the median income, as well as the employment rate in rural areas. A weak yet positive correlation was identified between CC and income and employment variables. Public corruption, i.e., the abuse of public office for personal gain, is a widespread problem that often exacerbates poverty-related conditions such as low income, poor health, and inadequate education.

Chronic poverty, which affects numerous countries, engenders an environment conducive to systemic corruption due to social and income inequalities in addition to negative economic incentives. Much empirical evidence (Zang et al., 2023; Crombach & Smits, 2024) shows a strong negative correlation between corruption and socio-economic outcomes, including poverty, substandard education, and health. A puzzle arises from the unexpected positive (moderate or weak) link between the institutional variables and the rural people experiencing long-standing illness or health problems. The findings of earlier cross-country research (Knowles & Owen, 2010) indicate that, for the majority of countries, enhancements in informal institutions seem to exert a more substantial positive influence on health status in comparison to improvements in formal institutions. Moreover, the benefits derived from improving informal institutions are most extensive for countries that exhibit the weakest institutions. The WGI dimensions used in our study are indicative of mainly formal institutions.

To account for the potential heterogeneity between countries that differ in the length of their EU membership and political legacies, the potential impact of domestic institutions on rural development was examined for two sub-groups of countries. The correlation analysis carried out separately for the EU14 and the EU-CEE states, incorporating institutional and development variables, over the

period 2015-2023, yields highly plausible results (Table 2). The correlation signs for all variable pairs demonstrate consistency across both sub-groups. However, the strength of association and the level of statistical significance vary between them.

Table 1

Pearson correlation coefficients between countries' institutional and rural development metrics for the EU27, 2015-2023

Variables	*N*	*RQ*	*RL*	*CC*
RQ	243	1.00	0.92	0.62
AROPE	239	-0.58	-0.67	-0.50
SMD	239	-0.63	-0.72	-0.54
INCOME	239	0.39	0.37	0.28
EDU	239	0.68	0.69	0.52
HEALTH	235	0.32	0.37	0.21
EMPL	166	0.52	0.52	0.20

Notes: N—number of observations; RQ—regulatory quality; RL—rule of law; CC—control of corruption; AROPE—persons at risk of poverty or social exclusion; SMD—severe material deprivation rate; INCOME—share of people having income greater or equal to specific national thresholds; EDU—share of people with tertiary education attainment; HEALTH—share of people having a long-standing illness or health problem; EMPL—rural employment rate. All Pearson correlation coefficients are statistically significant at the 0.01 level ($p < 0.01$), except for EMPL/CC, which is significant at the 0.05 level ($p < 0.05$).
Source: authors' research.

Table 2

Pearson correlation coefficients between countries' institutional and rural development metrics for the EU14 and CEE countries, 2015-2023

Variables	*EU14 (N=124)*			*EU-CEE (N=98)*[1]		
	RQ	*RL*	*CC*	*RQ*	*RL*	*CC*
RQ	1.00	0.93***	0.36***	1.00	0.82***	0.68***
AROPE	-0.76***	-0.80***	-0.38***	-0.38***	-0.59***	-0.45***
SMD	-0.74***	-0.77***	-0.20**	-0.50***	-0.70***	-0.63***
INCOME	0.23***	0.13	0.09	0.64***	0.67***	0.36***
EDU	0.61***	0.58***	0.24***	0.69***	0.79***	0.67***
HEALTH	0.28***	0.46***	0.17*	0.67***	0.67***	0.56***
EMPL	0.72***	0.76***	0.38***	0.47***	0.39***	0.10

Notes: EU14—the old EU member states (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, and Sweden); EU-CEE—the EU member states from the Central and Eastern Europe (Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, and Slovenia); other abbreviations as in Table 1; [1]—for EMPL variable N=30; *** p-value < 0.01; ** p-value < 0.05; * p-value < 0.1.
Source: authors' research.

In the old EU member states, control of corruption was the least or not statistically significantly correlated with all development-related variables. In contrast, in the post-communist countries of the EU, an inverse, ranging from strong to moderate, association between the CC and the risk of poverty or social exclusion, as well as the severe material deprivation rate, existed. Additionally, in these countries, the CC was strongly positively correlated with health and education variables.

In the EU14, as opposed to the CEE region, a stronger correlation was present between RL and RQ on the one hand, and AROPE, SMD, and rural employment rates on the other hand. In contrast, correlations between RL and RQ, on the one hand, and education, income, and health variables, on the other hand, were found to be weaker than those observed in the new member states. A small and statistically insignificant correlation coefficient was found between income and the rule of law in the EU-14 (as opposed to the EU-CEE). This suggests, among other things, that factors like improving judicial fairness and efficiency, reinforcing contracts and property rights, safeguarding private property, and enhancing safety measures for goods and persons are of negligible importance for income distribution in the older member states.

As discussed earlier in the paper, between 2015 and 2023, the older member states of the EU demonstrated better institutional performance compared to those from Central and Eastern Europe. As a result, marginal improvements in the institutions of these two groups are likely to yield different degrees of impacts on the development indicators.

Conclusions

1. Current research supports the prevailing consensus among institutional economists that stronger institutions are linked to better development outcomes and vice versa. The findings for the group of 27 EU countries from 2015 to 2023 indicate an interconnectedness between rural development and national-level institutions, embodied in regulatory quality, the rule of law, and control of corruption. The relationship nature is further substantiated by small differences in the degree, though not the direction, of the observed correlations between the EU14 and CEE countries.
2. The correlation signs and strengths for the entire EU and the two country subgroups reveal that institutions proxied by the Worldwide Governance Indicators – rule of law, regulatory quality, and control of corruption demonstrated an inclusive character. Their improvement was concomitant with positive rural development outcomes, including an increase in tertiary education, a lower risk of poverty and social exclusion, a reduction in severe material deprivation, and higher employment ratios.
3. An exception to the inclusivity exhibited by institutions, proven by their direct association with the subjective health status (long-standing illness or health problem) reported by rural individuals, suggests that domestic institutions in the EU may possess an extractive nature. This unanticipated finding requires further examination.
4. Several higher and more statistically significant correlations between development indicators and institutional proxies in the CEE countries suggest that institutional improvements, especially anti-corruption measures, may have a greater capacity to promote rural development in new member states than in the old ones.
5. Strengthening formal institutions would be most beneficial for countries with lower institutional ratings and less developed rural areas, such as those located in the CEE region, especially Bulgaria and Romania.
6. As this paper focuses primarily on national-level formal institutions, future studies could explore the role of local and informal institutions in shaping rural development. Additionally, rather than relying on aggregated indices of national institutional quality, future researchers might consider using narrower indicators (such as scores for regulatory burden, contract enforceability, conditions for the development of rural financial services, investment climate for rural businesses, access to agricultural input and product markets) to conduct a more in-depth analysis.
7. A potential shortcoming of the present study is the assumption of linear relationships between institutional and developmental variables. We suggest that future researchers employ more sophisticated methods.

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ECONOMIC ASSESSMENT OF BEEF CATTLE GENOMIC SELECTION: A LITERATURE REVIEW

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Abstract
The beef cattle genome provides a vital foundation for exploring genetic variations that affect key traits, including growth, reproduction and disease resistance. Recent progress in genomic research has facilitated more accurate breeding approaches, promoting greater efficiency within beef production systems. The economic assessment of genome in beef cattle breeding has emerged as a pivotal area of research, offering pathways to enhance productivity, sustainability and profitability in the livestock industry. The study aims to consolidate current research on the economic implications of genomic selection. The research employs the descriptive and analysis-synthesis methods. Genomic selection has proven economically viable, reducing generation intervals, improving selection accuracy and identifying genetic markers linked to desirable traits. While the long-term economic benefits - such as enhanced feed efficiency, improved carcass quality and reduced environmental impacts - are well-documented, barriers like high initial investment costs, regional variability in production systems and the need for specialised data infrastructures remain significant challenges. Ethical considerations, evolving regulatory frameworks and the demand for traceable, high-quality beef further influence the adoption and implementation of genomic selection. This review underscores the need for targeted policy interventions, financial incentives and industry-wide collaboration to maximise the economic potential of genomic technologies in beef cattle breeding. Despite its potential, the high initial costs of genomic technologies and the need for robust data infrastructures remain significant challenges.
Keywords: beef cattle, genome, economic trait, genomic selection, profitability.

Introduction

The beef cattle industry plays a crucial role in meeting the global demand for high-quality protein while addressing sustainability and economic efficiency challenges. The application of genomic technologies has emerged as a transformative approach in breeding programmes, providing tools to enhance traits critical for economic and environmental outcomes (Boaitey et al., 2019; Gao et al., 2024). Genomic selection (GS), a technique that uses dense genetic markers across the genome, has shown the potential to improve selection accuracy and reduce generation intervals. For example, genomic selection has successfully accelerated genetic progress in traits such as feed efficiency, meat quality, and disease resistance (Gao et al., 2024; Romero et al., 2024). Holman & Hopkins (2021) state that by enabling early selection of breeding candidates based on genomic data, GS reduces costs and increases the reliability of breeding value predictions. Key economically significant traits of beef cattle include carcass weight, longissimus muscle area, backfat thickness, and marbling score. Park et al. (2013) emphasise that genomic determination would be a valuable tool in identifying relevant genetic markers for economically important traits in beef cattle. According to Holman and Hopkins, by enabling early selection of breeding candidates based on genomic data, GS reduces costs and increases the reliability of breeding value predictions. Key genome sequencing and assembly advancements have expanded genomics' utility in the industry. High-throughput sequencing technologies have enabled the identification of genes linked to economically significant traits, such as marbling, tenderness and environmental adaptability. As discussed in recent studies, the pan-genome approach provides insights into structural variations and rare alleles; thereby, enriching the understanding of genetic diversity. Consumer research indicates that European customers are willing to pay a premium for guaranteed eating quality, provided such assurance schemes are transparent and independently verified (Gao et al., 2024; Farmer & Farrel, 2018).

Consumer satisfaction is a key determinant of economic viability in the food production industry, particularly in the beef sector, where quality and consistency significantly influence purchasing behaviour, according to Hocquette et al. (2014). Despite considerable efforts to standardise and enhance beef quality, variability remains a persistent challenge, contributing to consumer dissatisfaction and, in some cases, a decline in demand. Strengthening consumer confidence through grading systems, traceability, and quality assurance schemes has yielded economic benefits by fostering customer loyalty and willingness to pay premium prices. Furthermore, integrating economic efficiency with environmental sustainability and animal welfare - through optimised feeding regimes, reduced pre-slaughter stress, and the application of genetic markers - can result in mutually beneficial outcomes for both producers and consumers. These strategies enhance meat palatability and nutritional value and improve market positioning by addressing contemporary health, safety, and sustainability concerns. As economic pressures and societal expectations continue to evolve, aligning production practices with consumer preferences remains critical for ensuring the long-term resilience and competitiveness of the industry.

The economic sustainability of beef enterprises has to be shaped by both geographical constraints and market dynamics, requiring producers to make strategic decisions that balance profitability with risk management. Following Bowen & Chudlegh (2021),

each region has significant climatic variability, including unpredictable rainfall patterns, prolonged droughts, and extreme weather events, impacting pasture availability, herd productivity, and overall economic returns. In addition, the remoteness of many beef enterprises leads to high transport costs, limited market access, and increased operational expenses, further influencing financial viability. Economic frameworks incorporating farm-level modelling and discounted cash-flow analysis are essential in evaluating alternative management strategies, allowing producers to assess the long-term profitability, financial risks, and capital investment requirements associated with various interventions. Moreover, the ongoing disconnect between asset values and returns, alongside fluctuating commodity prices, necessitates a careful economic assessment of strategies such as herd restructuring, genetic improvements, and market diversification. By integrating economic principles with an understanding of geographical challenges, producers can enhance decision-making processes and improve the resilience of their enterprises against external shocks.

Some researchers emphasise that crossbreeding has long been utilised in the beef cattle industry to leverage heterosis for improved growth, reproductive traits, and economic efficiency. Hay & Roberts (2023) suggest that heterosis arises from non-additive genetic interactions often excluded in genetic evaluations. Advances in genomic technologies, including single nucleotide polymorphism (SNP) genotyping, allow detailed exploration of heterosis to quantify the effects of genomic heterozygosity on growth traits and identify genomic regions linked to dominance, ultimately contributing to economically beneficial crossbreeding practices. According to Popp et al. (2020), the economic performance of cow-calf operations is significantly influenced by genetic selection, forage management, and breed adaptability to environmental conditions. In regions where forage variability and climatic constraints challenge cattle production, optimising breeding strategies becomes essential for improving profitability and sustainability. The integration of genetic marker analysis in breeding decisions has been explored to enhance reproductive efficiency, growth rates and overall herd performance. However, the extent to which genetic markers contribute to economic returns remains controversial, particularly in environments characterised by fescue toxicosis and other forage-related stress factors. Economic modelling frameworks enable producers to evaluate the financial viability of different breeding and management strategies by considering factors such as breeding failure rates, weaning weights, and pasture quality. Insights into the role of genetic selection in optimising economic sustainability within the cow-calf sector are obtained by examining the interplay between genetic information, environmental conditions and financial outcomes.

The study aims to consolidate current research on the economic implications of genomic selection. To address the research aim, the study advances the following tasks: 1) to study the economic benefits of genomic selection, such as profitability and market competitiveness; 2) to review economic challenges in adoption and sustainability; 3) to state the role of emerging technologies.

The economic performance of the beef industry is increasingly linked to the quality of meat, which directly influences consumer preferences, pricing structures, and overall market demand. Given that beef tenderness, juiciness, and flavour play a crucial role in optimising meat quality through emerging technologies, nutritional interventions and management strategies have become a priority for producers. However, environmental variability, breed-specific genetic limitations, and the financial implications of dietary modifications challenge achieving economically viable quality levels. Advanced genomic selection, precision feeding strategies, and microbiome manipulation are key methods to improve quality while maintaining cost efficiency, according to Abebe et al. (2024). Moreover, implementing sustainable production systems that balance profitability with consumer expectations and regulatory frameworks is critical for ensuring long-term sector growth. By integrating economic principles with scientific advancements, the beef industry can enhance product quality, meet evolving market demands, and strengthen its competitive position in global trade.

Materials and Methods

The current study consolidates existing research, particularly on the economic assessment of the beef cattle genome, exploring genomic applications in areas such as meat quality selection, feed efficiency and disease resistance. The research employs descriptive and analysis-synthesis methods. Science Direct, Scopus and Ebsco databases were used to search for full-text articles in the English language published between 2013 and 2024. The following keywords and their combinations were used to narrow the search: beef cattle, economic effect, economic trait, genome, genomic selection, and genetic markers.

Results and Discussion

Economic Implications of Genomic Selection in Beef Production

Using genomic selection in beef cattle breeding and production offers substantial economic benefits, notably by improving breeding and production efficiency, enhancing production traits and meat quality, lowering costs and boosting overall profitability. By enabling precise identification of desirable traits such as feed efficiency, carcass quality, reproductive performance and disease resistance, genomic selection allows producers to optimise herd management strategies. Feed efficiency, in particular, is a key economic determinant, as feed costs represent one of the most significant expenses in beef

production. Boaitey et al. (2019) indicate that studies have shown that genomic selection for improved feed conversion ratios can significantly lower feed intake per kilogram of weight gain, reducing overall production costs while maintaining or improving output levels. Beyond direct cost savings, genomic selection facilitates accelerated genetic progress, leading to cumulative economic benefits over successive generations. Unlike traditional selection methods, which rely on phenotypic evaluation and require multiple breeding cycles to achieve genetic improvements, genomic selection allows for earlier and more accurate identification of superior animals. This enables producers to make informed breeding decisions that enhance herd productivity and profitability (Gao et al., 2024). Furthermore, improvements in disease resistance through genomic selection reduce veterinary expenses and mortality rates, further contributing to cost efficiency. Following Ibtisham et al. (2017) observations, traditional breeding methods have relied heavily on phenotypic selection, which requires multiple generations to achieve noticeable improvements. Contrastingly, Mohammaddiyeh et al. (2023) conclude that genomic selection allows producers to make earlier and more precise breeding decisions, reducing production costs and accelerating genetic progress. Gutierrez-Reinoso et al. (2021) indicate that one of the most economically significant applications of genomic selection is feed efficiency improvement, a major determinant of profitability in beef operations. Selecting animals with superior residual feed intake traits enables lower feed consumption while maintaining growth performance, leading to substantial cost savings. Besides, genomic selection for disease resistance lowers veterinary expenses, reduces mortality rates, and improves overall herd health, enhancing financial returns, acknowledge Mohammaddiyeh et al. (2023). Consumer acceptance of beef, assert Holman & Hopkins (2021), is primarily determined by its sensory attributes, including tenderness, flavour, juiciness and overall palatability. Consequently, identifying and selecting genetic markers associated with these traits, highlighted by Romero et al. (2024), allows for a more precise and economically efficient approach to meat production. Genomic selection enables breeders to enhance desirable characteristics such as intramuscular fat composition, a critical determinant of meat quality and consumer preference. By improving the predictability of meat traits, genomic selection reduces production costs associated with prolonged feeding times and inefficient resource allocation. Furthermore, Abebe et al. (2024) indicate that intramuscular fat levels significantly impact carcass valuation in premium beef markets, where marbling is decisive in pricing, while Romero et al. (2024) acknowledge that the ability to select optimal intramuscular fat levels through genomic testing allows producers to enhance carcass quality without excessive feed costs. This economic benefit is particularly relevant in countries where consumers are willing to pay a premium for high-quality beef and have established grading systems based on intramuscular fat content. Farmer & Farrell (2018) observe that consumer preference for high-quality meat is well documented, with studies indicating a willingness to pay premium prices for products that meet stringent quality criteria. Genomic selection enables producers to align beef quality with consumer expectations, particularly regarding flavour, texture, and juiciness, key determinants of purchasing decisions. Incorporating genomic data into quality assurance schemes has demonstrated tangible financial benefits, with price premiums generated for verified high-quality beef.

Enhancing Profitability Through Genomic Selection for Growth and Reproductive Traits

From an economic perspective, genomic selection accelerates genetic improvement, leading to higher-quality carcasses in fewer generations. This reduces the cost of prolonged feeding and management, state Holman & Hopkins (2021), while increasing revenue through improved carcass grading and consumer satisfaction. Furthermore, Romero et al. (2024) identify that studies indicate that integrating genomic selection with conventional breeding methods significantly improves the accuracy of predicting meat quality traits, thereby reducing the economic risks associated with inefficient selection. Integrating genomic selection into breeding programmes enhances overall herd profitability by improving production efficiency and product quality. One of the primary advantages is improved reproductive efficiency, which is critical for economic viability in cow-calf operations. According to Gao et al. (2024), shorter calving intervals, higher fertility rates and increased calf crop percentages lead to more significant revenue potential while reducing input costs per output unit. Furthermore, genomic selection aligns production outputs with market demands by selecting genetic traits linked to superior carcass attributes, such as increased marbling and tenderness. Genomic selection improves growth performance, reproductive efficiency, and carcass traits, directly influencing economic sustainability. Studies on heterosis in crossbred populations conclude Hay & Roberts (2023) have demonstrated that selecting for genetic dominance effects can result in increased growth rates and higher carcass yields, leading to improved market value. Genomic analyses have identified SNPs associated with birth weight, weaning weight, and yearling weight, enabling targeted selection for superior growth traits and reducing variability in production outcomes. Enhancing reproductive performance through genomic selection is particularly beneficial in cow-calf operations, where fertility rates and calving intervals significantly affect profitability. By identifying genetic markers linked to higher fertility, reduced embryonic loss and improved calving ease, following Bowen & Chudleigh (2021), genomic

selection helps producers optimise reproductive efficiency, ensuring consistent calf crops and higher revenue potential.

Economic Sustainability and Risk Management in Genomic Selection Adoption

Genomic selection also plays a crucial role in improving environmental sustainability, which has financial implications. Moreover, genomic selection is critical in environmental sustainability, which is increasingly linked to economic outcomes, suggest Hocquette et al. (2014), indicating that selecting cattle with higher feed conversion efficiency reduces feed costs and lowers methane emissions per kilogram of beef produced, aligning with evolving regulatory requirements and consumer-driven sustainability standards. Such improvements position genomic selection as a dual-benefit approach, enhancing profitability and environmental responsibility. Selecting for feed efficiency reduces input costs and minimises methane emissions per kilogram of beef produced. Following Gerber et al. (2013), methane emissions from enteric fermentation significantly contribute to agriculture-related greenhouse gas emissions, accounting for approximately 39% of total livestock emissions. By improving feed conversion efficiency, genomic selection contributes to lower environmental impact per production unit while supporting compliance with evolving sustainability standards. In jurisdictions where carbon offset schemes are implemented, state Boaitey et al. (2019), producers participating in genomic selection programmes can benefit from additional revenue streams through carbon credit trading. However, the extent to which these incentives drive adoption varies across regions due to differences in agroecological conditions and market structures. For carbon offset schemes to be effective, policy frameworks must account for spatial heterogeneity in breeding conditions and production systems.

Despite its clear advantages, adopting genomic selection presents particular challenges, primarily related to initial investment costs and knowledge barriers; thus, Mohammaddiyeh et al. (2023) conclude that genomic testing requires infrastructure and expertise in data analysis and breeding programme integration, which may be financially burdensome for small and medium-sized producers. However, Bowen & Chudleigh (2021) argue that economic modelling suggests that the long-term financial benefits, notably improved feed efficiency and higher carcass value, outweigh these initial costs. Another economic challenge is the integration of genomic selection into existing breeding programmes. While SNP-based selection significantly enhances the accuracy of trait prediction, the implementation process requires specialised knowledge and infrastructure, which may not be readily available in all production regions, as Romero et al. (2024) stated. In addition, Abebe et al. (2024) emphasise that genomic selection alone cannot guarantee economic success unless combined with optimal feeding regimes and stress-minimising management strategies. Genomic testing requires an initial investment in laboratory analysis and data interpretation, according to Romero et al. (2024), which may be a barrier for small and medium-sized beef enterprises. Furthermore, Holman & Hopkins (2021) state that environmental conditions influence the effectiveness of genomic selection, as intramuscular fat deposition is also affected by factors such as grazing strategies, feed composition, and climatic variability.

Market Competitiveness and Consumer Demand for Genomically Selected Beef

Genomic selection enhances market competitiveness by enabling beef production to meet regulatory and consumer-driven quality standards. Farmer & Farrel (2018) indicate that the European and North American beef industries face increasing consumer scrutiny regarding food safety, sustainability and traceability. Genomic selection supports traceability initiatives by providing genetic insights that link production practices to specific quality attributes. This, in turn, strengthens brand differentiation and allows producers to target niche markets where consumers prioritise ethically sourced, high-quality beef. Furthermore, genomic selection aligns with the growing emphasis on precision agriculture, wherein data-driven approaches optimise resource use and economic returns. By integrating genomic insights with farm management technologies, producers can implement breeding programmes that maximise efficiency while responding to shifting market demands. The ability to produce consistently high-quality beef enhances consumer trust and fosters brand loyalty, leading to long-term economic sustainability. Hocquette et al. (2014) emphasise that the economic benefits of genomic selection extend beyond production efficiency to market competitiveness and consumer demand. The beef industry increasingly integrates genomic technologies into quality assurance programmes using genetic insights to predict and ensure meat quality. Gutierrez-Reinoso et al. (2021) identify that incorporating genomic selection in these programmes strengthens brand differentiation, enhances consumer trust and secures higher price premiums for beef products that meet traceability and sustainability criteria. Moreover, genomic selection supports traceability and certification schemes, which are becoming critical in both domestic and export markets. Ibtisham et al. (2017) conclude that verifying genetic lineage, production history, and meat quality through genomic data gives producers a competitive advantage, particularly in premium markets where food safety, sustainability, and animal welfare concerns shape consumer purchasing decisions.

Economic Challenges and Adoption Considerations

Despite the clear economic benefits of genomic selection, several barriers to adoption persist. The initial investment in genomic testing and data analysis infrastructure can be substantial, particularly for small

and medium-sized enterprises. Moreover, the benefits of genomic selection are not always immediately realised, as genetic improvements often require multiple breeding cycles before they translate into measurable economic gains. In addition, regional variations in production systems can influence the effectiveness of genomic selection strategies. An animal's genetic potential may not always be fully expressed in extensive grazing systems, where environmental factors such as forage availability and climate variability dominate. This underscores the importance of integrating genomic selection with adaptive management strategies that account for environmental constraints, according to Boaitey et al. (2019). Targeted policy interventions, financial incentives and producer education programmes are needed to facilitate broader adoption. Government subsidies for genomic testing, cost-sharing initiatives and knowledge transfer programmes can help mitigate adoption barriers and ensure that genomic selection technologies are accessible to a broader range of producers.

Role of Emerging Technologies in Beef Market Competitiveness

The global beef industry is increasingly adopting emerging technologies such as genomic selection, transcriptomics, metabolomics, and microbiome manipulation to enhance meat quality and economic sustainability, following Abebe et al. (2024). Genomic selection enables targeted breeding for enhanced intramuscular fat composition, reducing variability in meat quality and improving consistency across production systems. Furthermore, integrating microbiome profiling and metabolomic analysis has provided more profound insights into how microbial populations in the digestive system influence fat deposition and muscle development. Economic benefits arise from the ability to optimise nutritional strategies based on genetic predispositions. For example, nutritional interventions such as high-energy diets, omega-3 fatty acid supplementation and precision feeding techniques have enhanced intramuscular fat deposition, increasing meat quality scores and market value, conclude Abebe et al. (2024), stating that hormonal and dietary management strategies, including castration timing and early weaning protocols, have been identified as practical tools for optimising intramuscular fat composition, further reinforcing the economic rationale for precision management.

Genomic selection and emerging technologies represent transformative advancements in beef production, offering substantial economic benefits through improved meat quality, enhanced feed efficiency and increased market competitiveness. Genomic technologies enable precise selection for traits such as intramuscular fat composition, tenderness, and juiciness, aligning beef production with consumer preferences while reducing input costs. While adoption barriers remain, the long-term economic advantages of genomic selection far outweigh the initial investment costs. Genomic selection represents a transformative approach to beef cattle breeding, offering substantial economic benefits through enhanced feed efficiency, improved carcass quality and reduced environmental impact. While challenges related to adoption costs and regional variability persist, the long-term financial gains and market advantages underscore the importance of integrating genomic technologies into breeding programmes. Moving forward, the integration of genomic data with precision nutrition and management strategies will be critical in maximising the profitability and sustainability of the beef industry as well as collaboration between researchers, industry stakeholders, and policymakers will be crucial in maximising the economic potential of genomic selection in the beef sector. In conclusion, genomic selection presents a compelling economic opportunity for beef producers by improving efficiency, reducing costs and enhancing product quality. The beef industry can achieve long-term economic sustainability by integrating advanced genomic technologies with strategic breeding decisions while addressing environmental and consumer-driven market demands.

Conclusions

1. The application of genomic selection in beef cattle breeding has demonstrated significant economic benefits, including improved feed efficiency, enhanced carcass quality and increased reproductive performance. By enabling a more precise selection of economically valuable traits, genomic technologies contribute to higher profitability while supporting the sustainability of beef production systems.
2. Integrating genomic selection into beef production enhances product quality and consistency and strengthens market competitiveness. There is a growing demand for high-quality, traceable, and ethically produced beef, and genomic technologies offer a means to meet these expectations while securing premium pricing in domestic and export markets.
3. Genomic selection plays a crucial role in reducing the environmental footprint of beef production. Improving feed conversion efficiency and disease resistance reduces resource consumption and methane emissions. These advancements align with global sustainability targets and carbon offset initiatives, positioning genomic selection as a win-win solution for economic growth and environmental responsibility.
4. Despite its advantages, genomic selection faces barriers to widespread adoption, mainly due to high initial investment costs and the need for specialised infrastructure and expertise. Small and medium-sized producers may find the costs of genomic testing prohibitive, highlighting the need for policy support, financial incentives, and educational programs to facilitate wider implementation.

5. As genomic technologies evolve, future research should focus on enhancing prediction accuracy, reducing costs and developing region-specific breeding strategies. Integrating genomics with precision agriculture and digital livestock management tools offers exciting opportunities to optimise efficiency and profitability in beef production further.
6. Maximising genomic selection's economic potential will require collaboration between researchers, industry stakeholders and policymakers. Supportive policies, investment in genomic infrastructure and knowledge transfer initiatives will ensure that genomic selection becomes integral to future beef breeding strategies.
7. Genomic selection represents a transformative innovation in beef cattle breeding. While challenges remain, its long-term economic advantages, sustainability benefits and potential to enhance market positioning make it a compelling strategy for modern beef production. With continued advancements and industry-wide adoption, genomic selection is set to play a pivotal role in shaping the beef industry's future.

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SOCIAL WORKERS IN RURAL COMMUNITIES AMIDST THE THREATS OF MILITARY CONFLICT

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Abstract
This article examines the perspectives of Latvian rural social workers concerning military threats arising from the ongoing war in Ukraine, within the broader context of public sentiments related to the conflict. The study aims to analyse the challenges faced by rural social workers amid uncertainty and the potential threat of military conflict. It focuses on three principal areas: (1) Macro-level social policy responses to the armed conflict, including challenges in service delivery; (2)The prevailing public opinion in Latvia regarding the war in Ukraine, as perceived by social workers; (3)The perspectives of rural social workers on these developments. The methodology includes desk research, an autoethnographic study, written interviews, and semi-structured interviews with social workers. The key findings highlight the rapid response to the needs of Ukrainian civilians displaced by the conflict. During the initial stages of the conflict, the primary focus was on addressing immediate crises; however, over time, attention shifted towards issues of integration. As the conflict persists, both the public and social workers in Latvia have become increasingly aware of the potential military threats facing the country. The study raises critical questions: How are rural social workers contributing to civil protection efforts? What are their experiences of working in the current conditions? These political and social challenges necessitate innovative approaches to mobilize and strategically utilize the resources and expertise of rural social workers to enhance community resilience. Living in conditions of war threat, it is important for social workers to identify information about all vulnerable groups in the municipality and to cooperate with rescuers and volunteers in providing support, if necessary.
Keywords: rural social workers, military threats, crisis solutions, rural community.

Introduction

The evolving landscape of social work policy in Latvia mirrors the contemporary complexities faced by social work worldwide. Considering the profound impacts of the recent Covid-19 pandemic and the humanitarian crisis stemming from the conflict in war-torn Ukraine, addressing these challenges necessitates a departure from micro-practice toward community-led, harm-reduction, and preventive approaches.

The study aims to analyse the social and professional challenges faced by rural social workers amid uncertainty and the potential threat of military conflict. It focuses on three principal areas: (1) macro-level social policy responses to the armed conflict, including efforts to provide humanitarian assistance while grappling with challenges in service delivery; (2) the prevailing public opinion in Latvia regarding the war in Ukraine, as perceived by social workers; (3) the perspectives of rural social workers on these developments. The study was initialized and finalized during 2024. The fieldwork was carried out in 2024 (May-December). It includes analysis of documents, statistics and data from the fieldwork. Elements of crisis intervention, narrative approaches and emergency social work theories are used as a basis for theoretical analysis. 'Emergencies—ranging from natural disasters like hurricanes and earthquakes to human-made crises such as terrorist attacks and industrial accidents—pose significant challenges to affected communities. The role of social workers in these scenarios is pivotal yet often underappreciated. These professionals are integral in managing the social and psychological aftermath, providing essential services that extend beyond the immediate crisis response' (Zakour & Harrell, 2003). Today, we also consider the military conflict in Ukraine an emergency. This war, initiated by an authoritarian regime in Europe, started in 2014 and escalated with Russia's full-scale attack on its neighbouring country in 2022. Social workers usually do emergency social work in special teams, services or other organizational units.

The research questions put forward by our team were: How do social workers perceive the proximity of the threat of war? How might it affect their target groups' security, as well as chosen strategies for work? Objectives to reach the answer to it were set as (1) Substantiate the theoretical background and methodology of the study; (2) Find out what is the opinion of social workers about the threat of war in Latvia. What feelings do the proximity of the threat of war evoke? (3) Find out how the threat of war could affect social security in rural municipalities? (4) Find out social workers' viewpoint on how to ensure social security for the target group they work with on a daily basis under the threat of war.

Socio-economic and political challenges (further 'social challenges') could be defined according to United Nations (UN) as 'issues that transcend national boundaries and cannot be resolved by any one country acting alone'. Social challenges could be understood according to UN initial goals of safeguarding peace, protecting human rights, establishing the framework for international justice and promoting economic and social progress, in the seven decades since its creation the United Nations has added on new challenges, such as AIDS, big data and climate change.

The formulation and implementation of social policies in response to military conflicts are geared towards addressing the immediate and long-term needs of affected populations. Research by Gough & Woods (2004) provides a comprehensive analysis of the

various policy measures adopted by governments and international bodies to mitigate the effects of military conflicts. These policies often include emergency relief, rehabilitation programs, and reintegration initiatives for displaced populations and former combatants.

Understanding public opinion and sentiment in relation to military threats is crucial for policymakers and stakeholders involved in conflict resolution and national security. Advances in sentiment analysis and big data analytics have enabled researchers to gauge public mood and opinions effectively. The study by Pang & Lee (2008) provides a foundational understanding of sentiment analysis techniques and their applicability to analyse public opinion on military threats. Furthermore, research by Tsytsarau & Palpanas (2012) delves into the methods of aggregating and interpreting large-scale opinion data from social media platforms and news sources. These studies reveal that public opinion is often influenced by media framing, governmental communication strategies, and historical context of the military threat. Governments and law enforcement agencies utilize sentiment analysis to monitor public responses to various events, enhancing national security efforts (Valsts kanceleja, 2025). The invasion of Ukraine in 2022 led to a significant negative sentiment towards Russia across various countries, with notable differences in sentiment between NATO and non-NATO countries (Pina, 2024). The Russian invasion also influenced public discourse on nuclear energy, with sentiment becoming more negative in response to military threats, despite a lack of polarized public argumentation (Zarrabeitia-Bilbao et al., 2023).

Social work in conflict zones has been extensively studied due to the complex and challenging environment in which social workers operate. The key challenges faced by social workers in conflict zones include 'emotional and professional stress' and 'complex interpersonal dynamics'. These challenges significantly impact both social workers and the communities they serve, necessitating targeted strategies for support and intervention. Social workers experience significant emotional stress and fear due to the violent political conflicts in their regions, which affect their well-being and professional performance. Competing national and religious identities create moral dilemmas for social workers, often testing their loyalty to universal social work values. Resilience is noted among social workers, indicating a capacity to cope despite the challenges posed by the conflict (Ramon et al., 2006). Complex interpersonal dynamics were found while working in such circumstances. Social workers in mixed ethnic communities face challenges in their relationships with colleagues, often leading to silence on political matters to maintain professionalism. The fear of discussing political issues can hinder collaboration and effective service delivery among social workers from different backgrounds. There is a need for social work training that addresses the impact of political conflict on professional relationships and service provision (Darawshy et al., 2024).

Existing literature highlights the critical role that social workers play in providing humanitarian aid, psychosocial support, and restoring community resilience. It emphasizes the unique skills required to navigate the cultural, political, and security dynamics of conflict settings. Studies by Jones & Truell (2012) underscore the importance of cultural competence and adaptive strategies in delivering effective social work services in such volatile environments, which made true also in Latvia, when in the March of 2022 facing the first flows of Ukrainian civilians, most of them affected by war – related trauma. Additionally, Al-Krenawi (2017) discusses the impact of armed conflict on mental health and the pivotal role social workers play in trauma-informed care. Government structures, such as the Ministry of Welfare, have implemented measures to equip social workers with essential skills. Further details of this approach are provided below.

Rural social work is a specialized field within social work that focuses on the provision and organization of social services in rural areas and towns characterized by low population density and limited access to services. Rural social workers encounter similar social issues as their urban counterparts but operate in environments with weaker service provision. The challenges faced by rural social workers include limited access to services due to geographical distance, accessibility issues, larger territories, and inadequate mobility infrastructure. Social interaction patterns in rural areas differ significantly, with greater emphasis on primary social ties and less opportunity for face-to-face interactions, resulting in a reliance on secondary social ties and increased trust in neighbours and local municipalities (Greenfield & Reyes, 2015; Mair & Thivierge, 2010; OECD, 2024). Rural social work is grounded in general social work practices but adapted to the unique characteristics of rural communities. The availability of professional social workers with specialization in various social groups is often problematic in rural areas (Bela & Rasnaca, 2023). Rural social workers employ appropriate context skills and knowledge to address the needs of rural communities, where social interaction typically involves place-based familiarity, local traditions, and mutual aid. Social work practice in rural areas addresses issues of disadvantage such as remoteness, distance, transport difficulties, limited-service choices, and hidden poverty. Farming, the predominant rural occupation, no longer provides adequate earnings for many rural residents, who often find better employment opportunities in urban areas. Data from the Latvian Central Statistical Bureau indicates a decreasing trend in employment in agriculture, forestry, and fishery, from 7.2% to 6.7% between years 2019 and 2023. Additionally, industrial accidents in agriculture result in more severe injuries and fatalities compared to urban occupations, as evidenced by a survey conducted by Purdue University (Stewart, 2010).

Materials and Methods

The research design and approach of this study are qualitative. Data collection involved qualitative written interviews. Additionally, desk research and secondary survey data analysis were employed to provide an overview of background information and the exposure of social workers to problems caused by the war in a neighbouring country over the past three years. A phenomenological approach was applied to the analysis of the written interview data. This approach does not require the researcher to adopt a neutral observer position; instead, it involves viewing the situation through the eyes of the interviewees, emphasizing their everyday experiences and feelings as reflected in the quotes (Raza, 2024). Desk research was conducted on the legal provisions for Ukrainian civilians settling in Latvia because of the war in their homeland. Additionally, an autoethnographic perspective was incorporated by one of the authors, who described her position and experience as a policy implementer while working at the Ministry of Welfare and providing professional development activities for practicing social workers in 2022. This subject, which forms an essential part of the author's professional identity, was chronologically revealed to readers within a social context. Autoethnography allows researchers to make sense of their own experiences within the context of their culture and society, sharing their insights with others. It enables researchers to examine how their cultural background and personal experiences influence their understanding of the world and explore the connections between their lives and the larger cultural and social structures in which they are embedded (Chang, 2013). Micro-level semi-structured interviews with social workers were conducted. Data from 35 interviews with social welfare specialists (social workers in social services and NGOs) were analysed during August to December 2024. Criterion sampling (based on professional status) was combined with convenience sampling. All respondents were women, as most social workers in Latvia are women. It took 45 to 90 minutes for respondents to answer the questions in written form. A phenomenological approach was used for the analysis of the written interview texts (Schiek, 2022). The three main stages of analysis were: description and understanding (interpreting what respondents mean by their text), reduction (identifying the main points in their experiences), and clustering of descriptive elements.

Results and Discussion

Macro-level Social Policy Responses

Since March 2022, Latvia has demonstrated a rapid and effective response to the needs of Ukrainian civilians displaced by the conflict. Key achievements include providing accessible housing, social services, healthcare, and employment opportunities. The cornerstone of these efforts is the Law on Assistance to Ukrainian Civilians (Latvijas Republikas Saeima, 2022), which is subject to periodic amendments based on comprehensive needs assessments and service provision monitoring. The most recent amendments were adopted by the Saeima in November 2024. On November 21, 2024, the Saeima approved amendments to the Law on Support for Ukrainian Civilians in its final reading, deciding to extend support measures for Ukrainian civilians for another year. Support for Ukraine remains a priority for Latvia. The country has provided substantial assistance to Ukraine during Russia's armed aggression, offering humanitarian and military aid and actively participating in security and economic initiatives. As before, Ukrainian civilians in Latvia will continue to receive support for housing and food at the current levels. Households hosting Ukrainian civilians will also remain eligible to apply for cost compensation. The 2025 state budget allocates €65 million for supporting Ukrainian civilians. However, even budget- grounded solidarity in service provision for war refugees with trauma is not enough: social workers in rural communities all over Latvia were confronted with common acknowledgement of lacking skills needed for the culturally sensitive and trauma – informed service provision.

One of authors tells her story from 2022. 'Idea to organize online Training for Practitioners in Trauma-Informed Care came from the Centre of Support for Adolescent, where my former student Alexanda Pavlovskaya worked. She was one to introduce Latvia with SFBT (Solution Focused Brief Therapy) in 2017 and now was approached by the global SFBT network offering free of charge online trainings Europe-wide for social workers handling support for Ukrainian civilians fled from war. It was rather easy to convince my ministerial supervisors of the necessity and justification, so the project started smoothly. Recognizing the importance of culturally sensitive care for conflict-affected individuals, a series of online training sessions was organized for clinical practitioners. This initiative, supported by the Ministry of Welfare, included six sessions led by esteemed professionals in Solution-Focused Brief Therapy (SFBT). I was one to coordinate the sessions with trainers and collect feedback from participants. Trainers such as Mark Gardiner, Criss Iveson, Carolyn Emanuel, and Guy Shennan introduced participants to trauma-informed practices for working with Ukrainian refugees. This training equipped social workers with the tools to support individuals experiencing trauma, with implications for preparedness in the event of similar challenges in Latvia. We have trained 131 persons from all over Latvia, and feedback was high in appreciation for a new knowledge and competencies they acquired'.

Public Opinion in Latvia: perceptions of the war in Ukraine

Understanding the general sentiment of the Latvian population is critical for contextualizing social work initiatives. Recent public opinion data from March

2024, compared to surveys conducted in 2022 and 2023, reveal shifting attitudes:

• Perceived Safety and Threats: Approximately 34.6% of respondents feel secure due to Latvia's NATO membership, though perceptions of military threat have increased. In spring 2022, 39.2% felt safe from direct military threats; by March 2024, this figure declined to 32.8%.

• Concerns about War: While 14.5% believe a Russia-NATO conflict is inevitable in the coming years, 11.5% foresee a Russian attack on a Baltic state.

• Fear and Anxiety: Experiences of fear related to nuclear war or invasion have decreased since 2022. In March 2024, 27.3% reported fear of nuclear war, down from 48.1% in 2022, while 21.1% feared foreign troop invasions, down from 46%. However, 20% still experience constant anxiety.

• Support for Ukraine: Support for Ukrainian war refugees has grown, with 60.1% of respondents favouring refugee reception, up 8.1 percentage points from 2023. Additionally, 56.3% support Ukraine until it defeats Russia, believing this helps protect the European Union (54.6%) and Latvia (53.6%).

• War Fatigue: A significant portion of the population (44.7%) reports fatigue from war-related news, and 43% express a desire to disengage from it (Valsts Kanceleja, 2025).

Since February 24, 2022, Latvia has invested €234 million in assistance to war refugees. Since February 24, 2022, 46,994 people have arrived in Latvia from Ukraine, of whom 32,304 are currently residing in Latvia. At the end of last year, support for Ukraine and belief in its victory increased, according to a public opinion poll commissioned by the State Chancellery. 61.7% of Latvians agree that they will support Ukraine until it wins the war against Russia. This compares with 50.7% in June 2024 and 53.8% in September - an increase of 11% since June (Valsts Kanceleja, 2025). The results show that 64.2% of the Latvian population want Ukraine to win the war against Russia, compared to 59.2% in June 2024 and 60.6% in September. Since June, there has been an increase of almost 5%. The number of people who agree that Ukraine can win the war has also increased. While in June last year 47.7% and in September 48.9% of respondents were convinced of Ukraine's ability to win, at the end of the year 51.5% of respondents were convinced. The share of people who agree that by helping Ukraine we are protecting Latvia from war has also increased significantly. The latest data shows that 64.2% of respondents agree. Last June, 51.7% agreed with this statement, while in September 53.3% agreed. Since June, confidence in the role of assistance to Ukraine in Latvia's security has increased by 12.5% (Valsts Kanceleja, 2025). The survey shows that the proportion of people who are tired of news about Russia's war in Ukraine and do not want to know about it has decreased. In June, 40.9% of the population expressed fatigue, in September 46.9%, and at the end of the year 38%, or almost 9% less. Moreover, when asked what topics are most interesting to them at the moment, most respondents, 37.9%, said they were interested in the Russian war in Ukraine. The survey was conducted online by Berg Research on behalf of the State Chancellery from 15 October to 24 November 2024 and was attended by 1,009 Latvian citizens aged 18 to 74 (Valsts Kanceleja, 2025).

Perspectives of Rural Social Workers

The analysis of semi-structured interviews reveals the following trends. The questions answered by respondents were divided into three main blocks: (1) What is the opinion of social workers about the threat of war in Latvia? What feelings does the proximity of the threat of war evoke? (2) How could the threat of war affect social security in rural municipalities? (3) What is the viewpoint of social workers on how to ensure social security for the target group they work with daily under the threat of war? The heuristic phenomenological approach to reading and understanding the interview texts allowed the authors to identify the main categories for analysing the experiences of social workers. The categories chosen by the authors (after describing and understanding the text) for linking the personal and professional experiences of social workers amidst the threat of war were empathy, denial, reflection, and action. The introductory part of the interviews includes the previous experiences of social workers working with Ukrainian refugees during the initial stages of the conflict in Ukraine. The first problems faced by social workers in rural areas of Latvia were related to refugees (civilian citizens from Ukraine). Most of the refugees were women, mothers with one or more children. Some of the refugees had dramatic experiences, including abuse and the consequences of trauma. 'Many survivors of abuse who suffer from PTSD have difficulty performing routine daily activities, let alone adapting to new circumstances' (SW, Talsi). Social workers must work with people who suffer from traumatic experiences or abuse. The necessary social work approach in working with refugees from Ukraine was crisis intervention. In the following stages of the work, social inclusion issues came to the fore. 'Not everyone is able to overcome severe losses equally quickly and regain the ability to actively shape their lives. This is especially true for people who have experienced severe injuries or the loss of loved ones because of the war. The traumatic experience of the injured and bereaved is a challenge for social workers who have not dealt with it before. We must live on' (SW, Aluksne). As hostilities in Ukraine continue for the third year, with disturbing news of battles and civilian casualties every day, there is a sense that the war is moving closer to Latvia. This creates anxiety, insecurity, and reflections on the role of social workers. The authors reread the interview texts. During coding, empathy, denial, reflection, and action were identified as the main categories that allowed for combining blocks of text.

Social workers feel *empathy* towards the target group they are involved with in their everyday work. They feel empathy towards family members, children, husbands, parents, and even domestic animals. They are also concerned about the possible general situation and all vulnerable people. 'When thinking about the threat of war, the conversation about safe shelters and how potential people will be provided with necessities in their area is important. What will happen to those residents who cannot cope with such situations on their own – elderly seniors, children in out-of-home care, people with limited mobility, people with mental disorders?' (SW, Cesis). Social workers are concerned if these (vulnerable) groups are precisely identified, and if there is a support plan that considers the needs of these individuals in case of emergency. What will happen to medical appliances and drugs, the availability of financial resources, necessities (food, hygiene products, drinking water, batteries)? Of course, their own family and its safety worries the respondents, especially those who are involved in the national guard and who may have to fulfil their duties at the place of duty while leaving the children in the care of other family members.

Denial? Denial is one of the defence mechanisms that people use in crisis situations. It is often easier not to think about danger, threats, and to cling to easier-to-solve issues and everyday responsibilities. 'Thinking about the threat of war, for me as a mother and a social worker, the first emotional reactions are denial, fear, hope, difficulty accepting the threat, empathy, and compassion for myself, family, society, animals, nature' (SW, Bauska). We could observe that society is somewhat used to the threat of war, but how we will act if it really happens is not thought of. 'Like ostrich politics, I also live in denial for my part, because there is a lot of resistance to developing this thought. To be honest, I don't like to think about this, but you must be ready for everything, but emotionally it's hard' (SW, Jēkabpils).

Reflection? Reflection is a crucial skill in the social work profession, necessary for understanding both short-term and long-term relationships formed with the people they encounter and the situations they deal with. 'The onset of the war in Ukraine in 2022 compelled Latvia to consider the potential threats of war in Latvia and other neighbouring countries of the aggressor more intensively. In my opinion, the war as a possible disaster has been ingrained in the minds of every resident of Latvia for a very long time' (SW Olaine). The availability of information about emergencies, particularly war, and the information necessary for professional duties is a significant concern for social workers. Although it seems impossible to prepare for such events, psychological preparation and information about action plans are extremely necessary. 'War is a tragic event that brings enormous negative changes and destruction, obliterating everything that the country, community, family, and individual have built up to this point. Thanks to social media, we all now see and understand what war truly looks like. The threat of war brings all of this to mind and can affect the course of a person's life' (SW, Bauska district). The feeling of insecurity created by the possible threat of war promotes a reorientation of basic needs and actions that are not clear and predictable. 'This insecurity leads people to avoid taking risks and fulfilling their desires, which worsens their mental health and increases feelings of social insecurity' (SW Limbazi). Negative experiences without intervention tend to lead to other negative experiences, creating chains-of-risk (SW Valka). 'War is a disaster in which crime thrives, including human trafficking. In my opinion, this issue affects not only those already identified as victims of human trafficking but all members of society' (SW, Gulbene).

Action? Action is an integral part of the social work profession, involving solving complex situations, respecting the values of social work, and supporting people's life prospects. Social workers emphasize their professional needs for emergencies in situations of war. We need 'a crisis management plan that explains the provision of social services in emergency situations and the continuity of basic services, including evacuation scenarios, which must be known to every citizen. During Covid, remote forms of communication were used, raising questions about the availability of the internet and how to address and promote the digitization of social services, as well as concerns about data protection' (SW, Aizkraukle). Greater emphasis should be placed on the decentralization of social services, as centralized systems may be disrupted during wartime. Therefore, more focus should be placed on municipalities and cities.

The analysis of semi-structured interviews reveals several key trends. Social workers express empathy towards the target group they are involved with in their everyday work, including family members, children, husbands, parents, and even domestic animals. They are also concerned about the possible general situation and all vulnerable people. Denial was identified as one of the defence mechanisms that people use in crisis situations, often leading to a reluctance to think about danger and threats. Reflection was highlighted as a crucial skill in the social work profession, necessary for understanding both short-term and long-term relationships formed with the people they encounter and the situations they deal with. Action is an integral part of the social work profession, involving solving complex situations, respecting the values of social work, and supporting people's life prospects.

Social interaction in a professional environment, as well as cooperation with professionals from other sectors, is a prerequisite for successful social work in emergency conditions. Also, during the threat of war. Latvian social work professionals are preparing to carry out social work at both the macro and micro levels. The question of work forms and coverage (how to reach each employee and consider the specifics of each target group) is debatable. The sense of security of social workers is sometimes threatened by previous

experience of informative cooperation and data security solutions. A heuristic approach is the mode of how to simplify social interaction patterns in emergency situations.

Conclusions

1. The Latvian state serves as a model for European nations in providing continuous and stable support for Ukrainian civilians. Additionally, Latvia has promptly implemented training programs of trauma-informed clinical social work for social work practitioners. Public opinion in Latvia remains supportive of the Ukrainian cause, advocating for either victory or sustainable peace.
2. Findings indicate that a more intensive involvement of the state, specifically the Ministry of Welfare, in the development of community social work in rural areas is essential to ensure safer environments for the rural population.
3. Greater emphasis should be placed on the decentralization of social services, as centralized systems may be disrupted during wartime. Therefore, more focus should be placed on municipalities and cities. This includes the implementation of early warning systems and community mobilization in situations of environmental disasters, crises, or military threats.
4. Municipal planners should collaborate closely with social service agencies to address these tasks, as the role of community organizer aligns well with the competencies and skills of community social workers. Furthermore, advanced training in crisis intervention and trauma handling is necessary for all municipal social workers.
5. The primary challenges encountered by social workers in conflict zones, as previously emphasized by the authors, encompass both 'emotional and professional stress'. Social workers endure significant emotional distress and fear due to the violent political conflicts in their regions. The findings indicate a substantial level of professional stress among the respondents, with anxiety and insecurity being experienced daily. Nevertheless, in terms of building resilience, there is a demonstrated commitment and readiness to support the local population. The authors present evidence-informed hope for the capacity to cope and extend assistance to community members despite the challenges posed by potential or ongoing conflicts.
6. Cooperation between social workers and other state and local government structures in the event of a crisis must be mutual, otherwise vulnerable groups may be left without support.

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ROLE OF POLICY AND REGULATION IN ENHANCING GREEN FINANCE FOR ECOLOGICAL PROBLEM MITIGATION

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Abstract
The increasing urgency of environmental challenges relating to climate change and biodiversity loss calls for immediate actions to mitigate risks and impacts and requires innovative methods for funding sustainable solutions. One of the solutions is green finance, which refers to financing and investments that support environmentally sustainable projects and initiatives. Although there is increasing interest and investment in green finance, it is a financial instrument whose effectiveness is dependent on regulatory efficiency. Well-designed and structured policy framework may provide important incentives for wider green finance use, increase transparency and reporting, simultaneously aligning investment and money flows with environmental goals. The study aims to explore the role of policy and regulation in promoting green finance and addressing ecological issues. The research employs a literature review, Pearson correlation analysis, descriptive statistical methods and data visualisation. The authors analysed international policies comprised of the EU Taxonomy for Sustainable Activities, the Paris Agreement, and the European Green Deal, concluding that they serve as benchmarks for linking financial flows with ecological objectives while encouraging innovation, accountability and transparency. The green bond market in the EU has grown significantly, which was influenced by policy implementation that increased issuers and investor confidence. By providing incentives for sustainable investments, ensuring transparency and addressing systemic problems, the study emphasizes the critical role that policy and regulation serve in fostering a favourable financial environment.
Keywords: green finance, policy and regulation, ecological problems.

Introduction

The escalating global environmental crisis, characterized by climate change, biodiversity loss and ecosystem degradation, has underlined the need for innovative financial mechanisms to support sustainable development. In this context, green finance has emerged as a critical tool for allocating funds to organizations and projects that promote environmental sustainability. Previous research has primarily focused on broad international agreements, for example, the Paris Agreement or the implementation of green finance policies within specific countries. Studies have also examined how national policies influence industry or company ability to utilize green finance. For example, Odugbesan et al. (2021) analysed the impact of financial regulations on green finance in Turkey. Despite extensive research on both international policies and green finance mechanisms, a gap remains in understanding how different policies influence each other and the development of green finance markets.

The research aim is to explore the role of policy and regulation in promoting green finance and addressing ecological issues. To reach the research aim, the following tasks are advanced: 1) to analyse international frameworks supporting green finance; 2) to examine the relationship between green finance and ecological problem mitigation.

Materials and Methods

In this study, the authors used a literature review to conduct a comprehensive review of academic articles, policy documents and reports to identify global trends, challenges and the best practices in green finance regulation. A Pearson correlation analysis was employed to examine the relationship between net emissions and the amount of green bonds. Descriptive statistical methods and data visualization methods were used as well. Information was collected from secondary sources, including government publications, reports and research articles. The study period (2014–2023) was chosen to align with major policy developments, including the adoption of the Paris Agreement (2015), the European Green Deal (2019) and the EU Taxonomy for Sustainable Activities (2020). Data were sourced from government reports, open-access databases and climate finance research institutions.

Results and Discussion

International frameworks supporting green finance

The effectiveness of green finance and subsequently ecological problem mitigation is dependent on the policies. They strengthen credibility while simultaneously providing incentives for green finance growth. According to Shen, Ma & Chen (2024), the policies benefit the environment by improving regional ecological conditions and promoting sustainable development. The EU Green Deal, the Paris Agreement and the EU Taxonomy for Sustainable Activities are the three most significant international policy documents in shaping the regulatory landscape for green finance and advancing efforts to mitigate ecological challenges.

The United Nations (2015) Paris Agreement is a legally binding treaty to battle climate change with the main goal of ensuring that the rise in average temperature is significantly less than 2 °C. It introduced many solutions that help fight climate change:

- set a legally binding commitment and created a global roadmap for countries to integrate climate goals into economic planning (Falkner, 2016);
- provided long-term policy certainty, increasing investor confidence in green bonds and sustainable finance instruments;

• promoted carbon pricing mechanisms that led to the expansion of the EU Emissions Trading System (Boyce, 2018).

While the Paris Agreement is an important step towards battling climate change, many debate its effectiveness. Van Asselt & Kulovesi (2017) argue that it lacks sufficient enforcement mechanisms and raises concerns about member countries ability to meet their commitments. Similarly, Liu & Raftery (2021) express concerns about the slow pace of implementation and the considerable challenge of aligning with different national interests. Despite these criticisms, other experts believe the Paris Agreement's flexibility is a strategic benefit. Falkner (2016) suggests that this 'lack of enforcement mechanisms' gives countries the freedom to tailor their policies to their national circumstances. It could lead to stronger long-term outcomes compared to strict enforcement. One of the most significant contributions of the Paris Agreement is its influence on global financial markets. Article 2.1.c encourages aligning financial flows with low-emission development and upon implementation changed investment patterns. For example, based on Statista (2024), the value of green bonds worldwide in 2014, the year before the Paris Agreement, was USD 37.1 billion. By 2023 the value had grown to USD 587.6 billion – the market experienced an approximate fifteen-fold increase. These data show that the policy significantly influences green finance markets, which in turn mitigate ecological problems. Based on Climate Bonds Initiative (2024) data, the biggest investments from 2014 to 2023 were in energy with 35%, 25% in buildings and 19% in transport.

The Paris Agreement represents a landmark global effort to address climate change, setting ambitious targets to limit global warming and encourage nations to transition toward low-carbon economies. However, because of the freedom to tailor the policies, there needs to be concrete and actionable strategies at regional and national levels. In response, the European Union has taken a bold step forward with the European Green Deal (EGD). It was introduced in 2019 with the aim to transform the EU into the first climate-neutral economy by 2050, with a 55% reduction in greenhouse gas emissions by 2030 compared to 1990 levels (European Commission, 2024). The EDG is not only a climate strategy but also an economic transformation agenda. It integrates principles of green growth theory, which suggests that sustainable economic expansion is possible by utilizing innovation, regulatory frameworks and market-based mechanisms (OECD, 2011). It has had a major impact on green finance by establishing a strong regulatory framework that directs funds into environmentally friendly endeavours. Dombrovskis (2021) indicate that key initiatives like the EU Taxonomy for Sustainable Activities provide a science-based classification system to identify environmentally sustainable investments, while the Sustainable Finance Disclosure Regulation enhances transparency, helping investors make informed decisions. While the EGD sets an ambitious vision for a sustainable and climate-neutral Europe by 2050, its implementation remains a challenge. Eckert & Kovalevska (2021) express concerns about the adequacy of financial resources allocated to support the transition and the feasibility of achieving the ambitious targets within the proposed timelines. Andersson et al. (2025) from the European Central Bank confirm those concerns, for example, in 2023 5.1% of EU's GDP was invested towards emission reduction but based on estimates to reach the EGD goal, the number should be about 8.3% each year until 2030. They also highlight the need for private sector support. Hereu-Morales et al. (2024) discuss concerns that the transition may lead to job losses in certain industries, particularly those in the energy industry reliant on fossil fuels. Although job losses in this industry are a real possibility, Ram et al. (2020) argue that created jobs in the renewable industry outweigh those losses and will account for approximately 80% of new jobs generated by 2050. Despite these challenges, the growth of green finance presents a significant opportunity to bridge the funding gap and accelerate the transition.

To ensure that investments are channelled effectively toward projects that genuinely contribute to climate neutrality, the EU Taxonomy for Sustainable Activities (henceforth, the Taxonomy) was created. It serves as a classification system that defines which economic activities can be considered environmentally sustainable. It sets clear and science-based criteria that help policymakers, businesses and investors determine which activities will contribute to environmental objectives (European Commission, 2025). The Taxonomy increases transparency and decreases greenwashing, clearly defines key performance indicators and helps better address the environmental and ecological challenges by linking the capital flow to sustainability goals (Dusík & Bond, 2022; Hummel & Bauernhofer, 2024; Pacces, 2021). It fosters investor confidence and accelerates green investments. The Taxonomy mandates detailed reporting on how economic activities align with its sustainability criteria. Empirical evidence indicates that stricter disclosure requirements contribute to an increase in capital allocation to environmentally friendly projects, for example, Su et al. (2023) found that environmental information disclosure significantly enhances the efficiency of capital allocation but the effect varies by company size, ownership, life cycle and region. While the transparency mechanisms are important to boost confidence and decrease greenwashing, there is still a debate about whether they are enough to bring about significant change or whether they are more of a hindrance. Hummel & Bauernhofer (2024) point out that there is an increased bureaucratic burden that could negatively affect smaller and newer businesses. Kooths (2022) argues that climate policies should include stricter regulatory measures like carbon taxes and bans on specific activities to hasten reaching the

goal. Despite the criticisms, the Taxonomy is undoubtedly an important policy that helps align financial markets with sustainability and climate goals. For example, in 2017 France issued their first sovereign green bonds and set a precedent for other governments (Agence France Trésor, 2024).

In general, international policies significantly influence green finance by providing important incentives for wider green finance use, increasing transparency and reporting, simultaneously aligning investment and money flows with environmental goals, especially low-emission development.

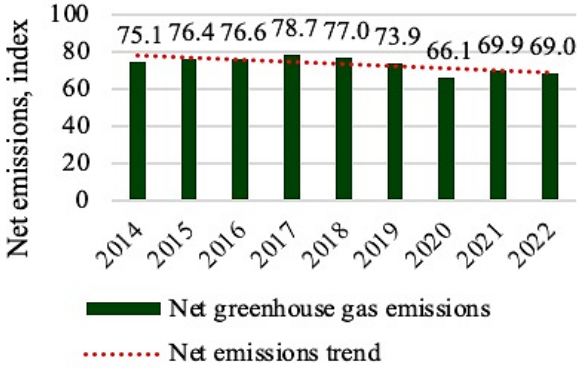
Ecological problems and green finance

The implementation of these international frameworks has significantly shaped the green finance market, particularly through the promotion of green bonds and sustainable investments. To assess the tangible impact of policy-driven finance on ecological outcomes, the following section presents statistical analyses examining the relationship between green bond issuance and net emissions.

Climate change is the most pressing environmental challenge. Since greenhouse gas emissions are the predominant driver of global temperature increases, extreme weather events and ecological disturbances, mitigating these emissions is the top priority for climate stability. The European Union has achieved measurable progress in reducing greenhouse gas emissions, Figure 1.

Figure 1

Net greenhouse gas emissions and trend in the EU-27 for 2014-2022, index 1990=100

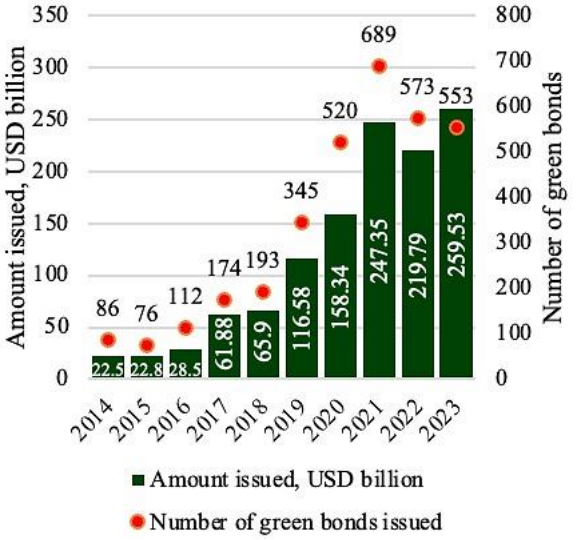


Source: authors' construction based on Eurostat, 2025.

The values indicate that emissions remained relatively stable between 2014 and 2018, fluctuating slightly but staying above 75. However, a notable decline was observed after 2019, with emissions dropping from 73.9 in 2019 to 66.1 in 2020, followed by a slight increase in 2021 (69.9) and stabilisation at 69.0 in 2022. One reason for the decline in emissions is the implementation of policies. Wang et al. (2024) emphasise the importance of green policies, as they provide economic incentives and help strategically allocate resources. Another factor driving this change is green finance - a tool that funds projects aimed at reducing emissions. The most utilised green finance instrument by the EU and its Member States is green bonds. These instruments are used to finance green projects and, based on Climate Bonds Initiative (2024) data, in 2023 in Europe region, the biggest investments were in energy with 29%, 23% in buildings and 20% in transport. Green bonds, a key instrument of green finance, heavily rely on the Taxonomy. The introduction of the European Green Bond Standard in 2023 reinforced regulatory requirements for green bond issuance. Data from the Climate Bonds Initiative (2024) in Figure 2 indicate significant growth in green bond issuance and investor interest following regulatory advancements.

Figure 2

Total issuance and value of green bonds in the EU-27 (2014–2023)



Source: authors' construction based on Climate Bonds Initiative, 2024.

From 2014 to 2017 green bond market increased by USD 39.36 billion because of the influence of the Paris Agreement, mainly Article 2.1.c, which encouraged aligning financial flows with low-emission development. In 2018, the total amount of green bonds issued increased by 10.9%, while the number of bonds rose by 19. This period coincided with the launch of the European Union's Sustainable Finance Action Plan, which laid the groundwork and served as a precursor to the Taxonomy. As a result, in 2019, the green bond market experienced a significant expansion, with the total issuance amount increasing by 76.9% and the number of bonds rising by 78.8%. This is mainly due to the establishment of the framework that increased credibility and transparency in the green bond market. Although 2020 was a challenging year, there was a steady growth in the amount issued by 35.8%, but the number of deals increased by 50%. In 2020, the average size of a single green bond issuance was USD 0.30 billion, marking the lowest value during the analysed period. This suggests an overall increase in the number of green

bonds issued, even though the average issuance size was comparatively smaller. On 1 July 2021, the Taxonomy came into force, and there was a second significant expansion, with the total issuance amount increasing by 56.2% and the number of bonds rising by 32%, which reflects increasing investor confidence because of regulatory clarity. The average size of a single green bond issuance also increased and reached USD 0.36 billion. The Taxonomy had such an impact on the green bond market because, in comparison to previous frameworks, it introduced a science-based, standardized and legally binding system for defining sustainable activities. It boosted investor confidence, attracted larger issuers and expanded the green bond market. In 2022, due to economic and geopolitical uncertainties, the total amount and number of green bonds issued decreased. However, the average size of a single green bond issuance increased by USD 0.02 billion, indicating a shift toward larger-scale issuances despite the overall market contraction. Although in 2023 the number of green bonds issued decreased by 20, the amount issued increased and reached its peak - USD 259.53 billion. The average size of a single green bond issuance also reached its peak - USD 0.47 billion. This trend suggests that while the total number of green bonds issued fluctuated, the market increasingly favoured larger-scale issuances, likely driven by institutional investors and regulatory advancements. The record-high issuance amount in 2023 highlights the resilience and growing maturity of the green bond market, despite prior economic uncertainties.

It is concluded that policies have an impact on green finance, especially on the green bond market. To understand the relationship between green bonds and net emissions, the authors conducted a Pearson correlation analysis. The results show a strong negative correlation ($r = -0.807$, $p = 0.009$), which indicates that a higher amount of green bonds is associated with lower emissions. A linear regression analysis revealed that green bond issuance explains 56.1% of the variance in net emissions ($R2 = 0.561$, $p = 0.009$). These findings underscore the critical role of green finance in accelerating emissions reduction. Policies create a positive feedback loop by fostering green finance, which is then channelled into projects that directly contribute to lowering emissions and mitigating climate change. Furthermore, the substantial growth of the green bond market in response to policy interventions emphasises the need for continued regulatory support and financial incentives to maintain this trajectory.

Conclusions

1. International policies, such as the Paris Agreement, EU Taxonomy for Sustainable Activities and the European Green Deal, positively affect green finance markets because they serve as benchmarks for linking financial flows with ecological objectives while encouraging innovation, accountability and transparency.
2. The green bond market in the EU has grown significantly in the period from 2014 to 2023 – by USD 237.01 billion, which was influenced by policy implementation that increased issuers and investor confidence.
3. Green finance is crucial for addressing ecological problems, which is supported by the results from Pearson correlation analysis between the amount of green bonds and net emissions that show a strong negative correlation – a higher amount of green bonds associated with lower emissions by directing financial resources towards sustainable projects.
4. Overall, policy and regulation have a critical role in fostering a favourable green financial environment.

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UNDERSTANDING PUBLIC SERVICES THROUGH LITERATURE: THEORETICAL FRAMEWORKS AND TRENDS

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Abstract
Access to fundamental public services is a cornerstone of the European Pillar of Social Rights, particularly in social protection and inclusion. As a driving force behind effective governance in the global economy, public services play a crucial role in ensuring society's stability, promoting prosperity and fostering economic growth. This research aims to analyse and systematise theoretical frameworks and current trends in the scientific literature on public services in order to understand their role in the development of the state and society. Employing theoretical research methods including the monographic method, synthesis-analysis method and descriptive method – this study examines a range of studies, official documents and case studies on public services. The findings reveal that international research highlights a strong link between public services, public trust in governance and satisfaction with governance in general. Specifically, both the quality of public services and citizens' perception of these services are identified as key factors in increasing trust in public administrations and enhancing public participation in the co-design of services. In contrast, inadequate citizen participation is highlighted as one of the major contributors to poor service delivery in municipalities. In an era characterized by rapid technological advancement and digital transformation, public administration shall adapt to address the evolving needs of citizens effectively. Digitalization emerges as a key solution to enable citizens to access the necessary public administration services more quickly and conveniently.
Keywords: public services, economics, digitalization, life satisfaction, trust.

Introduction

D. K. Basyal and S. Nepal point out that the development of public administration began with the formation of human civilization, gradually evolving from early social structures to complex administrative and legal mechanisms (Basyal & Nepal, 2021). Public services have developed as the state response to citizens' needs for order, security, healthcare, education etc. Access to essential public services is a key element of the European Pillar of Social Rights, particularly in the context of social protection and inclusion (European Commission, 2021). It is closely linked to the active integration of marginalized individuals in the labour market by providing tailored and individualized services. This approach includes timely identifying needs and providing targeted support (European Commission, 2008). According to E. A. Jackson, public services are a driving force in ensuring effective governance in the global economy (Jackson, 2021).

In scientific literature, the term 'public service' is often used in the sense of 'public utilities'; however, the meaning of public service is broader, encompassing also services provided by private companies for the public interest (such as electricity, water supply, telecommunications, etc.). The term 'public administration services' is also used, which is more specific and refers specifically to services provided by public administration institutions (such as issuing documents, tax administration, registration, etc.). In this study, the term 'public service' refers to services provided by the state, local government or state-funded institutions. It is also necessary to understand the term 'service' and its meaning, as its definition and interpretation vary depending on the perspective. For example, the Ministry of Smart Administration and Regional Development of the Republic of Latvia explains service as a collaborative process between the service provider and the recipient, where the main emphasis is placed on creating value and meeting the user's needs (Ministry of Smart Administration and..., 2024). In this context, the interaction between both parties is central, and the service is considered successful when it effectively addresses the specific requirements and expectations of the recipient, leading to a positive outcome or experience. This approach primarily emphasizes the client's perspective, which is essential in modern governance models, such as New Public Management (NPM). This framework encourages public institutions to adopt private sector principles, prioritizing efficiency and enhancing citizen satisfaction. In contrast, the European Union adopts a broader definition of public services as economic activities of general interest, which are determined, established and regulated by public authorities under a specific legal framework, irrespective of whether they are delivered by public or private entities. This approach emphasizes the legal-regulatory dimension while linking public services to their dual role in economic and social functions. Both approaches reveal a foundational tension in defining public services: whether they primarily serve as an instrument for addressing citizen needs, as emphasized by the Ministry of Smart Administration and Regional Development of the Republic of Latvia, or function as legally and economically regulated state mechanisms, as defined by the European Commission. In practice, both perspectives are indispensable, as public services shall balance operational efficiency and user-centric responsiveness with national and international legal frameworks. However, it is significant to note that not all activities carried out by the public administration can be considered public services (Spicker, 2009), for example, the implementation of institutional support and administrative functions.

While public services primarily focus on addressing individual citizens' needs, they have evolved into a

cornerstone of societal well-being, improving quality of life and national economic development. Anderson et al. (2019) highlight that a positive citizen experience with public services strengthens public trust in government institutions and overall satisfaction with public administration. This, in turn, fosters greater civic engagement in the development and improvement of public services. This approach aligns with social capital theory, as the concept of social capital is linked to issues of human behaviour and motivation, primarily as a result of social interaction (Claridge, 2018), thus, trust in institutions can be considered a critical element for effective governance and democratic participation. In contrast, Wadesango et al. (2018) note that a lack of citizen participation can lead to lower service quality, particularly at the local government level. This means that the absence of direct feedback from citizens as service users increases the risk of inefficiency.

Regarding the development trends of public services, attention is given to various public administration reforms, such as the NPM reform, which aimed to enhance efficiency and outcomes by introducing private sector management methods into the public sector (Lapuente & Van de Walle, 2020), and the Post-NPM reform, which focused on creating integrated governance and inter-institutional collaboration (Klenk & Reiter, 2019). Both reforms have significantly changed the way public services are organized and delivered. Meanwhile, current trends in technological development and the increasing economic, demographic and environmental challenges – such as an aging workforce, climate change and economic crises – are driving countries to seek sustainable and innovative solutions for public services delivery.

Despite the growing recognition that public services are a cornerstone of public well-being and a key component of effective public administration, there is still a lack of conceptual clarity and consistency in defining their nature, function and role in modern public administration. The duality between citizen-centred and regulated approaches confuses the public service discourse, while ongoing reforms and digital transformations further complicate the situation. This fragmentation hinders a comprehensive understanding and strategic development of public services that can respond effectively to the needs of modern society.

This research aims to analyse and systematise theoretical frameworks and current trends in scientific literature on public services in order to understand their role in state development and their impact on public trust in governance, citizen participation in service co-design, and overall quality of life in the context of the digital transformation of public services. To achieve this aim, the following tasks have been defined based on insights from research literature and development trends:

1) to identify the key characteristics of public services and their significance in the state and society development;
2) to analyse the theoretical approaches and conceptual interpretations of public services in scientific literature;
3) to provide an overview of historical and contemporary trends in the development of public services.

Materials and Methods

This research examines a range of studies, official documents and case studies on public services using theoretical research methods, including the monographic, synthesis-analysis and descriptive methods.

Results and Discussion

Characteristics and importance of public services

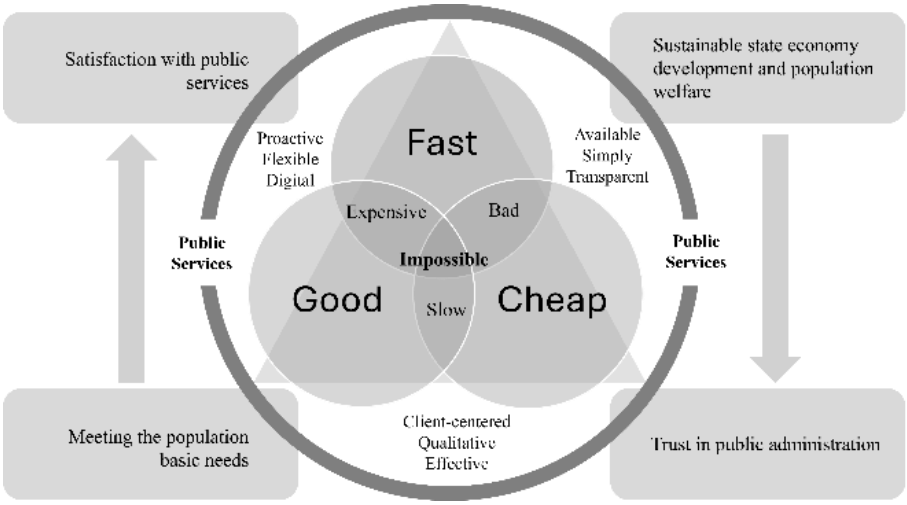
Public services are a primary channel of interaction between the state and its citizens, businesses and organizations (OECD, 2024a), and the state's ability to effectively deliver public services is crucial for society's and the economy's development. According to Jackson (2021), effective private business functioning often depends on the services provided by the state, which are more complex than those provided by the private sector because they relate to a broader range of service recipients. Therefore, it is crucial to ensure greater transparency of services (Osborne et al., 2013), meaning the justification for the use of public resources. As a result, public institutions face complex challenges in ensuring accessible services for all while maintaining high quality. The OECD (2022) notes that high-quality services are those that are delivered efficiently, providing users with a satisfactory experience and optimal outcomes, regardless of whether the service is mandatory (e.g., issuing building permits) or voluntary (e.g., registration for studies).

Public institutions create public value through the services they provide. One of the issues associated with the delivery of public services is the Trilemma – the challenge of balancing three objectives: delivering public services fast, good and cheap, of which only two can be achieved at the same time 'Figure 1'.

This Trilemma is significant because it highlights the trade-offs between service efficiency and quality. In this context, public institutions shall devise effective solutions to optimally allocate available resources and meet citizens' needs. It is also crucial to examine how these choices affect the quality and reliability of service delivery.

Research papers highlight various characteristics of public services, stating that they shall be accessible (Anderson et al., 2019), simple, client-centered (Scupola & Mergel, 2022), effective (Cuadrado-Ballesteros et al., 2013), proactive (Welby & Tan, 2022), agile and digital (Luna et al., 2024; Scupola & Mergel, 2022).

Figure 1
Public services characteristics and significance



Source: authors' construction.

C.-T. Hsiao and L. J. Shin emphasize that ensuring high-quality public services requires integrating clients' needs from the early stages of service development (Hsiao & Shin, 2008). Client feedback mechanisms, collaborative teamwork and a structured problem-solving framework enable organizations to address client concerns in a timely and responsive manner.

Luna et al. (2024) highlight the significance of digital public services and their potential to generate substantial public value by ensuring service availability anytime and anywhere, thereby saving citizens' time and reducing administrative burdens. While digital services offer significant advantages, it is crucial to ensure the availability of adequate digital infrastructure that supports 24/7 service delivery and protect these services from cyberattacks to maintain citizens' trust in digital services. In addition, greater attention should be given to the availability of digital services for various groups of citizens who have insufficient digital skills, such as seniors (Anderson et al., 2019). Therefore, targeted training programmes may be necessary, which, for example, could be provided by various non-governmental organizations as strategic partners (Luna et al., 2024). To fully harness the potential of digital services, a comprehensive approach is needed, integrating digital infrastructure, cybersecurity and citizen digital skills. Only by addressing these factors can digital services effectively contribute to the long-term development of the state and society.

An integral part of public service delivery is the effective and user-centred selection of service delivery channels. The choice of the appropriate delivery channel affects not only the service quality and the cost-effectiveness of the public institution but also the administrative burden on citizens. In the context of digital transformation, the multi-channel approach is becoming increasingly important. This approach combines traditional (in-person, phone-based) and digital (online portals, mobile applications, artificial intelligence solutions) forms of service delivery, adapting to the needs of various societal groups.

Cuadrado-Ballesteros et al. (2012) note that the most commonly used factors for measuring the quality of life of citizens are related to public services, thus establishing a link between the form of public service delivery (outsourcing, state-owned enterprises, public funds, etc.) and the quality of life of citizens. The results of the mentioned study indicate that the involvement of the private sector in the delivery of public services through outsourcing does not improve the efficiency level of Spanish municipalities. However, state-owned enterprises and mixed capital companies can enhance public administration efficiency although these forms of public service provision are rarely used in Spain (Cuadrado-Ballesteros et al., 2013). Meanwhile, Shareef et al. (2016) confirmed that citizens in the USA, India and Bangladesh are generally satisfied with the service delivery model via mobile phone SMS, provided that government agencies offer clear, accessible and useful information. When these conditions are met, citizens perceive the channel as effective (Shareef et al., 2016). In Latvia, the results of the State Chancellery's annual Public Administration Client Satisfaction Survey for 2024 shows that one-fifth of respondents prefer in-person communication with state institutions. Respondents believe that handling matters online is problematic, too complicated and unclear, admitting that they did not know how to properly handle specific issues electronically (The State Chancellery, 2024). Overall, a balanced approach is needed, which includes both an optimal service delivery model and appropriate communication channels. Furthermore, as evidenced by Latvia's experience, the development of digitalization should not overlook the segment of the population that requires additional support and explanations in using digital services.

Trends of public services development

The OECD highlights several future trends in the public service sector that reflect global changes and the needs of modern society:

1) future-oriented and co-created public services;

2) digital and innovative foundation for efficient public services;
3) personalized and proactive public services;
4) data-driven public services for better decision-making;
5) public services as opportunities for societal participation (OECD, 2024a).

These trends indicate a shift towards more progressive and inclusive public services, which will be agile and responsive to societal and technological changes. The development of technology plays the most significant role in ensuring efficiency. Hilhorst et al. (2022), analysing the efficiency of public services provided by Dutch municipalities from 2014 to 2018, found that investments in information technology (IT) had a positive impact on cost efficiency – each additional euro invested leads to a net cost efficiency gain of 1.08 euros. This means that digitalization and the application of technology can improve the efficiency of public service delivery. However, there is a threshold beyond which additional IT investments no longer enhance the efficiency of local governments, thus highlighting the need for a strategic approach to IT development. Moreover, the successful implementation of public service innovations is closely tied to the ability of public institutions to adapt to change. Almazrouei et al. (2024) study suggests that institutions open to change and innovation generally exhibit higher efficiency and a greater capacity to successfully adopt new technological solutions designed to meet societal needs. In general, these studies highlight that enhancing the quality of public services necessitates an integrated approach, which combines understanding clients' needs, leveraging digital solutions and fostering the ability of institutions to adapt to change and implement innovations. In addition, Hammerschmid et al. (2019) research contributes to the discussion on the impact of the NPM reform by analysing the perceptions of senior public sector officials regarding changes in public service delivery across 20 European countries. The study findings suggest that a client-centred approach and flexible employment practices are directly linked to improved service quality, more effective policy coordination, greater equity in access to services and an overall enhancement of public administration performance (Hammerschmid et al., 2019). Therefore, despite ongoing global changes, the need to understand clients and identify their needs remains both essential and constant (OECD, 2022a). A good practice is the approach to develop service management systems that are based on identifying the needs of citizens and businesses, and designing public services based on specific life situations. This approach enables citizens and businesses to more easily locate and access the necessary public services.

The ability of public services to meet citizens' needs is a critical factor influencing not only their satisfaction with these services but also their overall trust in public administration. Pribadi (2013), by studying the relationship between an institution's organizational structure and satisfaction with public services in the Licensing Department of Indonesia, found that a well-organized institutional structure improves the quality of public services. In particular, physical aspects (clean and comfortable environments, well-equipped rooms and infrastructure) and employee courtesy (politeness, respectful attitude and responsibility) increase citizens' satisfaction with the provided public services (Pribadi, 2013). According to the OECD data, on average, 65.7% of citizens in OECD countries are satisfied with public services. However, it is important to note that satisfaction with healthcare and education systems, which are key elements of citizens' well-being, has declined over the past two years. Daily interaction through public services between citizens and public institutions is crucial, as it not only fosters trust in public administration but also in local governments (OECD, 2024b).

Trust in public administration is important not only at the national level but also on a broader scale. In OECD countries, the average level of citizen trust in public institutions in 2023 was only 39.3% (OECD, 2024b). Trust in public institutions is a relevant research topic and a significant indicator for evaluating the effectiveness and legitimacy of public sector performance. For example, Palmisano and Sacchi (2024), analysing 28 European Union countries from 2003 to 2019, confirm a negative correlation between income inequality and trust in national governments – if income inequality rises, citizens' trust in public administration diminishes. The study also highlights digital interaction between citizens and the public sector as a potential mechanism to alleviate the negative impact of inequality on trust in public institutions (Palmisano & Sacchi, 2024). Effective and transparent public services can drive a country's economic development by providing essential infrastructure, fostering human capital development and creating a stable business environment, ultimately enhancing citizens' quality of life while stimulating national economic growth. Given that public services are delivered through complex bureaucratic systems (Mansoor & Williams, 2024), many countries prioritize enhancing public service efficiency and reducing administrative burdens for citizens.

C. Pawlowski and H. Scholta (2023) indicate that proactive services are the next level of development for digital services, meaning that customer involvement is not required for the service to be provided. This implies that the customer does not need to submit an application to receive the service (Pawlowski & Scholta, 2023).

Regarding other public service development trends, Hodgkinson et al. (2017) highlight the Public Service-Dominant Logic (PSDL), which states that public administration shall operate as a value co-creation ecosystem, where citizens, the private sector and other stakeholders actively participate in the development and improvement of services. This approach also aligns with one of the future development trends of services outlined by the OECD – forward-looking and co-created public services. Similarly, Scupola and Mergel (2022), in their research on the digital transformation of

the Danish public sector, indicate that public administration institutions invest in citizen-centred services and the digital transformation of internal administrative processes while involving various stakeholders in the co-creation process. The results of the study show that co-creation was a key element in the success of digital transformation, from strategy and policy formulation at the national government level to implementation at the decentralized public administration level (Scupola & Mergel, 2022).

Drawing from public administration theory and research on the role of IT in the public sector, countries and municipalities should adopt targeted strategies to generate public value by effectively integrating IT solutions. Central to the concept of public value is the capacity of public administration to deliver high-quality, accessible services, the effectiveness and utility of which can be significantly enhanced through the use of digital technologies.

Conclusions

1. Public services serve as a fundamental pillar for the functioning of any state, ensuring societal well-being, economic growth, social justice and the overall quality of life for its citizens. Their effectiveness, accessibility and quality are intricately tied to governance models and strategies for resource allocation.
2. Empirical studies confirm that high-quality and efficient public services have a significant impact on citizens' satisfaction and trust in government. This can be further enhanced through increased citizen participation in service design and improvement as well as closer collaboration between citizens and government agencies.
3. The advancement of digital technologies requires a transformation of public administration principles to deliver solutions that address the evolving needs of citizens. Digitalization of public services provides the opportunity to ensure 24/7 accessibility, accelerate service delivery and streamline administrative processes, ultimately fostering more efficient governance and optimized resource allocation.
4. Current trends in public service development are reshaping the traditional public administration model, prioritizing collaboration and innovation as essential drivers of value creation. This approach aids in modernizing public governance, enhances citizens' trust in state institutions and fosters more transparent, efficient, inclusive and sustainable public service delivery.
5. Although various theoretical and practical solutions have been developed to improve the quality of public services, challenges related to the Trilemma – 'fast-good-cheap' in governance persist. Consequently, future research could explore the role of digital technologies and innovations in improving service delivery efficiency and speed, while maintaining high-quality standards and fostering public welfare growth.

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DIGITAL TRANSFORMATION OF FINANCIAL MANAGEMENT TO PROMOTE REGIONAL DEVELOPMENT

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Abstract
Digital transformation is considered one of the drivers of the implementation of the European Green Deal. To accelerate the transfer of business processes in a remote environment, both international and European Union (EU) and individual Member State regulations have been developed or are in the process of being developed. This study analyses the scope of existing digital transformation regulations in the EU and Latvia. The descriptive method has achieved the goal of identifying significant aspects and shortcomings in the regulatory framework that limit the implementation of digital transformation in financial management in the short term in all business units in all regions and thus hinder the sustainable development of the national economy in Latvia. The study concludes that the problems are caused by limited access to financing due to the volume of regulatory framework and its fragmentation, insufficient digital skills, lack of information and communication technology specialists, inability to integrate digital technologies into business processes, and unavailability of broadband Internet. As a negative aspect of the digital transformation process, the involvement of several ministries in the development of the regulatory framework for digital transformation and other binding documents has been emphasized. In order to ensure the most comprehensive digital transformation and reduce regional differences, it is necessary to create appropriate infrastructure, fast, accessible broadband internet, increase the level of digital skills and understanding of the population, and it is essential to ensure that the majority of companies use cloud computing, big data and artificial intelligence.
Keywords: sustainability, digital skills, digital environment, regional development.

Introduction

Digital transformation is a catalyst for rapid global change. To manage and steer this process effectively and strategically, a robust legal framework, along with recommendations, guidelines, and various support programs are essential. Numerous planning and legislative documents are currently being drafted to this end.

Several academic articles within the banking and public sectors underscore the critical role of digital transformation in enhancing competitiveness. Lydiana, Gustomo, and Bangun emphasize that the rapid growth of digital transactions worldwide, particularly during the COVID-19 pandemic, has accelerated digital adoption and shifted consumption patterns towards digital platforms. (Lydiana et al., 2022).

In the public sector, Berezhna and Filonych argue that, in the context of digital transformation, it is crucial to promote transparency and outline the goals of developing the information society, to establish the core principles, strategic objectives, expected results, and the main directions, phases, and mechanisms for execution, considering current trends and specific development factors (Berezhna et al., 2020). This is particularly important for the digitalization of public sector processes in any country, including Latvia.

The purpose of this study is to identify the key aspects and shortcomings within the regulatory framework that impede the short-term implementation of digital transformation in financial management across all business units and regions. These limitations also hinder sustainable economic development in Latvia and restrict its competitiveness. The object of the study encompasses international legislation, European Union documents, and the regulatory framework of Latvia in the field of digital transformation. The aim of the study is to analyse the scope and effectiveness of existing regulations related to digital transformation.

Materials and Methods

The present research is based on a range of scientific publications and regulations related to digital transformation, using the descriptive analysis method and covers the period from 2016 to 2020.

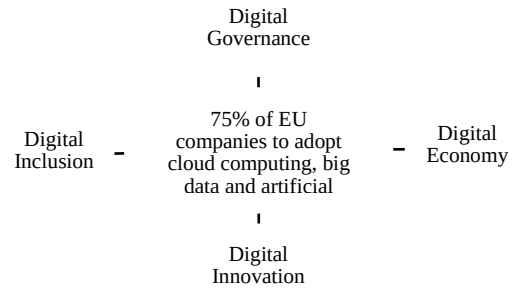
International framework for digital transformation

The digital environment is inherently comprehensive and international. The European Union is a signatory to the United Nations (UN) Framework Convention on Climate Change, adopted in 1995, a multilateral international treaty aimed at globally coordinating and stabilizing greenhouse gas concentrations in the atmosphere to levels that prevent dangerous anthropogenic interference with the climate system. One of the treaty's guiding principles is sustainable development, which seeks to promote economic growth in harmony with environmental protection. Key documents adopted to further reduce greenhouse gas emissions and limit global temperature increases include *the Kyoto Protocol* (1997) and *the Paris Agreement* (2015). Both *the Kyoto Protocol* and *the Paris Agreement* contribute to the advancement and application of digital technologies in climate change management, enhancing efficiency, transparency, and international cooperation (United Nations, 1995). Digital transformation is inherently dependent on the advancement and deployment of digital technologies. *The United Nations Development Programme (UNDP) Digital Strategy 2022-2025* aims to leverage digital technologies to promote sustainable development, enhance quality of life, and ensure equitable access to digital technologies for all. The Digital Strategy focuses on several key areas (Figure 1):

- Digital Inclusion: Ensuring that digital technologies are accessible to all by promoting the development

- of digital skills and infrastructure,
- Digital Governance: Enhancing data protection, privacy, and respect for digital rights while improving operational efficiency,
- Digital Economy: Supporting the growth of the digital economy by fostering entrepreneurship and innovation within the digital sector,
- Digital Innovation: Encouraging the development and deployment of new digital solutions to address the challenges associated with digital transformation (UNDP, 2022).

Figure 1
EU digital strategy and the goal



Source: authors' construction.

The behaviour of entrepreneurs and business participants is largely influenced by regulatory regulations. US researchers Thomas Donaldson and James P. Walsh emphasize that a business participant is anyone who interacts in the business environment (Thomas et al., 2015). It is believed that regulatory acts applicable to the business environment participate in its formation, regulation and also restriction.

On 11 December 2019, *the European Green Deal*, an EU strategy to make Europe the first climate-neutral continent by 2050, was introduced, building on documents adopted by the United Nations. This strategy encompasses a wide range of measures and initiatives aimed at promoting a sustainable economy, protecting the environment, and combating climate change. One of the key objectives of the *European Green Deal* is the integration of digital solutions within the business environment. The document includes a legally binding commitment to achieve climate neutrality in Europe, making it the first region in the world to do so (European Green deal, 2019).

To ensure that technology and innovation work for the benefit of people and to guide Europe's digital transformation by 2030, the European Commission has developed the European *Digital Decade Roadmap*. One of its primary objectives is to encourage at least 75% of EU companies to adopt cloud computing, big data and artificial intelligence. The program also aims to promote the digitization of small and medium-sized enterprises and to position EU companies as leaders in the global digital economy (Decision of the European Parliament, 2022).

EU legislation enhances the ability to achieve set objectives by incorporating them into various regulations. *The Regulation establishing a framework for promoting sustainable investment (2020)* stipulates that the EU taxonomy is an integral component of *the European Green Deal* (European Union, 2019). This taxonomy defines which economic activities are deemed environmentally sustainable. It is a critical tool for guiding Europe toward a sustainable and green future by providing clear standards for sustainable investment and entrepreneurship. Its objectives are:

1) To provide clarity and transparency for investors, businesses, and policymakers regarding which activities are environmentally friendly and sustainable.
2) To encourage the allocation of capital to sustainable projects and redirect investment away from environmentally harmful activities.

The taxonomy outlines specific criteria that economic activities must meet to be classified as sustainable (European Union, 2020).

The European Data Management Regulation (European Union, 2022) aims to enhance trust in data sharing, strengthen mechanisms to increase data availability, and address technical barriers to data reuse. This Regulation supports the creation and development of common European data spaces in strategic sectors, involving both private and public stakeholders (European Union, 2022).

The Regulation on Harmonised Rules on Fair Access to and Use of Data (2023) (Data Law) makes a significant contribution to the Digital Decade objective of advancing digital transformation. It regulates the European cloud market and protects companies from unfair contract terms imposed by more dominant players in the data sharing arena. The Regulation establishes a mechanism allowing the public sector to request data from companies when such data are urgently needed in emergency situations. It also introduces safeguards for data access and outlines essential interoperability requirements to ensure smooth data flow across sectors and Member States, facilitated by the Common European Data Area, as well as between data processing service providers (European Union, 2023b).

One of the primary aspects of *the Regulation on Electronic Identification and Trust Services for Electronic Transactions in the Internal Market (2014)*, commonly known as the eIDAS Regulation, is the establishment of mutual recognition of electronic identification documents (EIDs) issued by EU Member States. The main objective of the Regulation is to enhance trust in cross-border electronic transactions while improving the efficiency of online services and e-commerce platforms. The eIDAS Regulation facilitates secure cross-border transactions, which are crucial for international financial management (European Union, 2014b).

The Regulation on the Recovery and Resilience Facility (2021) aims to enhance Member States'

preparedness for crises, adaptability, and growth potential. It seeks to mitigate the social and economic impacts of the COVID-19 pandemic, support the achievement of the European Union's 2030 climate targets and 2050 climate neutrality objective, and facilitate the transition to a digital working environment (European Union, 2021b).

The Regulation declaring certain categories of aid compatible with the internal market (2014) applies to the following areas:

- regional aid,
- support for environmental protection,
- support for research, development and innovation,
- support for broadband infrastructure and local infrastructure,
- support for small and medium-sized business activities, investments and funding for digitisation processes European Union, 2014a).

The Temporary Recovery Instrument, *NextGenerationEU*, should be included in the legislation. Its primary objectives are to provide financial assistance to Member States for recovering from the economic and social impacts of the COVID-19 pandemic, support economic recovery and resilience against future crises, and promote the green and digital transition to foster a sustainable and competitive economy. This Temporary Recovery Instrument involves financing of up to EUR 807 billion by the European Commission through the issuance of EU bonds on capital markets (European Union, 2023a).

The relevance and interoperability of software, data migration and integration capabilities, and document management systems are crucial aspects of deploying digital technologies. *The European Interoperability Framework* (European Union, 2021a) addresses the exchange of information and knowledge between organizations by facilitating the integration of business processes through the exchange of data between relevant information and communication technology systems (European Interoperability Framework, 2021).

Artificial intelligence, which encompasses computer technology capable of performing tasks that typically require human intelligence, has become an indispensable tool in the digital transformation of numerous industries. The European Commission has developed *the European Parliament (2024)*, which outlines conditions for risk management based on a classification of risk levels specified in the document. The Act aims to establish a common framework for the use of artificial intelligence to ensure the security, reliability, and respect for human rights in AI systems (European Parliament, 2024).

The European Declaration on Digital Rights and Principles (European Commission, 2022) is a political document designed to promote and protect fundamental human rights in the digital age. The Declaration emphasizes the importance of sustainability and has been endorsed by the Presidents of the European Commission, the European Parliament, and the Council. It commits to:

- supporting the development and use of sustainable digital technologies that have minimal negative environmental and social impacts,
- stimulating sustainable consumer choices and business models, promoting responsible corporate actions across global value chains for digital products and services, and combating forced labour,
- promoting the development, implementation, and active use of innovative digital technologies with positive environmental and climate impacts,
- encouraging sustainability standards and labels for digital products and services (European Commission, 2022).

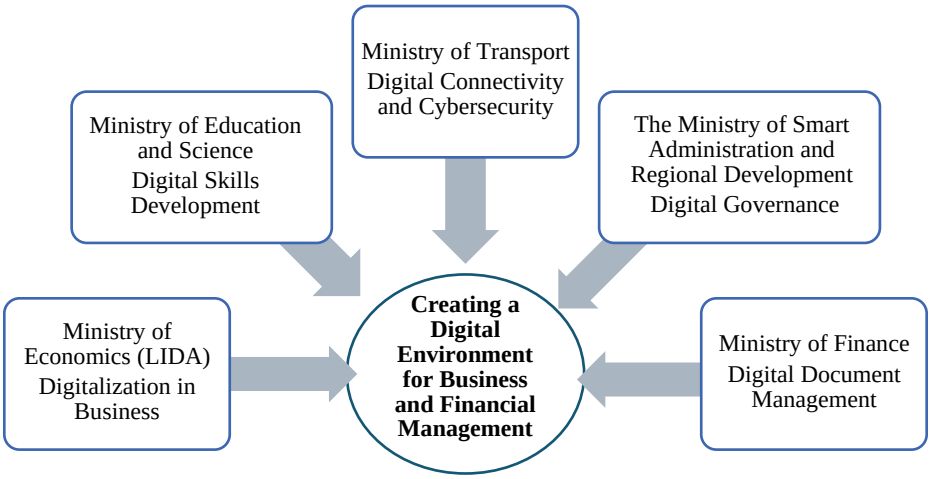
Latvian national legal framework for digital transformation

In Latvia, the legal framework for digital transformation is delineated by areas of responsibility among various ministries (Figure 2):

- the Ministry of Economics is responsible for allocating financial support for the digitization of processes in commercial activities and has delegated project implementation to the Latvian Investment and Development Agency (LIDA).
- the Ministry of Education and Science has received 212.9 million EUR from the European Recovery Fund, including 84.7 million EUR specifically for digital transformation. This funding is intended to enhance digital skills and raise awareness.
- the Ministry of Transport has developed regulations for the implementation of the *measure 'Single Cybersecurity Infrastructure' under the specific support objective 'Improving Digital Connectivity' of the European Union Cohesion Policy Programme 2021-2027*. The Ministry has also set priorities for the EU Funds in the 2021-2027 planning period, including enhancing Internet coverage and quality in rural areas.
- the Ministry of Smart Administration and Regional Development is responsible for digital transformation efforts, including the development of electronic governance, electronic identification, electronic documents, the information society, e-skills, and national information systems.
- the Ministry of Finance oversees the coordination of changes to the regulatory framework concerning the definition of the electronic format for accounting documents and the procedures for the circulation of documents and information.

The Digital Transformation Guidelines 2021-2027 articulate a vision for creating 'a favourable and modern living environment that leverages modern technologies and the ability of advanced societies to foster prosperity and economic growth through the effective application of digital technologies and the development of creative potential'.

Figure 2
Ministries involved in digital transformation and their areas of responsibility in Latvia



Source: authors' construction.

Digital transformation impacts all sectors and aspects of life. The guidelines address several current challenges:
• a shortage of digital skills,
• a lack of information and communication technology specialists,
• difficulties in integrating digital technologies into businesses.
The document outlines strategic actions to address or mitigate these issues. A key focus area for digital transformation is digital security, which encompasses:
1. Data protection, including personal data,
2. Protection of documents and information,
3. Business protection.
The guidelines emphasize that the most comprehensive digital transformation requires the establishment of appropriate infrastructure, including fast and accessible broadband internet. Developing this infrastructure is set as one of the primary goals of *the Digital Transformation Guidelines 2021-2027*. To support the provision of electronic communications networks, particularly high-performance networks, and the development of electronic communications services, *the Law on Electronic Communications (2022)* has been enacted. *The Development Plan for the Electronic Communications Sector for 2021-2027* identifies the following primary objectives:
1. Ensuring the availability of fast and reliable broadband internet throughout the country, including rural and remote areas;
2. Promoting the establishment and use of 5G mobile networks to enhance connectivity and support the deployment of new technologies and services;
3. Supporting investments in modernizing existing infrastructure and developing new communication networks;
4. Enhancing the security and reliability of electronic communications networks by protecting against cyberattacks and ensuring the continuous provision of services (Electronic communications sector Development Plan (2021).
Digital transformation, including digitization, is fundamental to business sustainability, innovation, productivity, efficiency and competitiveness. These aspects are supported by *the Regional Policy Guidelines 2021-2027*, which serve as a medium-term policy planning document. The guidelines outline the settings, strategic directions, and tasks associated with *the National Development Plan for 2021-2027* in the context of regional policy. The document aims to foster balanced regional development, reduce regional inequalities, and enhance the quality of life across all regions of Latvia. Key priority areas include the development of digital infrastructure to promote regional connectivity and accessibility (Regional Policy Guidelines, 2019).
One of the objectives is to enhance regional development and reduce inequalities between regions. Additionally, the Plan aims to promote environmentally friendly and sustainable development, improve infrastructure, and advance energy efficiency (Latvian national Development Plan, 2020).
The Latvian Sustainable Development Strategy 2010-2030 is a comprehensive framework outlining the country's sustainable development goals and priorities for the coming years. It includes measures to ensure economic growth, social well-being, and environmental protection, aiming to promote balanced and sustainable development throughout Latvia. The strategy emphasizes addressing regional disparities and fostering local potential to achieve a balanced regional development (Polsis, 2010). In contrast, one of the priority areas of *the Development Cooperation Policy Guidelines for 2021-2027* is to support economic development by creating jobs, promoting entrepreneurship, and encouraging innovation (For the Development Cooperation Policy Guidelines, 2021).

To structure comprehensive digital goals and targets aligned with the Digital Decade Roadmap of the European Parliament and the Council, the Latvian Ministry of Smart Administration and Regional Development has prepared an informative report on *the Strategic Roadmap for the Digital Decade in Latvia by 2030* (Latvian Ministry of Smart Administration and Regional Development, 2024). This report outlines key digital objectives:

1. Promoting the adoption and effective use of digital technologies across all sectors of the economy,
2. Enhancing digital literacy throughout society,
3. Ensuring universal and secure access to digital infrastructure.

To achieve these objectives, priority actions have been identified:

1. Stimulating entrepreneurship through the adoption of new technologies to create added value,
2. Improving digital skills by providing access to education and training for all segments of the population,
3. Modernizing public and municipal services by making them available in digital formats and enhancing their efficiency,
4. Developing and maintaining modern, secure, and high-speed digital infrastructure to ensure widespread internet access.

These objectives aim to ensure the sustainability of digital solutions through the integration of green technologies and enhanced cybersecurity (Latvian Ministry of Smart Administration and Regional Development, 2024). Latvia and other EU Member States face challenges related to insufficient funding in the commercial sector, particularly in regional areas. *The Recovery and Resilience Facility, as part of its operations to address these issues, provides financial support to mitigate the problem in alignment with the European Green Deal*. In Latvia, the support process for digitization in commercial activities from 2023 until 31 March 2026, or until funding is exhausted, is regulated by Cabinet Regulations (Implementation rules ..., 2023). The aim of these Regulations is to enhance the competitiveness of businesses through the adoption of digital technologies. They outline the activities eligible for support, as well as those excluded, and specify the conditions for implementation and oversight of the financing process. Transitioning financial management activities to a digital environment presents an opportunity to reduce the shadow economy.

In Latvia, *Shadow Economy Reduction Plan for 2024-2027* has been developed. A key component of this plan is the introduction and promotion of e-invoicing, which is pivotal for improving transaction transparency and control. Digital invoices facilitate the tracking of financial flows and contribute to more effective tax collection (Shadow Economy Reduction Plan, 2024).

Digital transformation in financial management processes is intrinsically linked to the digitization of accounting processes, facilitating real-time data access and enabling prompt decision-making in business operations. The digitization of all supporting documents and information is crucial for the effective transformation of accounting processes. During the transition from paper documents to e-invoicing, several laws have been enacted to manage the migration and content of financial documents into the digital realm. These laws regulate mandatory information to be included in documents, storage requirements, and document circulation procedures.

The Electronic Documents Law (2002) represents a significant advancement in promoting digital transformation in Latvia. It ensures more efficient and secure handling of documents across both public administration and the private sector. This Act governs the management of electronic documents, establishes principles for their development, storage, and management, and fosters international recognition and exchange of electronic documents (Electronic documents Law, 2002).

The Cabinet Regulations on *Procedures for the development, preparation, storage, and circulation of electronic documents in state and local government institutions, as well as procedures for the circulation of electronic documents between state and local government institutions and between these institutions and natural and legal persons (2005)*, outline the procedures for managing electronic documents within the public sector. These regulations also extend to the electronic documents of the private sector, where applicable (Procedures for the Development, 2005).

Cabinet regulations *procedures for converting public documents into electronic form* (2012) are also applicable in the private sector (Procedures by which public documents…, 2012).

The *electronic documents Act* provides that electronic documents have the same legal value as paper documents if they meet the required requirements. The requirements are defined in *the Law on legal force of documents (2010)*. The procedures for the drawing up *and drawing up of* documents (*2018) are laid down in the Cabinet Regulations as documents to* be drawn up in order to have legal effect. However, the procedures for the storage *of documents and information are* laid down in the Cabinet Regulation (Cabinet Regulation, 2024). The specific procedures for converting accounting documents into electronic form for electronic storage are laid down in *the Accounting Law* (2021).

Conclusions

1. In Latvia, *digital transformation guidelines for 2021-2027* have been developed based on the European legal framework. These guidelines address obstacles to digital transformation, such as shortages of digital skills and information and communication technology specialists, challenges in integrating digital technologies into businesses, and issues related to regional disparities and broadband internet accessibility.

2. *The Regional Policy Guidelines 2021-2027* emphasize the development of digital infrastructure to enhance regional connectivity and accessibility. The Ministry of Smart Administration and Regional Development has produced an informational report that identifies key challenges in areas such as digital skills, digital infrastructure, business digitization, and the digitization of public services, aiming to address these barriers.
3. A significant challenge to digital transformation is the lack of funding for the commercial sector in regional areas, a problem not only in Latvia but across other EU Member States as well. To address this issue, the EU has established *the Recovery and Resilience Facility*, which includes *a Recovery Fund program*. The procedures for obtaining financial support in Latvia are regulated by Cabinet Regulations.
4. A negative aspect of the digital transformation process is the fragmentation and complexity of the legislative framework, as well as the involvement of multiple ministries in developing regulations and other binding documents related to digital transformation.
5. To ensure a comprehensive and inclusive digital transformation, it is essential to develop appropriate infrastructure, including fast and accessible broadband internet coverage in all regions. This is a key priority for the Ministry of Smart Administration and Regional Development for the EU funding period of 2021-2027. Enhancing digital literacy and understanding among citizens is crucial for accelerating business processes and facilitating the transition of financial management to a digital environment. EU financial resources have been allocated to the Ministry of Education and Science to support this objective.
6. In the context of financial management digital transformation, it is vital for businesses to leverage cloud computing, big data, and artificial intelligence. The Ministry of Economics plays a crucial role in creating a conducive digital environment for financial management in the commercial sector by securing funding for the digital transformation of business processes. The Ministry of Smart Administration and Regional Development, by coordinating the digital transformation process and the Ministry of Finance, by determining the procedure for document and information circulation, can create a comfortable digital environment for financial management in the commercial sector, thus promoting the development of all regions of Latvia.

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POLICY, PRACTICE AND THE EXPERIENCES OF NEWCOMERS IN RURAL COMMUNITIES

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Abstract
Newcomers play a vital role in driving rural development, making attracting new residents essential for sustainable regional growth. As a result, the role of newcomers in rural areas, their attraction and integration are becoming increasingly important areas both in scientific research and within political discourse. This study aims to assess the relationship between measures included in policy planning documents for attracting residents and the practical experiences of newcomers in rural areas. By applying qualitative content analysis and analysing a range of national and regional level planning documents, the research delves into if and how the attraction of newcomers to rural areas and their integration into local communities are incorporated into these plans and policies. Simultaneously, the study explores the perspectives of newcomers based on previously published interviews, providing insight what attracts them to rural area and what are the challenges they encounter during the relocation process. The results reveal that policy planning documents mention attracting residents to rural areas as one of the priorities, and various support measures are planned to attract newcomers, including improving the quality of life, developing entrepreneurship, and providing social services. Analysis of practical experiences reveals a consistent disconnect between the measures outlined in planning documents and their effective implementation, thereby increasing the susceptibility of rural areas to depopulation.
Keywords: rural areas, newcomer attraction, place based policy.

Introduction

In recent years the role of more place-based approach in rural development increases in many European countries (Horlings, 2018; Vasta et al., 2019). In the context of rural depopulation, the role of municipal level population strategies, responsibility of municipality to attract new residents in many rural municipalities increases. Rural municipalities under depopulation more often are framed negatively in public discourse, and they could potentially pave the way towards alternative solutions and plans for local demographical strategies (Syssner & Siebert, 2020). The role of newcomers in rural areas and their integration are becoming increasingly important areas both in scientific research and within political discourse. Newcomers are a significant human resource asset for any rural community, especially in remote and depopulated rural areas (Bijker & Haartsen, 2012; Gieling et al., 2017). The vision, knowledge, skills and experience of newcomers enrich and empower local communities, contribute to the spread of remote work in the countryside, the creation of new economic practices, the development and recognition of places/territories (Dopitová, 2016; Goodwin-Hawkins et al., 2022; Kruzmetra & Bite, 2023; Merrell et al., 2022 a, 2022b; Píša & Hruška, 2019). Therefore, a place-based approach is also appropriate for addressing demographic challenges. Place based approach means that detailed local contexts are considered, resulting in development of specific solutions for each location. Place-based approaches argue that all places have untapped potentials to grow and that policies should consider a place's context and its diversity, it is spatially-aware policy (Barca, 2009; Hildreht & Bailey, 2014; Varga, 2017; Vasta et al., 2019).

One of the main elements in place-based approach is integrated planning. Effective rural development requires a holistic approach that integrates economic, social and environmental considerations. Place-based planning ensures that all these aspects are harmonized, promoting balanced and sustainable growth. Engaging local stakeholders, including residents, businesses and community organizations is crucial. Their intimate knowledge of the area's strengths and challenges allows for more relevant and effective development plans.

A place-based approach contributes by stimulating various local practices through policies as well as place-based policies and tools that let local resources to be the source of development. Place-based policy is an effective strategy to address these challenges by focusing on the unique characteristics and needs of specific areas, fostering sustainable development and revitalization, renewal of local society, attraction of newcomers. A place-based development policy can be defined as a long-term development strategy whose objective is to reduce persistent inefficiency (underutilisation of the full potential) and inequality (share of people below a given standard of well-being and/or extent of interpersonal disparities) in specific places (Barca, 2009).

Place based framework identifies two potential institutional weaknesses. Firstly, a tendency to lack both an understanding and knowledge of local places. This is identified in the literature as lacking a 'sense of community', which is a form of social capital that understands the local institutional context in which development takes place (Barca et al., 2012; Tabellini, 2010). Secondly, place based framework reveals weakness of capacity to adapt approach to mediate local consensus and trust between local actors as well as mobilize local resources effectively (Rodriguez-Pose & Storper, 2006).

At the same time recently it is possible to observe citizen-led initiatives, renewed interest in community, place, and 'local identity' (the privatization of public services; a re-emergence of the social economy; and tensions between 'bottom-up' initiatives and the changing role of the state). The co-production of governments and initiatives can potentially result in a shift from government-led to community-led planning (Silva et al., 2018). This research focuses on the policies and practices used against depopulation on municipality level, to increase the understanding on how municipalities work to counter depopulation, because the issue of depopulation is one of the most important challenges for many rural municipalities in Europe as well as in Latvia.

The aim of the research is to assess the relationship between measures included in policy planning documents for attracting residents and the practical experiences of newcomers in rural areas.

To achieve the aim, the following tasks have been set: (1) to investigate whether and how policy planning documents incorporate plans and measures aimed at attracting new residents to rural areas and (2) to analyse the practical experiences of newcomers to rural areas, to identify what attracts them to rural area and the challenges they encounter during the relocation process.

Materials and Methods

In order to assess the relevance of attracting newcomers to rural areas within policy planning documents, a qualitative content analysis method was selected for this research. This entailed the analysis of long-term and medium-term national policy documents, specifically the Sustainable Development Strategy of Latvia 2030 (hereinafter – Latvia 2030) and the National Development Plan of Latvia 2021-2027 (hereinafter – NDP 2027). Additionally, regional development programs for the planning regions of Kurzeme, Latgale, Vidzeme, and Zemgale (2021-2027), alongside the current development programs of all 36 municipalities in Latvia, were examined. The analysis evaluated whether and how these documents mention the attraction of newcomers to rural areas, whether specific measures are planned for their attraction and retention, and whether the integration of newcomers into the local community is reflected.

Content analysis as a research method was also applied to explore the lived experiences of newcomers in rural communities. The empirical study is based on published interviews with rural newcomers in the magazine 'Lauku māja' published between January 2024 and December 2024 (46 interviews in total were analysed), in which residents shared their experiences for relocating to rural areas and the challenges they encountered.

Results and Discussion

Analysis of policy planning documents

Rural areas, as an important living space for balanced and sustainable national development, are defined in key national-level planning documents – **Latvia 2030** and **NDP 2027**, which outline the general guidelines for state development. According to the vision expressed therein, Latvia will, in the long term, be a prosperous state of active and responsible citizens, while urban-rural partnerships will ensure a high quality of life throughout the territory of Latvia. The vision emphasizes the promotion of regional development, which will create preconditions for the development of the economic potential of all regions and the reduction of socioeconomic disparities among their residents. Latvia 2030 sets out a total of seven national priorities, several of which are related to the development of rural areas as a place of residence and the attraction and retention of residents therein. One priority is related to investments in human capital, including the provision of development directions such as mitigating the risk of depopulation, resource accessibility for residents, and education accessibility. The document mentions that schools serve as social networking hubs. Although these measures are not explicitly attributed to rural areas in the document, these areas face the most significant population decline and the implementation of these goals is particularly critical for them. Similarly, the document sets a special spatial development perspective as a priority, which highlights the Rural Development Space as one of the national interest spaces. It is also envisaged that urban-rural relations and functional linkages should become closer, and the development of transport infrastructure and communication networks should be promoted. It is planned to create equal living and working conditions for all residents, regardless of their place of residence, by promoting entrepreneurship in the regions and developing quality transport and communication infrastructure and public services. Regarding rural residents, the achievable indicator is set at a minimum of 30% of Latvia's population living in rural areas. Similarly, the long-term strategy sets innovative governance and public participation as a priority and emphasizes the need for public participation in governance processes, as this activates local communities and promotes the social inclusion of individuals in local communities.

In order to achieve the long-term vision, set out in Latvia 2030, the **NDP 2027** has set four main national strategic goals - Productivity and Income, Equal Opportunities, Social Trust and Regional Development which applies directly also to rural areas. They provide equal opportunities to receive good education, qualitative healthcare, decent work and be socially protected regardless of place of residence in all regions of Latvia, including rural areas. In turn, the promotion of regional development is intended to achieve the development of regional potential, the reduction of socio-economic disparities, and the improvement of the business environment. Regarding social integration, the document emphasizes the need to promote public trust in fellow citizens, which will

create a society in which everyone feels a sense of belonging and responsibility, thus increasing the common public good. The document mentions self-organization and cooperation skills and experience as essential for community cohesion, for example, participating in public organizations and doing volunteer work.

NPD 2027 also discusses in more detail the perspective of the **Rural Development Space** set out in Latvia 2030. It mentions the diversification of the economy in rural areas as a development direction in order to maintain rural population and reduce emigration, implementing interaction and cooperation with development centres. It also emphasizes the advantages of Latvia as a country rich in bioresources and the need to develop the use of bioresources in cross-sector partnerships in the production of high-quality, export-capable, high-value-added products. A significant role is also intended for strengthening community groups in order to maintain both urban and rural populations and promote an increase in living standards, to increase involvement in processes important to society, to promote civic interest and participation, and to promote mutual support initiatives.

Analysis of the development priorities outlined in **regional and municipality level development programs** reveals that local governments aim to attract **new residents through the following instruments**:

- improvement of the life quality - municipalities develop infrastructure, improve the availability of social services, ensure attractive living conditions and a family-friendly environment;
- promotion of education and employment - municipal scholarships are offered to young specialists, courses and training are organized, as well as career development measures are developed;
- improvement of housing accessibility – various programs for housing accessibility and rental support measures for young specialists, teachers and healthcare workers are developed;
- supporting entrepreneurship and attracting investment - municipalities develop industrial zones, offer support mechanisms for young entrepreneurs and organize marketing campaigns to promote local businesses;
- public involvement and strengthening the local community - organized resident forums, public consultations and surveys to promote the participation of young residents in the development of the municipality;
- improved accessibility of social and health services - health care centers are being developed and support programs are being created to attract doctors, especially to more remote areas.

The planning documents also provide **measures to attract new specialists**. For example, tax breaks and financial support are provided for young specialists - municipal grant programs for young entrepreneurs and specialists who want to start their own business. Various support measures for home production and small business are also provided, as well as tax breaks for entrepreneurs to motivate them to stay in the municipality. In their planning documents, local governments prioritize the recruitment of specialists within the education and healthcare sectors, specifically through scholarships for young professionals, especially teachers and medical personnel, with obligations to work in the municipality after graduation. It is also planned to create housing support programs, such as rental subsidies, that are offered to teachers and doctors.

In addition, in order to retain young people in the regions, youth employment promotion programs are being created. For example, there are:

1) financial support during and after studies: several regions implement scholarship programs that motivate young specialists to return after studies and work in a specific municipality;
2) professional education and career development opportunities: school career advisors actively encourage young people to choose specialties in demand in the region, such as medicine and education;
3) creation of jobs and internships: municipalities cooperate with local entrepreneurs to provide internships for young people;
4) some municipalities have developed a voluntary work system that gives young people their first work experience and improves employment prospects;
5) support for youth entrepreneurship: young people's business ideas are stimulated by municipal grant programs that provide financial support to young entrepreneurs;
6) non-formal education and training programs: organized courses and training that help young people develop skills needed for the labor market.

The analysis of municipality development programs highlights a correlation between municipal size and the observed trends in attracting new residents. In **large municipalities with more than 40,000 inhabitants**, economical aspects such as attracting business and investment is dominant. Housing accessibility improvement is also an important aspect - new residential projects and rental support programs are being developed. In **medium-sized municipalities** (20,000 – 40,000 inhabitants), development strategies are more versatile, as they combine economic stimulation with improving the quality of life. These municipalities try to ensure a balanced approach between quality of life, education and entrepreneurship. There is a strong emphasis on local community development and citizen participation in municipal decisions, as well as participatory budgeting programs. According to this study in **small municipalities** (under 20,000 inhabitants), development programs focus on retaining residents and mitigating demographic decline which was not so visible in the development programs of larger

municipalities. The main emphasis in them is on the development of local businesses and agriculture. Such municipalities try to attract new residents with housing support programs and initiatives to attract specialists. Promoting remigration is also an important strategic goal - support measures are organized to return residents who have left. Emphasis is placed on strengthening the local community - participation of residents in municipal decisions and support for public activities.

Experiences of newcomers in rural area

The analysis of practical experiences confirms that the **reasons why residents choose to move to the rural areas** can be classified into several groups. One of them is related to (1) **personal desires for a change in lifestyle**. This may be related to the desire for peace and greater privacy of living space. For many, life in the city has caused fatigue, stress and burnout; therefore, moving to the rural area has seemed like an opportunity to escape from that. The desire for the presence of nature in everyday life is also important for Latvians: 'Why do people need the countryside? To remember where we all came from, to be closer to the land. Namely, the countryside gives more grounding, an understanding of who you are and where you come from'. Another important factor is sentiment and the romanticization of rural life, which is significantly influenced by childhood memories of carefree time spent in the countryside. It is important to note that this empirical analysis is primarily based on middle-class residents, which may lead to a more positive look on rural life compared to those from lower socio-economic groups.

The second reason for changing residence to the rural area is related to (2) **family circumstances**. The desire for a safer living space and proximity to nature is significantly created by the arrival of children in the family. 'Over time, you, a person, mature and understand that, for example, you do not want to raise children in Riga. 'In the countryside' [..] at least the children will be able to go out into the countryside, they will be able to keep chickens there and grow a minimum of food in the garden. 'Similarly, the expansion of the family creates a greater emotional connection with one's family, thus often a desire arises to return to family home, preserve it and renovate it'. Often, the availability of family homes or the opportunity to purchase property close to one's hometown has been one of the main attractors for returning to the countryside.

An important factor in moving to the rural area is (3) **economic factors and the availability of properties**. Housing in the rural area is often cheaper than equivalent housing in the city, which is one of the decisive factors in choosing a place to live, especially for families with children. Practical experience shows that the rural area also has the potential to be a living space where you can create and develop a business. Some of the interviewees have developed home production, others have learned new skills in pottery processing and creating a pottery workshop, others have created a metalworking workshop on their rural property. Several have acknowledged that local governments have also played an important role in the development of small businesses, both by offering premises and providing other types of support. It is mentioned that they have received significant support for the development of business thanks to the opportunities to write projects and receive financial resources from various European co-financing support funds available to rural residents. Similarly, rural tourism and hospitality are one of the areas that can provide additional income in rural areas. One of the interviewees admitted that he initially purchased a rural property with the aim of investing financial resources to create an airbnb-type dwelling and offer it to tourists. However, having invested so much of himself, the new place of residence became dear to him, and he did not want anyone to ruin it. The Covid-19 pandemic and the remote work opportunities it provided were a significant turning point that allowed for many to fulfill their dream of living in the rural area. It has allowed to maintain a connection with work and educational institutions in cities, while at the same time farming in the countryside, which has often also created a desire to stay in the countryside forever.

Practical experiences also reveal the biggest **challenges and difficulties** in the process of residents moving to the rural area. The identification of challenges constitutes a crucial factor in the future retention of newcomers within rural areas. One of the most significant challenges mentioned by newcomers to the rural areas is the accessibility of education. Families with children are concerned about the impact of school reforms and the potential closure of schools on their ability to continue providing their children with access to education close to their place of residence. 'Behind the cold Excel calculations and inevitable change slogans stand real, living people and destinies. It is clear that there will be changes in the immediate vicinity, and not the kind that inspires choosing a rural life. Education and its convenient accessibility should be seen as an investment in our future. 'There is also an opinion that 'providing quality education and developing other talents while living in the countryside requires more investment than living in the city', as wider opportunities for children's education are still available in cities.

The availability of quality and affordable housing in rural areas is also often mentioned as a significant challenge for residents to move to the countryside. Several newcomers have admitted that finding suitable property has taken time. At the same time, several newcomers have acknowledged that the municipality has been interested and has provided support in the housing search process. Although properties in rural areas are empty, many of them are uninhabitable due to long-term uninhabited properties and require significant investment to improve them.

Despite the fact that necomers have consciously chosen a more peaceful life in the countryside, several

of them admit that they feel a lack of social and cultural life in their new place of residence. 'One of the biggest challenges is the distance to the epicenters of social life. If there's a concert in the evening, then after coming home from work and sitting there for two hours, I won't want to drive the forty km back'. At the same time, empirical research reveals that socializing with local residents and neighbors plays a particularly important role in rural areas. Most newcomers highly valued close neighborly relations and mutually beneficial support in various everyday situations, such as lending equipment, clearing roads in winter, or driving to the store together. This shows that the social integration of newcomers in rural areas has been successful.

Additional challenges for newcomers to rural areas are posed by disorganized infrastructure, including roads in poor condition. This makes it difficult for residents to reach the administrative centers of the regions, where the most essential daily services are concentrated, and also makes it difficult to develop small businesses. In addition, high-quality internet access plays a very important role in the quality of life in rural areas and the development of entrepreneurship, which, according to newcomers, is something that could be improved in many remote regions.

Analysis of policy planning documents and practical experiences reveals that, in general, policy strategies are aimed at attracting newcomers to rural areas. They include the most important directions for newcomers, which can encourage new residents to move to the countryside, such as economical benefits, improvement of life quality and integration in local community. For example, the promotion of entrepreneurship in rural areas is one of the main priorities included in policy documents, the practical implementation and municipal support of which has been positively assessed by newcomers in rural areas. Newcomers in rural areas have also positively assessed the interest of municipalities in the housing search process, which is also defined as a priority in the planning documents of many municipalities. At the same time practical experiences reveal a consistent disconnect between the measures outlined in planning documents and their effective implementation. Newcomers often face limited social and cultural life opportunities in rural areas and poor-quality infrastructure. This indicates that, although the improvement of quality of life is emphasized in policy documents, in practice this goal is not always achieved. Similarly, the equal opportunities for access to education services for all, as defined in policy documents, do not always correspond to reality and pose a potential risk of further depletion of rural areas. In order to attract and retain newcomers in rural areas more effectively, it is necessary not only to include visions and priorities in policy documents, but also to ensure their effective implementation and take into account the real needs and challenges of residents. It is important not only to emphasize economic aspects, but also to pay attention to social, cultural and infrastructure issues that are essential for the quality of life of newcomers in rural areas.

Additionally, examples from abroad indicate that location marketing campaigns can be successful in attracting new residents (Niedomysl, 2007), since they popularize the rural life idyll and a romantic perception of it, which, according to the analysis of practical experiences of this study, are some of the most crucial expectations urban residents have for living in rural areas. Unfortunately, the analysis of local government planning documents does not clearly indicate that these kinds of activities are included in their programs with the aim to attract new residents. Perhaps municipalities should place more emphasis on different types of location marketing initiatives.

The fact that municipalities, especially those with the smaller amount of residents, plan actions for strengthening the local community in their strategies can be evaluated very positively, because sense of community often is a weak point of them. Also, experiences of newcomers confirm that activity of local community is very important for the successful integration of newcomers in rural areas. Studies (De Haan, 2019; Larsson, 2014) show that an active local community contributes to the efficiency of local governance. When residents are encouraged to feel a sense of belonging to a community, the prerequisites are created for them to take greater responsibility for their place of residence, their wellbeing and also physical living environments. In this way, a 'participation society' is created. According to De Haan (2019), entailing more active citizen participation, implies a change in role patterns, responsibilities and power relations for both residents and governments. Thus, it also benefits administrative institutions, basing the future development plan on the real needs of the municipality.

Conclusions

1. Rural areas as a living space and their inhabitants are identified in national planning documents as one of the priorities for balanced regional development.
2. In regional and local development strategies, the attraction of new residents is addressed through key action directions focused on: improvement of the quality of life, promotion of education and employment, improvement of housing accessibility, supporting entrepreneurship and attracting investment, public involvement and strengthening the local community, and improved accessibility of social and health services.
3. Differences in resident attraction measures can be observed between municipalities of varying sizes. In large and medium-sized municipalities, planning documents primarily focus on economic development, ensuring housing availability, and improving the quality of life for their residents. In contrast, the measures included in the planning documents of small municipalities are more practical and specifically aimed at retaining existing residents and attracting new ones.

4. The main reasons that attracts residents to rural areas are related to personal desires for a change in lifestyle (including the desire for peace and quiet), family circumstances and a reluctance to raise children in an urban environment, as well as economic factors and the availability of properties.
5. Although the most significant priorities for newcomers, which would attract them to relocate to rural areas, are included in various level policy planning documents, their practical implementation is often not fully achieved and it poses a potential risk of further depletion of rural areas.

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TECHNOLOGY TRANSFER MODELS AND INNOVATION ECOSYSTEMS - COMPARATIVE INSIGHTS FROM STANFORD, MIT, CAMBRIDGE, AND OXFORD

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Abstract
Technology Transfer Offices (TTOs) are instrumental in translating academic research into market-driven innovation, acting as core enablers of university–industry collaboration. However, TTO models and their effectiveness differ substantially across institutional settings and regional innovation ecosystems. This study conducts a comparative analysis of TTO models at four leading universities—Stanford, MIT, Cambridge, and Oxford—focusing on the structural, strategic, and contextual factors that drive technology transfer efficiency. Applying a mixed-methods approach that integrates comparative case studies, secondary data synthesis, and patent analytics, the paper identifies critical differentiators in TTO operations. These include intellectual property governance, spin-off facilitation, licensing flexibility, and the adoption of emerging digital tools such as AI-based patent analysis and blockchain-enabled IP management. Findings reveal that US-based institutions prioritise commercial agility and entrepreneurial integration, while UK-based counterparts emphasise institutional stability and regulated knowledge dissemination. The research offers a strategic framework for aligning TTO governance with regional innovation capacities and institutional priorities. It also highlights the importance of ecosystem-specific adaptation, suggesting that hybrid models combining agility with regulatory depth may enhance technology transfer outcomes in diverse settings.
This study contributes to the ongoing discourse on innovation ecosystems by providing empirically grounded, comparative insights that are relevant for university administrators, innovation policymakers, and stakeholders involved in commercialising academic knowledge.
Keywords: technology transfer offices (TTO), innovation ecosystems, knowledge commercialization.

Introduction

Technology Transfer Offices (TTOs) play a pivotal role in the knowledge commercialisation ecosystem, facilitating the transformation of university-generated innovations into economically viable solutions. By doing so, they reinforce the strategic positioning of universities within both regional and global innovation architectures (Bozeman et al., 2015; Wright & Drori, 2021). Technology transfer is not merely a linear diffusion process but rather a dynamic, interdisciplinary mechanism, intricately interwoven with regional economic structures, institutional frameworks, and investment ecosystems (Rothaermel et al., 2007).

Leading universities such as Stanford, MIT, Cambridge, and Oxford have developed specialised technology transfer mechanisms, but their effectiveness varies with regional innovation capacity, regulations, and financing models (Debackere & Veugelers, 2005; Shane, 2004). Stanford, MIT, Cambridge, and Oxford are consistently ranked among the top institutions in global innovation output and university spin-off performance (e.g., THE World University Rankings, UBI Global, 2024). Understanding these differences is key to optimising TTO governance and innovation diffusion (Markman et al., 2005). The study compares Technology Transfer Office models at four leading universities to identify key factors influencing technology transfer efficiency. It examines structural, administrative, and market mechanisms shaping TTO performance (Hughes & Kitson, 2012). The methodology combines theoretical and empirical modelling, document analysis, and interregional comparison to reveal universal and context-specific strategies (Fischer & von Proff, 2020; Roberts & Eesley, 2011). The study holds dual significance. Theoretically, it contributes to the discourse on universities' roles in regional innovation systems and technology transfer dynamics, integrating the Triple Helix framework (Etzkowitz & Leydesdorff, 2000) and Open Innovation paradigm (Chesbrough, 2003). Practically, the findings provide strategic recommendations for universities, innovation policymakers, and TTO leadership to enhance market-oriented and economically productive technology commercialisation models.

In the contemporary knowledge economy, where university-driven innovation is a key vector of economic transformation, TTO efficiency not only determines institutional competitiveness but also influences regional innovation systems' capacity to integrate and monetise knowledge assets (Audretsch & Feldman, 1996). This study offers a holistic perspective on TTO functionality in higher education institutions, delivering a strategically granular analysis that facilitates the adoption and adaptation of best practices in university-led innovation governance. For clarity, this study does not present a global scope but focuses on two advanced innovation regions: the United States (Stanford, MIT) and the United Kingdom (Cambridge, Oxford). Although the UK is not part of the EU, it is included as a European benchmark for regional TTO strategies. The study aims to develop a comparative framework that explains how structural, policy, and ecosystem factors shape TTO efficiency in leading US and UK

universities, with the goal of extracting transferable strategic insights applicable to other institutional contexts.

Materials and Methods

The study uses a mixed-methods approach, combining literature review, case studies, and patent registry analysis. Theoretical grounding was established through a systematic review on TTO operations, efficiency factors, and regional innovation ecosystems. Case studies of Stanford, MIT, Cambridge, and Oxford examined structural models and commercialisation strategies. Patent data from EU and US registries assessed IP management and innovation trends. Document analysis included TTO reports, licensing data, and governance strategies. The comparative approach highlighted both shared and context-specific TTO practices.

While this study does not rely on original fieldwork or primary survey data, it employs a triangulated secondary data methodology. This includes a comparative synthesis of university TTO structures, annual patent and licensing reports, policy frameworks, and sectoral performance indicators. The methodological design emphasises interpretive depth over statistical generalisability, in line with the case-oriented qualitative paradigm appropriate for institutional ecosystem analysis.

Results and Discussion

(A) Theoretical Framework of TTOs and Their Role in Innovation Ecosystems

Technology Transfer Offices (TTOs) represent a critical interface in the knowledge flow between academia and industry, facilitating the transformation of scientific discoveries into commercially viable solutions (Bozeman et al., 2015; Wright & Drori, 2021). The Triple Helix model conceptualises TTO operations as an interdependent collaboration system among universities, industry, and government, where institutional synergies drive innovation development (Etzkowitz & Leydesdorff, 2000). The efficiency of TTOs is closely linked to knowledge management effectiveness, which encompasses intellectual property protection, optimisation of licensing strategies, and fostering industry collaborations (Markman et al., 2005; Debackere & Veugelers, 2005).

TTO performance is traditionally measured through patent volume, licensing revenues, and spin-off firm creation, yet the significance of these metrics depends on the regional innovation model (O'Shea et al., 2005; Fischer & von Proff, 2020). The literature presents contrasting perspectives on the role of TTOs in innovation ecosystems. Some scholars emphasise TTOs as catalysts accelerating knowledge commercialisation, while others critique them as bureaucratic intermediaries that hinder technology transfer processes (Siegel et al., 2003).

Leading global universities—Stanford, MIT, Cambridge, and Oxford—have developed distinct TTO models tailored to their institutional priorities, funding mechanisms, and regional innovation dynamics. Their approaches illustrate varied strategies in balancing commercialisation efficiency with academic and industry collaborations, reflecting broader structural and policy-driven differences in technology transfer frameworks.

Technology transfer efficiency within these institutions is a dynamic yet heterogeneous process, shaped by historical developmental trajectories and institutional adaptability to commercialisation challenges (Shane, 2004; Kenney & Patton, 2011; Lawton Smith & Ho, 2006). Stanford and MIT exhibit a high degree of adaptability, responding proactively to market fluctuations and maintaining close integration with venture capital ecosystems. In contrast, Cambridge and Oxford prioritise stable, long-term academic-industry partnerships, ensuring gradual innovation commercialisation, particularly in highly regulated sectors such as biomedicine and pharmaceuticals (Huggins, 2008).

Stanford's Office of Technology Licensing (OTL) has established a high-efficiency, low-bureaucracy model, optimising technology transfer within the fast-paced Silicon Valley innovation ecosystem. The emergence of spin-off giants such as Google and Genentech exemplifies the success of this model (Murray, 2004; Kenney & Mowery, 2014). With over 250 patent applications annually, Stanford demonstrates a strong intellectual property commercialisation capacity (Stanford OTL, 2024).

MIT integrates technology transfer into its broader entrepreneurial strategy, with the Technology Licensing Office (TLO) combining IP protection and structured spin-off support. This model effectively supports high-tech sectors like AI, robotics, and energy, where rapid market dynamics prevail (van Pottelsberghe & Françon, 2023; Roberts & Eesley, 2011). With around 350 new patent filings annually, MIT demonstrates strong performance in technology transfer efficiency (MIT TLO, 2024).

Cambridge's technology transfer model, led by Cambridge Enterprise Ltd., follows a centralised and highly regulated approach. Unlike US institutions focused on rapid commercialisation, Cambridge builds long-term partnerships with industry and government, emphasising full technology maturation before market entry. This reduces market risk but extends the innovation uptake cycle (Lawton Smith & Ho, 2006). With a more selective commercialisation strategy, Cambridge files around 150 patents annually (Cambridge Enterprise, 2023).

The Oxford technology transfer model, overseen by Oxford Innovation Ltd., adopts an even more conservative stance, focusing on high-value licensing agreements and publicly funded research initiatives. Its core emphasis lies in biotechnology and

pharmaceuticals, where long-term investments and clinical validation requirements significantly influence the pace of technology transfer (Hughes & Kitson, 2012). Oxford's annual patent output averages around 130, reflecting a selective but high-quality intellectual property management strategy (Oxford Innovation Ltd., 2023a).

A detailed analysis in Table 1 reveals structural divergences in university TTO models, largely influenced by their degree of integration within regional innovation ecosystems. US universities exhibit greater entrepreneurial dynamism and adaptability, driven by their close ties with venture capital networks and more flexible licensing frameworks (Kenney & Patton, 2011). In contrast, European universities, particularly Cambridge and Oxford, maintain a more conservative approach, fostering stability and long-term industry collaboration but simultaneously introducing greater barriers to rapid technology transfer (Huggins, 2008).

Table 1

Comparative Analysis of Strategic Models, Structural Dynamics, and Regional Influence of Technology Transfer Offices (TTOs)

Criterion	***Stanford***	***MIT***	***Cambridge***	***Oxford***
TTO Model	Decentralised, entrepreneurship-driven	Hybrid model, strong industry collaboration	Centralised, academically structured	Centralised, state- and industry-regulated
Spin-off Enterprises	Very high volume, closely linked to Silicon Valley	High volume, strong VC and incubator links	Moderate volume, long-term industry partnerships	Moderate volume, specialising in biotech and pharmaceuticals
IP Management	High autonomy, simplified patent transfer	Flexible, pro-entrepreneurship policy	University retains ownership, licensing control	Strictly regulated IP management, slow commercialisation
Annual Patent Filings	~250 new patents (Stanford OTL, 2024)	~350 new patents (MIT TLO, 2024)	~150 new patents (Cambridge Enterprise, 2023)	~130 new patents (Oxford Innovation Ltd., 2023b)
Licensing Strategy	Flexible, prioritising spin-off enterprises	Multi-tiered royalties, startup-friendly models	Long-term contracts with industrial partners	Conservative approach, priority to the biomedical sector
Market Analysis	Early-stage analysis, strong investor ties	Specialised analysis within TLO operations	Market analysis conducted at later stages	Cautious market evaluation before deployment
Key Collaboration Areas	IT, artificial intelligence, biomedicine	Robotics, energy, pharmaceuticals	Biotechnology, materials science	Focus: pharma, biotech, sustainability.
Regional Innovation Influence	Silicon Valley dynamics, strong VC engagement	Boston biotech cluster, corporate innovation	Cambridge cluster with long-term industry ties	Government-funded Oxford biomedical hub

Source: Author's structured synthesis based on theoretical frameworks and empirical literature analysis.

Note: While the comparative data presented reflect institutional self-reported indicators, further quantification through longitudinal analysis could enrich the causal interpretation of TTO model effectiveness. For instance, correlation between IP policy autonomy and spin-off volume may warrant econometric modelling in future studies.

Stanford and MIT employ decentralised, entrepreneurship-driven TTO models closely tied to the venture capital ecosystem, enabling high spin-off rates and active licensing (Shane, 2004; Kenney & Mowery, 2014). This has accelerated commercialisation significantly. Since 1970, Stanford's TTO has grown its annual patent filings to over 250, reflecting an adaptive strategy aligned with market dynamics (Zou et al., 2020). MIT similarly curates its IP portfolio to match market demand, enhancing industry engagement and fostering entrepreneurial innovation (MIT TLO, 2025).

Unlike the market-driven US models, Cambridge and Oxford follow a centralised TTO structure focused on long-term academic-industry collaboration (Hughes & Kitson, 2012; Lawton Smith & Ho, 2006). This promotes in-depth technological development but can slow commercialisation due to centralised IP

ownership and tighter regulation. Oxford's IP policy requires university ownership of all inventions developed with its resources, supporting a controlled transfer model that emphasises structured knowledge dissemination over rapid market entry (Oxford University Intellectual Property Policy, 2020).

Technology transfer efficiency depends on a university's capacity to align with market demands and adapt to regional innovation policies (Debackere & Veugelers, 2005). MIT exemplifies this through a proactive market strategy and flexible licensing, allowing swift responses to technological shifts and industry needs, ensuring effective commercialisation and global competitiveness.

Patent strategies differ notably across leading universities. MIT and Stanford maintain high patenting rates, promoting faster commercialisation, while Cambridge and Oxford emphasise extended technology maturation. US institutions offer researchers more IP autonomy, encouraging entrepreneurship, whereas UK counterparts exercise greater institutional control, often slowing the process.

Licensing strategies also contrast: MIT and Stanford apply market-driven models early in development, accelerating deployment. Cambridge and Oxford prioritise long-term partnerships and broader knowledge dissemination, reflecting a more conservative commercialisation approach (Cambridge Enterprise, 2023; Oxford Innovation Ltd., 2023c).

Although all examined TTOs aim to facilitate technology transfer and innovation, their strategies differ based on institutional context, resources, and priorities. Stanford and MIT pursue flexible, market-driven models focused on spin-offs and venture capital, while Cambridge and Oxford emphasise long-term partnerships with industry and government. These structural distinctions shape TTO efficiency, market adaptability, and regional economic impact.

A key challenge for TTOs is limited funding and resource constraints, which hinder effective IP management and slow commercialisation (Fischer & von Proff, 2020). Even resource-rich institutions like Stanford and MIT struggle to commercialise all innovations promptly, as insufficient early-stage capital can restrict the growth of their technology transfer ecosystems (MIT TLO, 2024; Stanford OTL, 2024).

Administrative barriers play a significant role in hindering academic innovation commercialisation, especially in European universities where IP is tightly centralised (Siegel et al., 2003). At Cambridge and Oxford, researchers have limited autonomy, as the universities retain patent ownership and control licensing terms (Cambridge Enterprise, 2023; Oxford Innovation Ltd., 2023b). In contrast, US universities offer more flexible IP policies—academics engage directly in licensing and receive a larger revenue share, boosting commercialisation outcomes (Baldini et al., 2007). MIT, for example, provides substantial financial incentives to faculty, supporting an entrepreneurial innovation culture (MIT TLO, 2024). Conversely, Oxford and Cambridge prioritise institutional control, limiting spin-off activity and slowing technology transfer (Oxford Innovation Ltd., 2023b).

Market adaptability remains a key challenge, as many university innovations fail to commercialise due to poor market fit (Wright et al., 2007). This is especially evident in biomedical and deep-tech sectors, where trials and regulation slow progress. Oxford's biomedical spin-offs often face delays in IP protection and funding, unlike their US peers in more agile investment environments (Oxford Innovation Ltd., 2023a).

To mitigate key challenges, leading universities implement targeted strategies aimed at accelerating technology commercialisation and minimising risks. Early-stage industry collaboration is a critical mechanism that reduces uncertainties in technology transfer and expedites innovation deployment (Ankrah & Al-Tabbaa, 2015). Stanford and MIT have developed integrated collaboration platforms that are deeply embedded within entrepreneurial ecosystems, facilitating the efficient scaling of spin-off enterprises (MIT TLO, 2024; Stanford OTL, 2024).

Flexible licensing accelerates technology transfer. MIT and Stanford use tiered royalties and VC integration to speed market entry (van Pottelsberghe & Françon, 2023). Oxford and Cambridge, though traditionally conservative, are gradually adapting in biotech and digital sectors (Cambridge Enterprise, 2023; Oxford Innovation Ltd., 2023a).

The integration of digital technologies is emerging as a key driver of TTO optimisation. Artificial intelligence and blockchain applications are increasingly utilised for intellectual property management, automating patent processing and licensing workflows. MIT and Stanford actively experiment with these advancements, aiming to accelerate commercialisation cycles and enhance industry collaboration frameworks (MIT TLO, 2024; Stanford OTL, 2024).

Table 2 provides a comparative analysis of challenges and strategic responses in university technology transfer offices (TTOs).

The findings indicate that Stanford and MIT TTO models exhibit high dynamism and flexibility, particularly in licensing structures, spin-off formation, and the integration of digital tools, which enhance their competitiveness in rapidly evolving technological landscapes. In contrast, Cambridge and Oxford TTO strategies emphasize stability and long-term partnerships, fostering a structured but slower technology transfer process.

Table 2
Comparative Analysis of Challenges and Strategic Responses in University Technology Transfer Offices (TTOs) for Innovation Commercialisation

Challenge	***Strategic Responses to Mitigate Challenges in University TTOs***			
	Stanford	***MIT***	***Cambridge***	***Oxford***
Funding and Resource Constraints	High self-financing via licensing, but VC reliance adds financial volatility (Stanford OTL, 2024).	Significant funding from spin-off equity and industry partnerships, yet early-stage financing remains a constraint (MIT TLO, 2024).	Limited early-stage funding; high reliance on public and private grants (Cambridge Enterprise, 2023).	Strong public and EU funding, but slow administration delays investment flow (Oxford Innovation Ltd., 2023b).
Bureaucratic Barriers and Governance Flexibility	Decentralised model with minimal regulatory oversight, expediting commercialisation (Murray, 2004).	Balanced governance between academia and industry, requiring robust administrative capacity (van Pottelsberghe & Françon, 2023)	Centralised IP management slows down processes but ensures institutional stability (Lawton Smith & Ho, 2006).	Highly regulated and administratively complex framework, delaying decision-making (Hughes & Kitson, 2012).
IP Ownership Conflicts	Researchers retain higher autonomy over patents, accelerating commercialisation (Stanford OTL, 2024).	Academics receive a substantial share of licensing revenues, incentivising involvement (MIT TLO, 2024).	University retains full IP rights, limiting researcher motivation for commercialisation (Cambridge Enterprise, 2023).	Strict university-controlled IP ownership complicates spin-off formation (Oxford Innovation Ltd., 2023b).
Technology Readiness and Market Adaptability	Early industry engagement and accelerator programs enhance product-market fit (Kenney & Mowery, 2014).	TLO conducts extensive market analysis and develops adaptive commercialisation strategies (MIT TLO, 2024).	Market analysis occurs in later innovation stages, reducing adaptability (Cambridge Enterprise, 2023).	Biotech and pharma commercialisation cycles are long and require high initial investment (Oxford Innovation Ltd., 2023b).
Spin-off Formation Dynamics	High spin-off formation due to venture capital accessibility and an entrepreneurial ecosystem (Shane, 2004).	MIT shows high spin-off activity in high-tech, driven by strong innovation infrastructure (Roberts & Eesley, 2011).	Moderate spin-off formation, prioritising long-term industry partnerships (Cambridge Enterprise, 2023).	Oxford prioritises high-value spin-offs in biomedicine and pharma (Oxford Innovation Ltd., 2023b).
Licensing Flexibility and Market Adaptation	Adaptive licensing strategy with flexible royalty and equity-sharing schemes fostering startup growth (Murray, 2004).	Licensing tailored to diverse industry sectors, including biotech and engineering (MIT TLO, 2024).	Long-term corporate licensing ensures stability but delays innovation rollout (Cambridge Enterprise, 2023).	Conservative licensing approach, focusing on high-value technology sectors (Oxford Innovation Ltd., 2023c).

Challenge	***Strategic Responses to Mitigate Challenges in University TTOs***			
	Stanford	***MIT***	***Cambridge***	***Oxford***
Digitalisation and AI Integration	Proactive AI-driven patent analytics and automated licensing processes (Stanford OTL, 2024).	TLO integrates blockchain solutions for IP management and protection (MIT TLO, 2024).	Digitalisation is nascent, with some use of automated patent analysis tools (Cambridge Enterprise, 2023).	Gradual adoption of digital tools, primarily in biotech and pharma (Oxford Innovation Ltd., 2023c).

Source: Author's structured synthesis based on theoretical frameworks and empirical literature analysis.

(B) The Impact of Regional Innovation Ecosystems

The regional innovation environment plays a crucial role in determining the efficiency of university Technology Transfer Offices (TTOs) and the dynamics of technology commercialization (Audretsch & Feldman, 1996). Stanford University's TTO is deeply embedded in the Silicon Valley ecosystem, where venture capital availability and a strong entrepreneurial culture create favorable conditions for spin-off development and rapid technology deployment, particularly in IT and biotechnology (Saxenian, 1996). Similarly, MIT's TTO strategically collaborates with the Kendall Square biotechnology and pharmaceutical cluster, securing close partnerships with industry leaders and access to specialized investment funds, which accelerate the commercialization of high-value technologies (Roberts & Eesley, 2011).

The University of Cambridge has developed a structured TTO model, prioritizing long-term industry collaborations and a strong emphasis on academic excellence (Hughes & Kitson, 2012). Cambridge dominates the biotechnology and life sciences sector, leveraging partnerships with AstraZeneca and the Wellcome Trust Sanger Institute to foster a stable but slower-paced commercialization process (Cooke, 2001). In addition, the university has expanded its focus on information technology and artificial intelligence, as evidenced by the success of companies such as DeepMind, which later became a part of Google (McCann & Oxley, 2019).

Oxford University operates within one of Europe's leading biomedical innovation hubs, where deep-tech and pharmaceutical sectors shape its technology transfer strategy. However, strict regulatory constraints and complex licensing procedures slow down spin-off creation, making its commercialization trajectory less dynamic than that of leading U.S. universities (Hughes & Kitson, 2012).

Table 3 illustrates the structural influence of regional innovation ecosystems on the strategic models of Technology Transfer Offices.

The evaluation underscores that the effectiveness of TTO operations is contingent not only on internal university policies but also on external ecosystem dynamics, including regional investment climates, industry demand, and technological absorption capacity. U.S. university models, which are deeply embedded in dynamic innovation ecosystems, exhibit higher flexibility and entrepreneurial intensity. In contrast, European universities rely on more stable but less agile collaboration frameworks with industry and government, prioritizing long-term partnerships over rapid commercialization cycles.

Table 3

Structural Influence of Regional Innovation Ecosystems on the Strategic Models of Technology Transfer Offices (TTOs)

University	***Regional Innovation Ecosystem***	***Key Influence on TTO Operations***
Stanford	Silicon Valley: VC-driven, rapid innovation cycle	High spin-off formation rate, adaptive licensing mechanisms
MIT	Boston/Kendall Square: Biotechnology and pharmaceutical hub	Strong industry integration, specialized licensing strategies
Cambridge	Cambridge Cluster: Long-term academia-industry collaborations	Structured IP governance, stable but slower commercialization trajectory
Oxford	Biomedical hub with public-private ties	Regulated spin-off processes, emphasis on deep-tech development

Source: Author's structured synthesis based on theoretical frameworks and empirical literature analysis.

Limitations and Future Research Directions

The scope of this study is confined to a qualitative comparative framework based on secondary data sources and publicly available institutional reports. While this approach enables strategic cross-case interpretation, it limits the capacity to capture first-hand insights from practitioners within Technology Transfer Offices or spin-off enterprises. Additionally, the absence of quantitative metrics such as licensing

success rates, spin-off survival, or time-to-market dynamics may constrain broader empirical generalisability.

Future research should incorporate primary data collection through expert interviews, longitudinal case studies, or cross-sectional surveys targeting TTO stakeholders and industry collaborators. Moreover, integrating econometric or network analysis techniques could uncover structural causality between governance models and innovation outcomes, thus enhancing theoretical robustness and predictive power. Such studies would complement the current findings and help formulate evidence-based policy recommendations tailored to regional innovation capacities. The comparative model developed in this study may serve as a strategic blueprint for emerging TTOs in developing regions aiming to align with international innovation performance benchmarks.

Conclusions

1. TTO efficiency depends on regional ecosystem adaptability, entrepreneurial culture, and funding access. Stanford and MIT use flexible, VC-integrated models for rapid commercialisation, while Cambridge and Oxford favour structured, long-term partnerships suited to regulated sectors, enabling steady but slower tech transfer.

2. A hybrid model combining U.S. dynamism with European stability could strengthen TTO performance. Stanford and MIT focus on flexible licensing and strong spin-off support, enabling fast market entry. Cambridge and Oxford emphasise IP protection and long-term stability—vital for biomedical and deep-tech sectors with longer, regulated development cycles.

3. Integration into innovation clusters and strong industry ties boost TTO efficiency. Stanford and MIT benefit from VC-rich environments like Silicon Valley and Kendall Square, accelerating tech transfer. In contrast, Cambridge and Oxford operate in more regulated ecosystems with stricter IP policies, leading to longer, stability-focused commercialisation cycles.

4. Targeted specialisation boosts commercialisation efficiency. MIT and Stanford lead in IT and AI, backed by VC and tech industry ties. Cambridge focuses on biotech and materials science, while Oxford excels in pharma and medical fields. These strengths allow tailored tech transfer strategies aligned with sector-specific needs.

5. Digital technologies and AI boost TTO efficiency through enhanced transparency and faster processes. MIT and Stanford use AI-driven tools for strategic licensing, while Cambridge and Oxford apply them selectively in biotech and pharma. Full digital adoption is key to future, data-driven tech transfer performance.

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HARMONIZING INNOVATION DYNAMICS - MULTIDISCIPLINARY APPROACHES TO DRIVING REGIONAL DEVELOPMENT

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Abstract
Innovation ecosystems in regional contexts remain fragmented despite growing investment and policy focus. This fragmentation results from weak institutional coordination, the absence of integrated theoretical models, and a limited capacity to align innovation with regional sustainability and competitiveness goals. Addressing these systemic challenges, the study develops a conceptual framework that synthesizes key innovation theories to guide strategic governance in complex, multidisciplinary environments. The research applies a mixed-methods approach, combining a systematic literature review with semi-structured expert interviews. The literature analysis identifies seventeen innovation theory paradigms, while expert input helps contextualize theoretical insights with practical considerations in regional innovation policymaking. This integration provides a robust basis for assessing how theoretical frameworks translate into operational strategies that enhance innovation performance and reduce systemic fragmentation. The synthesized framework incorporates Innovation Systems Theory, the Triple and Quadruple Helix Models, Dynamic Capabilities, Open Innovation, and Sustainability-Oriented Innovation, among others. Findings demonstrate that regional innovation ecosystems perform more effectively when governance is grounded in integrated, theory-driven approaches that prioritize collaboration, adaptability, and strategic alignment with digital and sustainable transformation agendas. This study contributes to both academic and practical discourse by offering a model for theory-informed innovation governance. It equips policymakers, universities, and industry actors with actionable insights to strengthen institutional resilience, facilitate knowledge transfer, and drive inclusive, innovation-led regional growth.
Keywords: innovation ecosystems, regional development, systems thinking.

Introduction

In contemporary regional development discourse, innovation ecosystems are widely recognized as critical drivers of economic growth and social transformation (Demirdag & Nirwansyah, 2025; Wang et al., 2024). However, empirical research consistently reveals a paradox: despite substantial investments in innovation infrastructure, many regions continue to struggle with achieving sustained innovation-led growth (Du & Jian, 2024; Zemtsov, 2024). This discrepancy suggests that the core challenge is not a mere lack of resources but rather the fragmentation of innovation processes and the absence of a coordinated approach that integrates multidisciplinary collaboration and systemic thinking (Edquist, 2005).

Innovation ecosystems operate within complex, interdependent networks in which universities, businesses, policymakers, and financial institutions must align their actions to facilitate knowledge transfer, technological adoption, and regional competitiveness (Chesbrough, 2003; Powell et al., 1996). Nevertheless, empirical evidence suggests that this coordination is often ineffective due to structural barriers, misaligned incentives, and regulatory inconsistencies (Qiao et al., 2025). For instance, studies on the role of universities in Turkey's regional development indicate that knowledge transfer and university-industry partnerships can foster economic convergence. However, their impact varies significantly across regions, depending on institutional capacity and human capital distribution (Demirdag & Nirwansyah, 2025). This underscores the need for a more structured and strategic approach to innovation governance.

Similar studies on digital innovation ecosystems suggest that regional resilience and adaptability to technological change are highly contingent upon systemic integration and strategic resource management (Du & Jian, 2024). The absence of such integration leads to uneven growth, wherein innovation hubs in major cities thrive while peripheral regions lag behind (Zemtsov, 2024). Moreover, insights from China and ASEAN health innovation collaborations reveal that even well-funded initiatives can suffer from systemic inefficiencies if regulatory harmonization and cross-sectoral coordination remain insufficient (Qiao et al., 2025).

One of the fundamental challenges in regional innovation policy lies in aligning the interests and operational models of various stakeholders (Chesbrough, 2003; Wang et al., 2024). Traditional innovation frameworks, such as the Triple Helix and Quadruple Helix collaboration models, provide a theoretical foundation for fostering synergies between universities, industry, and government (Etzkowitz & Leydesdorff, 2000). However, empirical evidence suggests that these models require adaptation to regional specificities by incorporating mechanisms for adaptive governance and institutional learning (Duchek & Höne, 2024; Wang et al., 2024). Without such contextual adaptation, innovation ecosystems risk becoming either overly reliant on state support or excessively dominated by private-sector interests, potentially hindering balanced and sustainable long-term development (Zenkienė & Leišytė, 2024).

Access to funding is a key factor in innovation diffusion and commercialization (Pierrakis & Saridakis, 2019). Regions with strong venture capital networks enable faster scaling and smoother research-to-market transitions. In contrast, regions without such mechanisms face major hurdles in technology scaling and sustaining growth (Du & Jian, 2024). This highlights the need for systemic financial support in regional innovation strategies to boost long-term competitiveness and technological progress.

The core issue is the lack of a holistic, systems-based approach that unifies diverse innovation theories into a coherent regional development strategy (Edquist, 2005). Current policies often overlook the complexity of innovation ecosystems, treating them as isolated rather than interconnected systems (Zemtsov, 2024). This study addresses that gap by analyzing seventeen innovation theories and proposing a structured framework to improve innovation governance. The resulting synthesis offers strategic guidelines to strengthen regional ecosystems, support sustainable growth, and build institutional resilience.

Materials and Methods

The study employs a mixed-methods approach, combining a systematic literature review, expert interviews, and empirical data analysis to develop a conceptually grounded and practically applicable framework for analyzing innovation ecosystems.

A systematic literature review was conducted to identify, categorize, and synthesize key innovation theories relevant to regional development. The databases Scopus and Web of Science were used, covering the period from 2000 to 2024. Keywords included: *'regional innovation ecosystems'*, *'open innovation'*, *'innovation diffusion'*, *'dynamic capabilities'*, and *'sustainable innovation'*. After initial screening and duplicate removal, a total of 192 articles were analyzed. The studies were thematically coded, resulting in the identification of 17 key innovation theory paradigms, each linked to specific regional development challenges.

To complement and validate the theoretical insights from the literature, semi-structured interviews were conducted with 14 experts from academia, public administration, and innovation policy. Experts were selected based on their experience in regional development projects and innovation governance. The interviews focused on current ecosystem gaps, institutional challenges, and the applicability of theoretical frameworks to real-world innovation dynamics.

Findings from the literature and interviews were triangulated with empirical data and regional innovation policy documents, including comparative assessments of strategies across EU regions. A qualitative comparative analysis approach was used to identify context-specific enablers and bottlenecks.

Results and Discussion

(A) Innovation Theory Paradigms in Regional Development

Regional development complexity stems from the diversity of innovation theories that guide ecosystem design and governance. This study identifies 17 core theory groups, covering areas like diffusion, systems integration, resource use, regulation, sustainability, digitalisation, and risk. Together, these paradigms inform adaptive, resilient policy strategies for building high-performing regional innovation ecosystems.

Empirical findings underscore the necessity of integrating these theoretical perspectives into regional development strategies to ensure sustainable and systematic progress. The Innovation Diffusion Theory (Rogers, 1962) highlights the role of communication channels and adopter categories in the dissemination of innovations. Regional policymakers and industry leaders must actively foster knowledge exchange through targeted incentives and stakeholder engagement to accelerate innovation adoption (Greenhalgh et al., 2004; Valente, 1996).

This aligns with Innovation Systems Theory (Lundvall, 1992), which emphasizes the interplay of institutions, education, and market structures in shaping regional innovation. Empirical studies confirm that robust university-industry collaboration and structured public funding mechanisms are pivotal in fostering dynamic innovation networks (Freeman, 1987; Nelson & Winter, 1982). A structured, system-oriented approach is required to enhance regional innovation capacity by aligning financial, institutional, and market mechanisms.

At the firm level, Resource-Based View (RBV) of Innovation (Barney, 1991) and Dynamic Capabilities Theory (Teece et al., 1997) emphasize that competitiveness is contingent upon acquiring, developing, and leveraging unique resources. Regional enterprises that invest in adaptive learning, research infrastructure, and strategic alliances demonstrate greater resilience to economic fluctuations and technological disruptions (Eisenhardt & Martin, 2000; Helfat et al., 2007). Complementing this, the Triple Helix Model (Etzkowitz & Leydesdorff, 2000) highlights the significance of synergistic interactions among universities, industry, and government in fostering innovation-driven regional competitiveness.

The Open Innovation Paradigm (Chesbrough, 2003) posits that knowledge exchange beyond firm boundaries accelerates technological progress and commercialization. Empirical research suggests that leveraging open innovation networks—particularly through digital platforms and regional clusters—enhances collaborative problem-solving and co-creation, driving sustainable growth (Bogers et al., 2019; West & Bogers, 2014). This closely aligns with User Behavior Theories (Von Hippel, 2005), which emphasize the value of user-driven innovation for

market-adaptive solutions (Carlgren et al., 2016; Liedtka, 2015).

Disruptive Innovation Theory (Christensen, 1997) explains how breakthrough technologies and novel business models create new markets while challenging incumbents. Regions supporting disruptive innovations—particularly through venture capital investments and flexible regulatory frameworks—experience higher entrepreneurial activity and employment growth (Markides, 2006; Yu & Hang, 2010). Servitization and Business Model Innovation Theory (Baines et al., 2009) further underscores the strategic significance of service-oriented business models in enhancing regional economic adaptability.

Regulatory Theories (North, 1990) emphasize the critical influence of governance structures and cultural norms in shaping innovation ecosystems. Regions with transparent policies, robust intellectual property protections, and innovation-friendly regulations tend to attract greater research and development investments (Scott, 2008; Williamson, 2000). Simultaneously, Sustainability Theories (Boons & Lüdeke-Freund, 2013) highlight the imperative of integrating environmentally responsible and socially inclusive innovation strategies.

Finally, Network Innovation Theory (Powell et al., 1996) underscores the role of inter-organizational linkages in fostering innovation diffusion and knowledge transfer. Empirical data suggest that well-connected innovation networks, particularly those integrating academia, industry, and government, outperform fragmented ecosystems in patent output, technology transfer, and startup success (Burt, 2004).

Table 1 encapsulates the diverse theoretical perspectives that inform regional innovation strategies, illustrating how each theory provides critical insights for addressing specific challenges in regional development.

Table 1

Systematized Synthesis of Innovation Theories – Conceptual Features and Their Strategic Impact on Regional Development

Innovation Theory	***Key Characteristics***	***Impact on Regional Development***
Innovation Diffusion Theory	role of communication channels and adopter categories	accelerates innovation dissemination
Innovation Systems Theory	institutional and market interactions	strengthens university-industry collaboration
Resource-Based View	effective utilization of unique resources	enhances firm competitiveness
Dynamic Capabilities Theory	adaptive learning and research infrastructure	improves firm resilience
Triple Helix Model	synergistic interaction between universities, industry, and government	enhances regional competitiveness
Open Innovation Paradigm	knowledge exchange and networking	strengthens collaborative innovation processes
Risk Management Theories	identification and mitigation of risks in innovation processes	ensures more stable innovation implementation
Creativity Theories	encouragement of creative thinking and new idea generation	enhances innovation quality and diversity
Cost-Benefit Theories	economic evaluation of innovation investments	ensures optimal resource allocation and efficiency
User Behavior Theories	analysis of consumer attitudes towards new technologies	facilitates market-driven innovation development
Materials Science & Engineering Theories	development of new materials and technological solutions	supports high-value-added product innovation
Regulation Theories	influence of regulatory frameworks on innovation	provides a supportive legal environment for innovation
Sustainability Theories	integration of sustainable development into innovation	promotes eco-friendly and long-term innovation

Innovation Theory	***Key Characteristics***	***Impact on Regional Development***
Information Theories	management of data and knowledge in innovation development	enhances innovation efficiency and accessibility
Project Management Theories	structured approach to innovation project execution	reduces risks and increases innovation success rates
Technology Readiness & Adaptation Theories	assessment and adaptation of technology readiness levels	ensures successful market adoption of technologies
Connected Systems Theories	integration of digital and cyber systems into innovation	strengthens connectivity and digital transformation

Source: Author's synthesis of theoretical frameworks validated and structured based on literature analysis and expert interviews.

The selection of these 17 innovation theories is based on their conceptual robustness, empirical relevance, and applicability to the complexities of regional innovation ecosystems. These theories collectively provide a multi-layered analytical framework, capturing the interplay between institutional structures, technological capabilities, market dynamics, and policy interventions. By integrating perspectives from innovation diffusion, open innovation, dynamic capabilities, sustainability, and risk management, this framework enables a holistic understanding of innovation-driven regional development, addressing both structural barriers and strategic enablers. Furthermore, these theories were validated through systematic literature analysis and expert consultations, ensuring their relevance to contemporary regional innovation challenges and policy imperatives.

While the previous section outlined the theoretical underpinnings that shape innovation ecosystems, the following part builds on this foundation by examining how these theories translate into practice. Specifically, it explores the alignment between regional innovation challenges and the conceptual models discussed above, offering a synthesis of theoretical relevance and strategic applicability. Having laid the theoretical foundation, the following section bridges conceptual insights with practical challenges faced by regional ecosystems.

(B)Regional Challenges and Their Link to Innovation Theories

Universities are crucial drivers of regional innovation, yet their impact varies significantly based on local innovation capacity and economic development levels (Demirdag & Nirwansyah, 2025). In advanced regions, they primarily support entrepreneurship and technology commercialization, whereas in less developed areas, their role in knowledge transfer and economic convergence is more pronounced (Zenkienė & Leišytė, 2024).

The Innovation Diffusion Theory (Rogers, 1962) explains this dynamic, emphasizing that effective communication channels and adopter categories are key to accelerating innovation dissemination. To foster innovation adoption in lagging regions, targeted incentives and structured cross-sectoral collaboration must be developed, aligning with the Innovation Systems Theory (Lundvall, 1992). Strengthening institutional ties between universities, industry, and policymakers is essential for mitigating regional disparities in innovation diffusion.

Technological advancements tend to cluster in innovation hubs, particularly in AI, biotechnology, and other high-tech industries, while peripheral regions often rely on adapting existing technologies rather than developing breakthrough innovations (Zemtsov, 2024). Dynamic Capabilities Theory (Teece et al., 1997) underscores that firms' adaptive capacity is critical for enhancing research infrastructure and accelerating technology adoption, thereby reducing disparities in innovation-led growth.

The Triple Helix Model (Etzkowitz & Leydesdorff, 2000) highlights the synergy between universities, industry, and government as a cornerstone of regional innovation ecosystems. However, empirical evidence warns that overly broad collaboration without clear strategic governance can lead to resource misallocation and inefficient innovation diffusion (Wang et al., 2024).

The Quadruple Helix model (Carayannis & Campbell, 2012) expands on traditional frameworks by integrating societal actors, fostering user-driven innovation and reinforcing sustainable innovation pathways. This aligns with the Open Innovation paradigm (Chesbrough, 2003), which emphasizes that broader knowledge exchange—involving firms, research institutions, civil society, and end-users—enhances innovation effectiveness and market adaptability. Incorporating these multi-actor dynamics strengthens regional innovation ecosystems, making them more adaptive, inclusive, and resilient.

Digital innovations have become central to regional resilience, mitigating economic shocks and enabling greater adaptability to market volatility (Du & Jian, 2024). The Technology Readiness and Adaptation Theory highlights that successful digital innovation

deployment depends on both corporate and governmental capacity to establish the necessary infrastructure and skills for sustained technological advancement.

At the same time, sustainable innovations are reshaping regional competitiveness, as environmentally responsible innovation confers strategic advantages in the global economy (Boons & Lüdeke-Freund, 2013). Firms adopting circular economy principles and sustainable business models achieve long-term growth while ensuring responsible resource management (Adams et al., 2016; Geissdoerfer et al., 2017). The convergence of digital and sustainable innovation highlights the need for integrated regional policies that maximize both economic resilience and long-term sustainability.

The regulatory environment plays a crucial role in shaping innovation diffusion, influencing how effectively firms and research institutions can develop and implement new technologies (North, 1990). Empirical evidence shows that regions with stable, transparent regulatory frameworks and strong intellectual property protections attract higher R&D investments (Scott, 2008; Williamson, 2000).

Beyond regulatory stability, access to venture capital and diversified financing mechanisms remains a critical determinant in the scalability of innovation. The Connected Systems Theory suggests that regions fostering both digital and physical networks among businesses, investors, and research institutions exhibit faster innovation adoption cycles. Empirical research confirms that regions with well-developed venture capital ecosystems enable innovation-driven firms to transition more rapidly from R&D to commercialization, whereas regions with restricted access to funding face significant challenges in market validation and scaling of technological advancements (Du & Jian, 2024; Pierrakis & Saridakis, 2019).

Table 2

Synthesis of Regional Innovation Ecosystem Challenges, Corresponding Innovation Development Theories, and Strategic Policy Approaches

Regional Innovation Ecosystem Challenges	***Relevant Innovation Development Theory***	***Strategic Policy Approach Derived from Innovation Theory***
Uneven regional development and innovation concentration in metropolitan areas	Innovation Systems Theory (Lundvall, 1992)	Development of regional innovation ecosystems through cluster-based policies and Smart Specialisation Strategies (RIS3)
Insufficient collaboration between universities, industry, and government	Triple Helix Model (Etzkowitz & Leydesdorff, 2000)	Establishment of synergistic innovation platforms integrating enterprises, academia, and government for joint projects
Low innovation diffusion in less developed regions	Innovation Diffusion Theory (Rogers, 1962)	Targeted facilitation of knowledge and technology transfer through regional innovation brokers and intermediary institutions
Limited regional innovation financing and venture capital availability	Resource-Based View (Barney, 1991)	Creation of regional investment funds and development of public-private partnership mechanisms to enhance innovation financing
Mismatch between regulatory frameworks and innovation ecosystem needs	Regulation Theories (North, 1990)	Design of adaptive innovation policies with dynamic regulatory frameworks to support experimental innovation development
Insufficient user engagement and market orientation in innovation processes	User Behavior Theories (Von Hippel, 2005)	Support mechanisms for user-driven innovation, including the integration of Living Labs in regional innovation ecosystems
Challenges in commercialising breakthrough innovations and transitioning to servitization	Dynamic Capabilities Theory (Teece et al., 1997)	Expansion of start-up accelerators and incubators, alongside the promotion of servitization models (product-as-a-service)
Slow adoption of sustainable innovations and circular economy principles	Sustainability Theories (Boons & Lüdeke-Freund, 2013)	Implementation of green innovation funds and sustainable public procurement policies based on circular economy principles
Weak knowledge and technology transfer across industries and organisations	Open Innovation Paradigm (Chesbrough, 2003)	Development of digital innovation platforms, co-creation spaces, and cross-sectoral innovation partnerships

Source: Author's structured synthesis of theoretical perspectives, validated and refined through an in-depth literature review and expert interviews.

The findings reveal that regional innovation ecosystem challenges are not isolated occurrences, but rather systemic issues rooted in inadequate collaboration, limited financial accessibility, regulatory rigidity, and inefficiencies in technology diffusion mechanisms. Each of these challenges has a strong theoretical foundation and can be addressed through targeted strategic approaches grounded in innovation ecosystem governance. By systematically integrating relevant innovation management theories into policy design—encompassing both strategic frameworks and operational tactics—regions can achieve a more balanced and sustainable innovation-driven growth trajectory. This underscores the necessity of a holistic, interdisciplinary approach that merges academic knowledge with practical application in regional innovation strategies.

Conclusions

This study demonstrates that regional innovation ecosystems can only thrive when guided by a structured, theory-driven approach. The integration of 17 innovation development theories provides a holistic framework for understanding the multifaceted challenges and opportunities in regional innovation governance.

1. The synthesis of Innovation Systems Theory, Dynamic Capabilities, and Open Innovation Paradigms creates a strong foundation for designing innovation policies that are adaptive, collaborative, and context-sensitive. These frameworks ensure that regional strategies are not only theoretically sound but also practically effective in fostering technological advancement and institutional resilience.
2. The findings confirm that synergistic collaboration among universities, industries, and governments – anchored in the Triple Helix and Quadruple Helix models – remains essential for building agile and inclusive innovation ecosystems. However, such collaboration must be supported by clear governance mechanisms, avoiding coordination failures and ensuring strategic focus. Thirdly, regional disparities in innovation adoption require targeted policy instruments, particularly in less-developed areas. The research emphasizes the need for enhanced knowledge transfer mechanisms, inclusive stakeholder engagement, and financial support structures—derived from theories such as Innovation Diffusion, User Behavior, and Risk Management.
3. Sustainability-oriented innovation is increasingly a strategic necessity. The incorporation of Sustainability Theories and Circular Economy principles into regional planning enhances both economic competitiveness and environmental responsibility, laying the groundwork for long-term resilience.
4. The digital transformation of regional economies must be rooted in Technology Readiness and Adaptation frameworks, ensuring that technological infrastructure and human capital development go hand in hand. This enables regions to navigate uncertainty, capitalize on emerging trends, and position themselves competitively in the global innovation landscape.
5. The study offers a validated, theory-based framework for policy-makers, academic institutions, and regional planners. By aligning innovation strategies with multidisciplinary theoretical insights, it is possible to overcome fragmentation and guide regions toward sustainable, inclusive, and innovation-driven growth.

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ESSENTIAL RESOURCES FOR GREEN HYDROGEN INDUSTRY DEVELOPMENT IN THE LATVIAN REGIONS

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Abstract
Hydrogen is one of the renewable fuels that might replace fossil fuels in a wide range of various applications, driving environmentally sustainable economic growth in the EU. According to the International Energy Agency, the use of hydrogen between 1975 and 2023 globally increased from 18 Mt to 97 Mt per year, but in 2023, EU member states produced 10.3 Mt hydrogen, or 10.6% of global output; green hydrogen accounted for less than 1%. The study's aim is to assess the Latvia region's green hydrogen production capacity in terms of the availability of the necessary renewable energy resources (RES) – solar power, wind and hydro energy – to assess available infrastructure suited for the green hydrogen industry. Secondary data on renewable energy (RE) in Latvian regions were collected and analysed according to the research framework; to conduct a detailed comparison, statistical data on RES and infrastructure were collected and assessed by assigning a value to each criterion examined. The research highlighted that Latvia's regions have an unequal distribution of RES, especially in terms of wind power and hydro energy; hydroelectric stations (HES) generate 60% of Latvia's total electricity. At present the Zemgale region is home to the largest HES, which defines its leading position in the RE sector, while the Kurzeme region is rising as a potential wind and solar energy hub of Latvia. Nevertheless, green hydrogen production has not been developed for commercial use in any region of Latvia.
Keywords: green hydrogen, renewables, hydrogen production.

Introduction

The European Union's Green Deal agenda highlights the need for environmentally friendly energy sources to drive further economic progress. Hydrogen, as one of several renewable fuels, has the potential to replace fossil fuels in various applications. The production of green hydrogen derived from RES across Europe plays a pivotal role in achieving this objective. Additionally, the shared EU hydrogen strategy (European Commission, 2020), along with national policy roadmaps from 18 member states, underscores the significance of hydrogen as a key fuel for supporting continued economic growth.

Green hydrogen is important in the energy sector from various perspectives. Hydrogen can play a crucial role in energy storage and maintaining grid stability. Additionally, as an energy carrier, it can be used for heat and power generation, act as a raw material in the production of synthetic fuels and various chemicals, and serve as fuel for transportation.

The International Energy Agency reports that global hydrogen demand increased from 18 Mt to 97 Mt per year between 1975 and 2023. However, in 2023, low-carbon and green hydrogen represented less than 1% of total hydrogen production (International Energy Agency, 2024). Meanwhile, the World Bank predicts that by 2050, hydrogen demand will increase to about 600 Mt annually (World Bank, 2022). In 2023, EU member states produced 10.3 Mt of hydrogen (EU Agency for the Cooperation of Energy Regulators, 2024), constituting 10.6% of global production.

Electricity generated from wind, solar, and hydropower is a key source for green hydrogen production in the EU. Between 2014 and 2023, the combined use of these three RES grew by 64% in the EU (Eurostat, 2024). The availability of these three RES is a fundamental factor in the development of the green hydrogen industry in a specific region.

The object of this study is the hydrogen production potential across Latvia's regions. The subject of this research is to assess the hydrogen production capacity of these regions based on the availability of essential RES and the existing infrastructure.

The aim of this study is to evaluate the capacity of Latvia's regions in terms of wind, solar, and hydropower resources and to assess available infrastructure suited for the green hydrogen industry. The defined aim is accompanied by the following tasks: reviewing the major necessary resources for green hydrogen industry development; identifying and analysing statistical data regarding RES, electricity production, and appropriate infrastructure for green hydrogen production in Latvia regions.

This study aims to provide a valuable resource for industry professionals, researchers, and policymakers in shaping and updating initiatives within the hydrogen industry and related fields of the economy. Its importance lies in being the first study to assess the potential for green hydrogen production across Latvia's regions. Moreover, it provides a basis for future studies aimed at advancing the green hydrogen industry and establishing new production facilities locally.

Materials and Methods

According to the aim of this research to evaluate the capacity of Latvia's regions in terms of wind, solar, and hydropower resources and to assess potential locations for green hydrogen production, secondary statistical data on the RES, electricity-producing capacity, energy balances, available for green hydrogen production, and transportation infrastructure in Latvia regions – Vidzeme, Latgale, Kurzeme, Zemgale and Riga are provided. The statistical data in this research describe the period from 2019 until 2024. The majority of statistical data was sourced from the databases and publications of the Central Statistical Bureau of the Republic of Latvia.

To facilitate a detailed comparison, the collected data on RE, infrastructure, and industries has been organised by assigning a value to each evaluated criterion (Table 1). A higher value (A) indicates the greater significance of a specific criterion in the

development of the green hydrogen industry, taking into account both potential and existing capacities, with a focus on prioritising existing facilities. Moreover, the differences between the data of the five Latvia regions are categorised (Lejnieks & Pelse, 2023) into eleven ranks, with decimal values from 0 to 1, where 1 indicates the smallest difference and 0 highlights a huge gap between statistical data of the regions. The most advanced region receives a score founded on the criteria value multiplied by the difference coefficient or relative percentage difference between the most and least advanced regions (B). The second-place criteria value is determined according to the relative percentage difference between the first two higher-rated regions; for the third-ranked region, the criteria value is determined regarding the relative percentage difference between the first and third-placed regions and so on. Regions with the poorest results in certain criteria obtained only the base value of the analysed criteria. If there is no distinction between two or more regions data, or if its value is equal to or less than 5%, they receive identical scores. For indicators indicating specific counted objects or projects, the outcome is calculated by counting each object as 0.1 of point and multiplying it by its importance value. In this case, the difference coefficient does not apply.

According to the research framework about green hydrogen industry evaluation, 22 indicators were divided into the four categories of analysis: existing and potential RES, possible and current hydrogen-suitable infrastructure (Table 2).

In the beginning, the research provides some important assumptions determining suitable RES for green hydrogen generation and the overall growth of the hydrogen industry within the particular region.

Table 1

Criteria and difference coefficient values for green hydrogen industry potential assessment in a certain territory

Criteria for the green hydrogen industry	***Value for existing capacity (A)***	***Value for potential capacity (A_1)***	***Difference between regions in statistical data***		***Value (B)***
Adjacent fields	10	*	No	≤ 5%	1
Connected fields	20	*	Micro	≤ 10%	0.9
Integrated fields	30	10	Minor	≤ 20%	0.8
			Below Average	≤ 30%	0.7
			Average	≤ 40%	0.6
			Above Average	≤ 50%	0.5
			Solid	≤ 60%	0.4
			Significant	≤ 70%	0.3
			Major	≤ 80%	0.2
			Substantial	≤ 90%	0.1
			Huge	≤ 100%	0

Table 2

Four categories and 22 indicators for analysis for the green hydrogen industry in Latvian regions

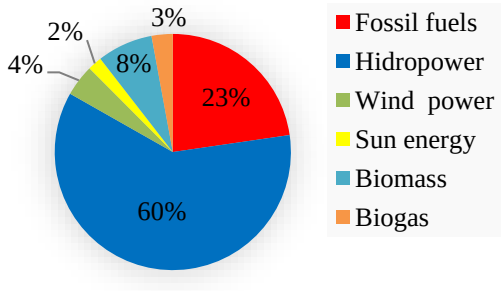
Available renewable energy sources	
Existing capacity	***Potential capacity***
1. Wind power density 2. Photovoltaic power output 3. Hydropower potential 4. Renewables in electricity 5. Wind, solar, hydro energy in electricity 6. Wind power in electricity 7. Solar energy in electricity 8. Hydropower in electricity 9. Solar farms capacity 10. Wind farms capacity 11. Hydro plants capacity	12. Planned wind farms 13. Solar farms projects 14. Hybrid renewable energy parks
Hydrogen-suitable infrastructure	
Existing infrastructure	***Planned infrastructure***
1. Hydrogen fuel stations 2. Sea ports 3. Natural gas (NG) network density 4. Major cities in gas network 5. NG storage capacity	6. Planned hydrogen production sites 7. Potential hydrogen fuel stations 8. Liquid NG terminals

Results and Discussion

An essential element of green hydrogen production is the availability of RE in a particular territory. The share of energy from RES varies significantly among EU member states. According to available data in 2023, RE accounted for 24.5% of total EU energy consumption. In the last 10 years, the amount of RE used has increased by 29% (Eurostat, 2025). Meanwhile, Latvia has 43% of RE in the energy balance, which is an increase of 13% since 2015. In 2023, RES provided 77% of total power generation (Central Statistical Bureau, 2025). The most important renewables in 2023 in Latvia in electricity production were hydropower, highlighting this RES as a cornerstone of electricity production (Figure 1).

Figure 1

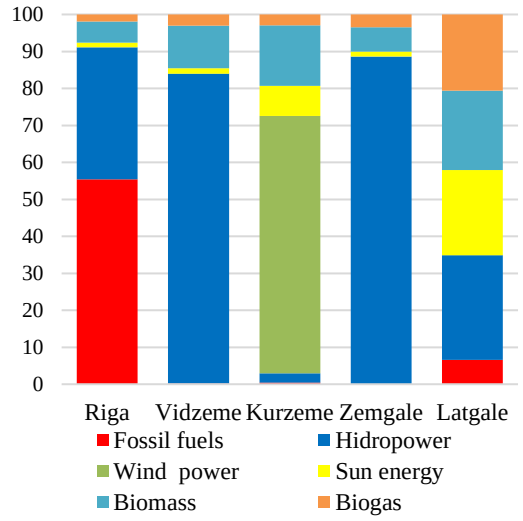
Proportion of produced electricity by source in Latvia in 2023, %



Within Latvian regions composition of RES used for electricity generation differs radically (Figure 2).

Figure 2

Proportion of produced electricity by source in Latvia regions in 2023, %



Two of five Latvia regions rely heavily on hydropower for electricity production (Zemgale – 89%, Vidzeme – 84%). While only the Kurzeme region is highly focused on wind power utilisation for electricity generation with 70% of produced electricity. Only the Latgale region has obtained a balanced mix of all RES. Apart from hydro energy, which accounts for 60% of the country's electricity production, biomass and biogas continue to play key roles in the country's RE sector. In recent years, a significant reduction in the bioenergy proportions within electricity production can be identified; between 2019 and 2023, biomass amount dropped by 17%, while biogas utilisation plummeted by almost 49% (Central Statistical Bureau, 2025). During the same period, the decline in EU countries was less significant; biogas decreased by 6%, and the total biomass use in electricity generation dropped by 3% (Eurostat, 2025). In the EU regulatory documents, RES such as solar and wind energy have priority over biogas (Millers et al., 2023). According to existing tendencies in the RE sector, large-scale production of green hydrogen in Latvian regions is more probable from wind, solar, and hydro energy sources than from biomass.

From 2019 till 2023, wind and solar energy utilisation for electricity production has risen significantly in EU member states. Electricity produced from wind power increased by 25%, while solar power generated 52% more electricity. In the same time period, Latvia generated 57% more electricity from wind power and almost 99% more from solar energy (Eurostat, 2025). The importance of these RES is increasing significantly.

Geographical location and climate characteristics define the necessity for the utilisation of different RES applications for balanced green hydrogen production throughout the year. Using integrated wind and solar power installations for electricity generation in hydrogen production is an important aspect in attaining consistent production patterns (Algburi et al., 2024; Stolte, 2024; Martinez & Iglesias, 2024).

Apart from the importance of the availability of RES, appropriate infrastructure must be established for the hydrogen sector to evolve. The NG pipeline network is the best solution for hydrogen transportation and long-term energy sector growth (Jansons et al., 2023). When assessing hydrogen production, it is critical to evaluate the distance between local production facilities and the gas grid. If the hydrogen production facility is located far from the gas grid, the hydrogen must be delivered to the injection point (Kleperis et al., 2021). The NG network facilitates stable hydrogen flow from production to consumer; a sophisticated and diverse grid, especially via the largest cities, increases opportunities for parties involved in the hydrogen industry.

Moreover, hydrogen can play a key role in energy storage, especially in combination with RES. Intermittency of RES can be addressed by storing excess energy via electrolysis process, splitting water into hydrogen and oxygen. Then the hydrogen is stored for later use, generating electricity when RES production is low. Unlike batteries, hydrogen storage systems are expandable to store large amounts of

energy long-term, and have a higher energy density (Zemite et al., 2023).

The crucial importance for the green hydrogen industry is the possibility to export and import hydrogen via seaports (Shu-Ling Chen et al., 2023). Moreover, seaports are not just gateways of trade but can also be used as green hydrogen production sites due to large industrial areas, rail, pipeline networks, and near-existing offshore wind harvesting potential. At the same time, green hydrogen may be used to reduce carbon emissions created by operating port infrastructure and machinery (Pivetta et al., 2024; Mio et al., 2023). Finally, refuelling of sea transport can be provided within the port area.

A widespread and well-established network of hydrogen refuelling stations is crucial for the growth of hydrogen demand. However, technical challenges and high costs are significant barriers to the development of these networks (Karayel & Dincer, 2024). For last year's hydrogen-driven commercial and heavy-duty transport and its refuelling options are in focus (Rose & Neumann, 2020; De Padova et al., 2024). The location of major hydrogen refuelling stations must be considered by proximity to three major infrastructure elements—ports, railways, and highways (Vidzeme planning region, 2024). The proximity to highways connecting regions and countries facilitates green hydrogen demand for long-range transport requiring large amounts of hydrogen.

The growth of hydrogen infrastructure is closely tied to the development of the hydrogen economy. The infrastructure scale depends on hydrogen's role in the future energy mix, while the growth of the supply chain could be limited by the absence of connection facilities. Prioritising the creation of green hydrogen hubs, aligned with demand from synthetic fuels, industry, and power, is crucial in the near term (Dergunova & Lyden, 2024).

To assess how the previously outlined general guidelines for green hydrogen industry development and facts about Latvia are applied to the country's five regions, we conducted a detailed comparison using statistical data on existing and potential RES, along with infrastructure for future hydrogen utilization. (Table 3). Each criterion is assigned a specific value, which is then summarised for further analysis (Table 4).

Table 3

Statistical data on RE and connected infrastructure for potential hydrogen utilisation in Latvia's regions

Nr	***Indicators for available RES***	***Riga***	***Vidzeme***	***Kurzeme***	***Zemgale***	***Latgale***
1	Wind energy, W/m^2	422	421	509	418	405
2	Photovoltaic. power, kWh/day max	2.95	2.94	3.03	2.94	2.88
3	Hydro power pot. rivers ≥ 0.01 TWh/y	1.75	2.15	0.3	2.25	1.85
4	Major RE, GWh, 2023	1,140.509	887.217	384.576	2,382.765	51.545
5	Wind, solar, hydro, GWh, 2023	946.655	757.946	310.190	2,144.419	28.326
6	Hydro power, GWh, 2023	912.257	745.072	9.852	2,111.405	15.622
7	Wind energy, GWh, 2003	1.324	0.098	268.707	0.628	0.001
8	Solar power, GWh, 2023	33.074	12.776	31.631	32.386	12.703
9	Solar farms cap. ≥2MW, 2024	55.44	93	47.4	55.4	43.7
10	Wind farms cap. turbines ≥0.6MW, 2024	0	1.2	100.7	0	0
11	HES cap. plants ≥5 MW, 2024	402	248	0	908	0
12	Potential wind parks cap. ≥10MW	245	1,870	8,444	2,821	2,413
13	Potential solar plants cap. ≥2MW	117	138	1,215	268.4	490
14	Planned hybrid parks wind/solar ≥2MW, pcs	0	2	1	2	1
Nr	***Hydrogen-suitable infrastructure***	***Riga***	***Vidzeme***	***Kurzeme***	***Zemgale***	***Latgale***
1	H_2 fuel stations, pcs, 2024	1	0	0	0	0
2	Sea ports and terminals, pcs, 2024	1	2	6	0	0
3	NG network, % of adm. territory, 2024	80	11	13	42	12
4	NG network in cities ≥ 5.000 inh., %, 2024	100	50	33	100	57
5	NG storage ≥ 1m m^3, pcs, 2024	0	1	0	0	0
6	Planned H_2 production sites, pcs	0	0	3	0	1
7	Potential H_2 refuelling stations, pcs	1	0	0	0	0
8	Potential liquid NG terminal, pcs	0	1	0	0	0

Table 4
Assessment of criteria for green hydrogen industry potential in Latvia's regions

Nr	*Indicators*	*Value (A)*	*Riga*	*Vidzeme*	*Kurzeme*	*Zemgale*	*Latgale*
1	Wind energy, W/m^2	30	24	24	30	24	18
2	Photovoltaic. power, kWh/day max	30	30	30	30	30	30
3	Hydro power pot. rivers ≥ 0.01 TWh/y	30	21	30	3	30	24
4	Major RE, GWh, 2023	20	8	6	2	20	0
5	Wind, solar, hydro, GWh, 2023	30	12	9	3	30	0
6	Hydro power, GWh, 2023	30	12	9	0	30	0
7	Wind energy, GWh, 2003	30	0	0	30	0	0
8	Solar power, GWh, 2023	30	30	9	30	30	9
9	Solar farms cap. ≥2MW, 2024	30	18	30	15	18	12
10	Wind farms cap. turbines ≥0.6MW, 2024	30	0	3	30	0	0
11	HES cap. plants ≥5 MW, 2024	30	12	6	0	30	0
	Total	320	167	156	173	242	93
12	Potential wind parks cap. ≥10MW	10	0	2	10	3	2
13	Potential solar plants cap. ≥2MW	10	1	1	10	2	3
14	Planned hybrid parks wind/solar ≥2MW, pcs	10	0	2	1	2	1
	Total	30	1	5	21	7	6
1	H_2 fuel stations, pcs, 2024	30	3	0	0	0	0
2	Sea ports and terminals, pcs, 2024	10	1	2	6	0	0
3	NG network, % of adm. territory, 2024	20	20	2	2	10	2
4	NG network in cities ≥ 5.000 inh., %, 2024	20	20	10	6	20	10
5	NG storage ≥ 1m m^3, pcs, 2024	20	2	0	0	0	0
	Total	100	46	14	14	30	12
6	Planned H_2 production sites, pcs	10	0	0	3	0	1
7	Potential H_2 refuelling stations, pcs	10	1	0	0	0	0
8	Potential liquid NG terminal, pcs	10	0	1	0	0	0
	Total	30	1	1	3	0	1
	Overall score	*480*	***215***	***176***	***211***	***279***	***112***

The evaluation of 22 criteria revealed significant differences regarding RES among Latvia regions. For instance, a significant disparity can be observed regarding the availability of hydroelectric capacity, positioning Kurzeme and Latgale at the lowest ranks. Moreover, Latgale suffers from lesser natural wind power. At the same time, solar power is more evenly spread across Latvian territory and can be harnessed more easily than wind or hydro resources. It must be highlighted that regarding importance in the energy mix, hydropower capacities heavily influence the overall score of regions in the RES assessment, and in this case, Zemgale has a much higher score than other regions.

In discussions about electricity production from solar power, it is important to highlight that the production volumes in 2023 were significantly lower and more unevenly distributed across Latvia's regions compared to the capacity of newly built solar farms in 2024. This shift has an impact on the current assessment, which is influenced by the rapid growth of solar energy production in Latvia.

Regarding potential RES, the planned solar parks in Kurzeme have a larger total capacity than those in all other regions combined, and a similar trend is observed with wind energy. It must be highlighted that solar parks are more easily built than wind parks, which have more complexities regarding formal procedures and the overall attitude from society about wind turbines harmful influence on neighbourhoods (Aaen et al., 2022; Dallenbachn & Wustenhagen, 2022). Accordingly, solar park development is more dynamic, and more planned solar parks are aiming to be built than wind farms.

As part of the broader push for increased RES utilisation, the development of wind and solar hybrid parks is emerging as a new strategy to ensure sustainable energy production year-round (Hassan et al., 2023; Couto & Estanqueiro, 2023). As solar parks are easier to build, they are often considered the first step in hybrid park development. In other cases, solar panel plantations can be added to existing wind turbine installations.

Existing hydrogen-suitable infrastructure in Latvia is very limited; only one hydrogen refuel station is located in Riga. As ports are considered crucial for hydrogen production facilities; Zemgale and Latgale are landlocked territories, which puts them at a disadvantage against other regions. Furthermore, Ventspils, as a potential hydrogen-producing site, lacks an NG network. Vidzeme, Latgale, and Kurzeme have

limited dispersion of NG networks in their territories, which is an obstacle for pure hydrogen or mixed hydrogen transportation for potential consumers. Currently, priority is being given to expanding the NG grid in areas where it is economically justified and offers a higher return on investment, such as the Riga region (Jansons et al., 2023).

In the beginning of 2025, no existing commercial green hydrogen production sites are in Latvia. There are some green hydrogen plant projects in the early planning stages. Few are connected with green ammonia production initiatives (Purple Green, 2023; The Energy and Environment Agency, 2024). The initiatives regarding hydrogen refuelling stations and liquid NG terminals are of a more conceptual or theoretical nature.

Conclusions

1. The research examined 22 criteria related to the RES and hydrogen industry, with the results highlighting the Zemgale region's notable lead in the RES sector. Overall, the Zemgale region received 279 points from 480 available, the Riga region gained 215, Kurzeme – 211, Vidzeme – 176, and Latgale – 112 points.
2. The research focused on measuring both the existing and potential RES capacity, with two-thirds of the total available points allocated to this topic. The Zemgale region gained 242 points from 320 available in this category. Riga, Vidzeme, and Kurzeme regions fall behind significantly with similar scores, and Latgale gained just 38% of Zemgale points in this list of criteria. A key factor that influenced the score was the presence of HES in the regions, as HES generates 60% of Latvia's total electricity. The Zemgale region is home to the largest HES in terms of electricity production and holds significant potential for green hydrogen production near HES, which can be complemented by nearby solar farm capacities.
3. Regarding available and potential infrastructure for hydrogen utilisation, the Riga region has a notable lead with 47 points, while Zemgale has 30 points, and other regions are falling behind significantly. Riga's leading position is attributed to its well-developed NG network and the presence of an existing hydrogen fuel station.
4. Despite the research findings, it must be acknowledged that if the main green production scenario is wind farms or solar/wind hybrid parks, then the Kurzeme region has an advantage in this scenario because of the times higher existing wind farm capacity than other regions and a large list of future wind park projects. Besides, this region has the largest number of ports in Latvia and a significant potential for offshore wind projects.

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ASSESSMENT OF THE AVAILABILITY OF CITY BUS SERVICES IN JELGAVA IN THE CONTEXT OF A COMPOSITE SERVICE

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Abstract
The dynamic development of urban areas and the phenomenon of suburbanization forces public transport operators to develop changes to ensure the accessibility of public transport. The accessibility of public transport services increases mobility and can also be a factor accelerating urban development. It should be emphasized that public transport services perform a social function, ensuring the right of citizens to free movement and meeting the needs of citizens for movement and demand for public transport services. The aim of the study is to assess the availability of city bus route services in the city of Jelgava in the context of the interconnection of bus and train schedules. To analyse the availability of public transport in relation to the interconnection of city bus route trips with regional train route trips, the study used a cumulative method – an assessment of destinations and effort available at a given time. The study found that in Jelgava there is an insufficient connection between the organization of regional and national city public transport, where as a result of divided planning, intercity and urban transport infrastructures are often incompatible, and there is no unified regional and urban route network and billing system. In practice, this means that the railway and urban infrastructure and public transport connections are not sufficiently coordinated and thus do not ensure easy movement for inhabitants.
Keywords: sustainability, public transport, accessibility, composite service.

Introduction

The transport sector is one of the most important sectors of the national economics, and its development and competitiveness is an essential prerequisite for ensuring the economic stability and overall development of the country in both – national and international level. In all sectors, including transport, the importance of new technologies, innovations and digitalization, environmental (climate change) aspects are increasing, taking into account the emissions generated by the transport sector. The public transport services perform also a social function, ensuring the right of citizens to free movement and satisfying the movement needs of citizens and the demand for public transport services (Ministru Kabinets, 2021). The rate of motorization is increasing in cities, which is defined as the ratio of the number of vehicles to the number of residents in the given area. This is the result of changes in people's lifestyles, created habits and increasing conveniences associated with personal transport. However, individual transport also has a negative impact on the environment due to air pollution, noise and energy consumption, which in turn can lead to deterioration of the health of citizens (Barchański et al., 2022).

The European Green Deal aims to achieve climate neutrality by 2050 (Eiropadome, 2019), indicating that **automated and connected multimodal mobility**, as well as smart traffic management systems and intermodal services, will play an increasingly important role, that will be influenced by the growing topicality of digitalisation solutions. The European Union (EU) transport system and infrastructure are planned to be prepared for new sustainable mobility services that can reduce congestion and pollution, especially in urban areas (Ministru Kabinets, 2021). Reducing the use of private transport primarily requires improving the possibilities for using public transport. The Public Transport Development Concept for 2021-2030 identifies railways as the 'backbone' of the public transport system and buses complement rail transport (Satiksmes ministrija, 2019).

Public transport must meet many requirements and passenger expectations in terms of directness, frequency, availability, reliability, low cost, speed, punctuality, regularity, accurate information, comfort, level of crowding, cleanliness, connections, environment, staff courtesy, safety and security. Accessibility research allows identifying areas where improvements are needed (Żochowska et al., 2022). **Accessibility** is widely described in the literature, but it does not have a single, united definition. Access to transport is defined as the ability to use transport services and reach certain destinations with them (Kaszczyszyn & Sypion-Dutkowska, 2019), while accessibility to public transport is defined as easy **access** to public transport options and easy **reach** of destinations with this transport (Żochowska et al., 2022).

Research hypothesis: Jelgava city bus services ensure accessibility to regional train services. The aim of the research is to assess the accessibility of city bus route services in the city of Jelgava in the context of the interconnection of bus and train schedules. To achieve the aim, the following tasks are set: 1) to identify and assess public transport accessibility assessment indicators; 2) to characterize and analyse the interconnection of Jelgava city bus services with regional train services.

The research concluded that several measurement methods can be identified for measuring the accessibility of public transport services. To analyse the accessibility of public transport in terms of linking city bus routes with regional train routes, a cumulative method was used – an assessment of destinations and effort available at a given time. The research provides the insight into the level of interconnection between public transport modes - trains and city buses, providing conclusions about its accessibility in

Jelgava. According to the data of the Jelgava City Municipality, in 2022 the total number of employed Jelgava residents was 32,754, of which 39.4% (12,910) worked in Jelgava, while 35.5% (11,644) worked in Riga. Based on these conditions, a limitation of the research was set – the accessibility of public transport in Jelgava was studied on weekdays.

Materials and Methods

In the regulatory framework of the Republic of Latvia, accessibility of public transport is explained as access to public transport, which is ensured by **connections** with various types of public transport and the possibility for passengers to transfer to another type of public transport (Ministru Kabinets, 2010). In the Law on Public Transport Services, the term accessibility is understood much more broadly, as it is included in the purpose of the law, which is *to ensure the availability of public transport services to residents* in the route network (Ministru Kabinets, 2007).

Scientific studies distinguish **two basic components of accessibility**: *the transport component* and *the land use component*, as well as two additional components: *time* and *individuality*. The transport component reflects the ease of movement between two stops, while the land use component is the attractiveness of a particular place as a destination in the transport system (Barchański et al., 2022). The time component determines the availability of public transport within a 24-hour period, while the individual component focuses on the individual characteristics and needs of passengers (Olsson et al., 2021). All these components are interconnected.

Although several **methods for measuring transport accessibility** can be found in the scientific literature, five main ones can be distinguished in R. Żochowska's research: the infrastructure equipment method; the distance method; the cumulative method; the potential method and the personified method (Żochowska et al., 2022).

To analyse the availability of public transport in terms of linking city bus routes with regional train routes, in this research **a cumulative method** is used – *an assessment of destinations and effort available at a given time.*

Several public transport accessibility indicators are also used to determine the accessibility of public transport. P. Śleszyński (2014) describes six transport **accessibility indicators**: spatial (determines accessibility that occurs between two points in space); communication (determines accessibility that occurs using means of communication – transport); time (determines accessibility that can occur at a certain physical time); socio-cultural (the subject of accessibility is individuals and human communities); economic (availability of technical, financial, etc. aspects); goal (determines accessibility after effort that occurs as a result of cause-and-effect relationships, according to the classic Weberian definition, actions can result from a goal, values, habits and emotional nature). The most important among the indicators are the time and spatial indicators (Sierpiński et al., 2020), which are analysed in this study in conjunction with the cumulative method.

The time accessibility indicator can refer to both the time needed to reach a bus stop from a starting point and the time needed to travel between two bus stops using public transport (Żochowska et al., 2022). When studying time accessibility, three groups of accessibility measures are most often used: the frequency of public transport, which is usually determined by the number of trips in the period under consideration; vehicle availability, which is described as the time needed to get to the stop; and the time needed to travel by vehicle, which is also described as the time needed to get to the destination by vehicle (Żochowska et al., 2022). Waiting time at bus stops is one of the elements that also significantly affects passengers' opinions about the quality of transit services (Psarros et al., 2011).

Y. Hadas et al. (2023) conducted a study on the attitude of public transport passengers towards a dynamic fare model in Israel, based on the level of vehicle congestion and additional waiting time, and found a relationship – *the longer the waiting time, the less willing they are to wait for the next vehicle*. The study analysed 4 waiting times (5, 10, 20 and 40 minutes), where the waiting time was chosen to compare short waiting times (5 and 10 minutes) and long waiting times – starting from 20 minutes (20 and 40 minutes).

The spatial accessibility indicator is related to the distance travelled and is most often determined by the access to public transport infrastructure in a given area (Washington et al., 2021). The concept of spatial accessibility can be identified with transport accessibility in certain circumstances, but usually it operates as a narrower concept. The maximum walking distance, which is adopted in most cases in research, is 300 meters in city centres and 800 to 1000 meters in areas with single-family housing (Pot et al., 2021).

Results and Discussion

An important term that is linked to the accessibility of public transport is public transport **connectivity**. It describes the ease with which a journey can be made on the public transport system, from any public transport stop to another public transport stop or station in an area. Public transport services operate in a networked market, in which the ability of a customer to consume a particular service depends on location, and no single service provider can satisfy all customer demand given the location-specific nature of these different demands. Therefore, in a networked market, a combination of different services (and service providers) is needed to create **composite services** that can satisfy the majority of customer demand. The more these composite services become a seamless product, the more viable the market becomes and the more meaningful the services become for larger customer demand (Public Transport EGUM Subgroup, 2022).

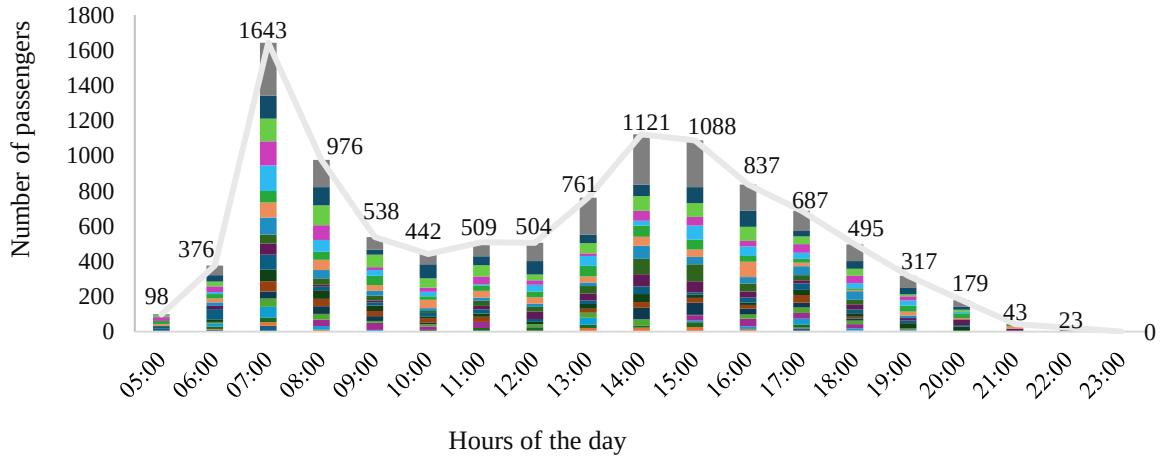
In order to specify the various interpretations of the

term 'public transport accessibility' and to determine the boundaries of its scope, the following **definition of public transport accessibility** has been established within the framework of this research*: public transport accessibility is the interconnection of different modes of public transport (train and city bus, etc.), which ensures that passengers, in the shortest possible time and distance between these modes of transport, access related public transport services and continue their journey to reach their destination*.

The research found that on weekdays in Jelgava, public transport is used by an average of 10,000 passengers per day between 5:00 and 23:00. The highest passenger flow is around 7:00 and 8:00, when approximately 2,600 passengers use the service, see 'Figure 1'. Therefore, it can be concluded that residents use public transport more often to get to work and/or school, where a large part of the population travels to and from Riga.

Figure 1

Number of passengers transported on city bus routes of Ltd. 'Jelgavas autobusu parks' during working hours in March 2023



By studying the connection between train and bus schedules, which is an important factor in creating a coordinated public transport network and providing quality public transport services, several criteria and factors were evaluated to gain a comprehensive understanding of this connection.

In the cumulative method of assessing the accessibility of public transport, which takes into account the assessment of destinations available at a given time and the effort, a point system is applied to the assessment of destinations available at a given time, which is necessary to categorize and evaluate various criteria depending on their significance and importance. The criteria indicated as essential for the research are evaluated by points (Table 1), which show the level of interconnection of public transport modes (trains and city buses) and allow conclusions to be drawn about the accessibility of public transport.

Table 1

Scoring criteria

Connection	***Connection evaluation by waiting time (evaluated each route trip)***	***Connection assessment based on destination accessibility***
Short connection	From 3 or 7 minutes (according to specific bus stop) to 20 minutes – 2 points	Connect all 4 city zones (number of points scored multiplied by 4), connect 3 city zones (number of points scored multiplied by 3), connect 2 city zones (number of points scored multiplied by 2) if you connect 1 city zone (number of points scored multiplied by 1).
Long connection	From 21 to 40 minutes – 0.2 points	Connect all 4 city zones (number of points scored multiplied by 4), connect 3 city zones (number of points scored multiplied by 3), connect 2 city zones (number of points scored multiplied by 2) if you connect 1 city zone (number of points scored multiplied by 1).
Not considered a connection	From 41 minutes and longer (no points awarded)	-

The determination of destinations is based on the zoning of the Ltd. 'Jelgavas autobusu parks' city territory into four zones: A, B, C and D. Points are awarded to each public transport connection - train and city buses - depending on the time factor, that is, the waiting time (how quickly the connection is provided) and the number of available destinations (with how many city zones the connection or accessibility is provided).

The research takes into account that two city bus stops are used in passenger transport with the destination (the railway station 'Jelgava'): 'Jelgavas stacija' and 'Stacijas iela'. Therefore, in this particular case, the spatial assessment criterion is also assessed. The mentioned bus stops are located approximately 300 meters from each other, which creates a different time for passengers at each stop, which they need to transfer from the bus to the train or from the train to the bus.

Using the online cartography service 'Google Maps', which provides directions to various locations around the world, the distance and time required for a pedestrian to get from bus stops 'Stacijas iela' and 'Jelgavas stacija' to the train stop at the railway station 'Jelgava' were determined, see 'Figure 2'.

Figure 2

The time required for a pedestrian to get from the bus stop 'Stacijas iela' and 'Jelgavs stacija' to the train at the railway station 'Jelgava'

It is acceptable to use the built-in functions of your word processor to create equations. Note that while variables and numbers should be italicized, the following elements of equations should be set in roman type: function names, units, words, and abbreviations thereof. Formulas should be numbered (1), (2), (3), etc. and referred to in the text according to their numbers.

As part of the study, one additional minute was added to the calculated time (6 or 2 minutes), which is intended to safely cross the regulated pedestrian crossing on Pasta Street and to board the train. Taking the above into account, the latest bus arrival time at the stop 'Stacijas iela' is assumed to be 7 minutes before the train departure time from the railway station 'Jelgava', and at the stop 'Jelgavas stacija' – 3 minutes. An identical time is also determined for getting from the train arrival at the railway station 'Jelgava' to the bus stop.

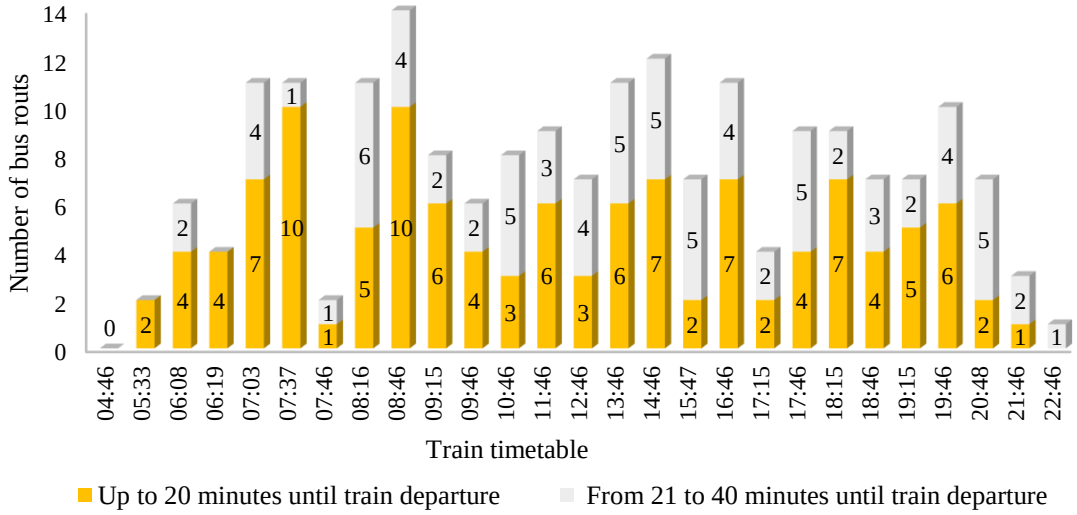
A connection of up to 20 minutes, where the passenger waiting time is up to 13 or 17 minutes, is evaluated with 2 points (assessed as a short waiting time, usually 5, 10 or 15 min.), while a connection of 21 to 40 minutes, where the passenger waiting time can reach up to 33 or 37 minutes, is evaluated with 0.2 points (assessed as a long waiting time, usually 20, 25, 30 or 35 minutes, assuming that in most cases passengers will not choose a connection with such a long waiting time). Waiting times exceeding 33 or 37 minutes are not assessed in the study, and such public transport connections are not considered to be interconnected. A similar assessment of waiting times is also given in the study by Y. Hadas et al. (2023) on the attitude of public transport passengers towards the dynamic fare model.

In the final stage of the points system, for each train route, which creates a connection between city bus services and ensures public transport connectivity with Jelgava city zones, a total number of points is calculated, indicating the level of public transport connectivity. This approach cumulatively takes into account factors that affect the accessibility of public transport: *train and bus connections* (the accessibility of transport services provided by both trains and buses and their interaction are taken into account); *accessibility of city zones* (the accessibility of city zones is taken into account, checking whether each train is connected to city buses that transport passengers to all four city zones, thus ensuring wide accessibility within the city).

When analysing the interconnection of train and bus schedules, the train route schedule on the **Riga – Jelgava – Riga** line was used as a basis, against which all available bus routes of Jelgava city significance were compared, assessing their compliance with the previously set accessibility criteria and assigning an appropriate number of points, see 'Figure 3'.

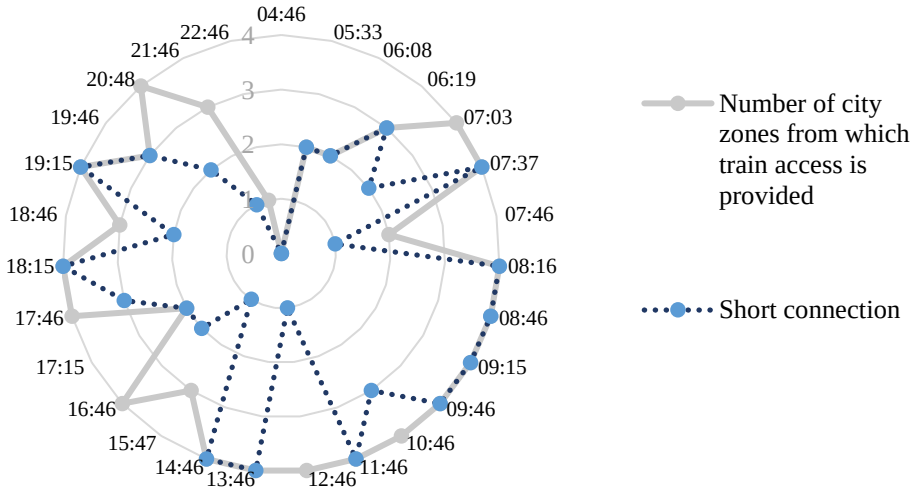
Taking into account that the number of rout connections in itself does not indicate a good level of connection, as it is essential to ensure the availability of public transport services to residents of all city areas, the study conducted an evaluation of city bus routes, determining the city areas served by bus routes and, in accordance with the criterion of available destinations, determining the number of city zones from which train routes are provided to city bus passengers on weekdays.

Figure 3
Number of Jelgava city bus routes available on weekdays by connection duration with trains to Riga



As the research data shows, according to the train travel times, the majority of them (16 trips) are available to all 4 city zones (A, B, C, D). However, several train trips are not available to some city zones. When assessing the availability of public transport provided to city zones for connections with short waiting times, it is seen that out of all four city zones, this level of connectivity is provided by only 10 train trips on weekdays, see 'Figure 4'.

Figure 4
Number of city zones (A, B, C, D) from which city bus passengers are provided with access to train routes to Riga on weekdays



By summing up the points obtained for each train route Jelgava - Riga on weekdays, which creates a connection between city bus routes and ensures public transport connectivity with Jelgava city areas, an assessment of the accessibility of city bus services in points was obtained for the aforementioned train routes, see 'Figure 5'.
The connection of city bus routes with train routes on the Jelgava - Riga route on weekdays is provided at a very good level for 11 out of 27 routes, which makes up 41% of the total number of routes, while 16 out of 27 routes, which makes up 59% of the total number of routes, can be characterized as good connections.
Analysing the available train routes on weekdays that arrive at the Jelgava railway station every working day from Riga, it was found that the situation is similar with outgoing routes, see 'Figure 6'.

Figure 5
Assessment of the availability of city bus routes at points for each train route Jelgava - Riga on weekdays

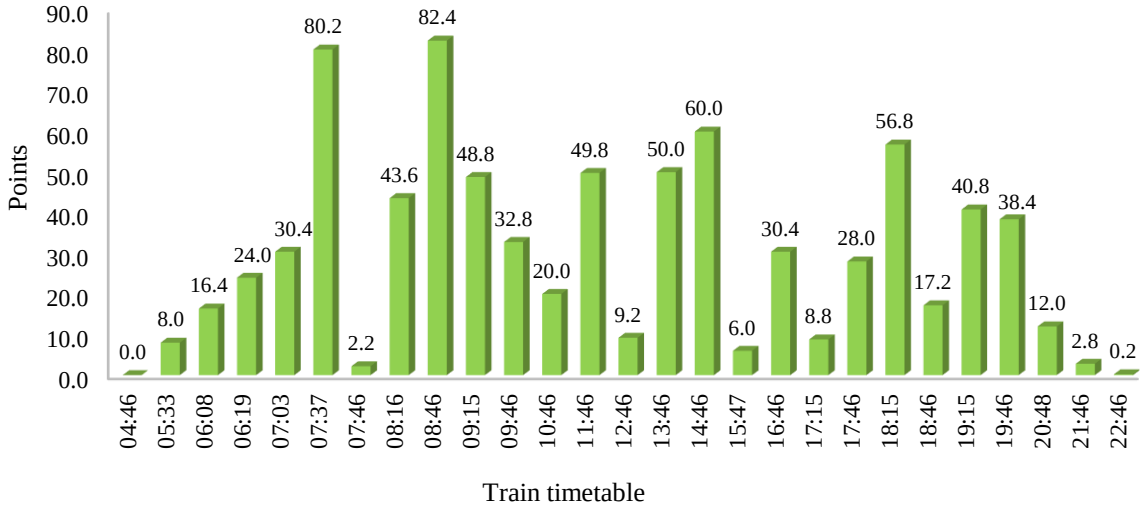
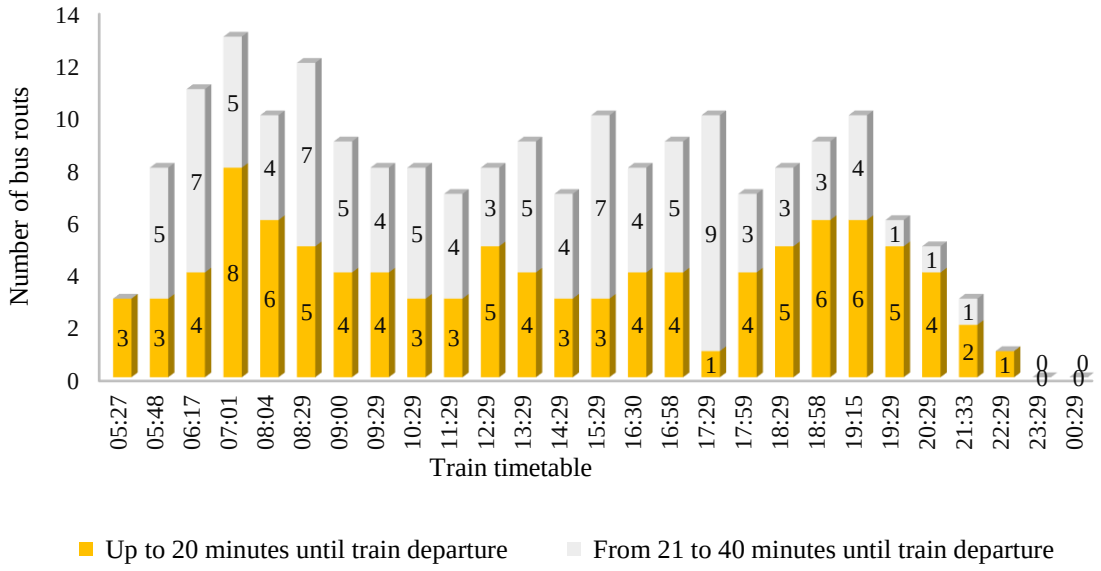


Figure 6
Number of city bus routes available to Jelgava city areas on weekdays for passengers on the Riga - Jelgava train route

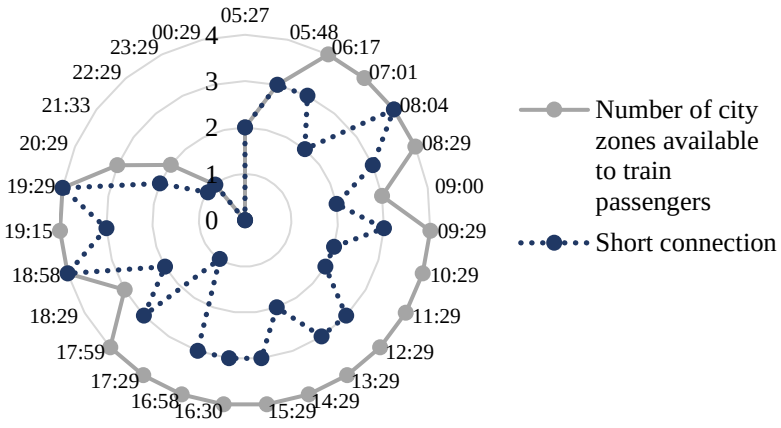


Similar to the first route connection analysis, the evaluation of city bus services was carried out, determining the city areas served by bus services and, in accordance with the destination accessibility assessment criterion, the number of city areas to which city bus services are provided for train passengers on weekdays was determined.

According to the train timetables, most of them (18 trains) provide connections with buses that transport passengers to all 4 city zones (A, B, C, D). However, there are several train services that do not provide bus connections to certain city zones, see ‘Figure 7’.

Overall, the research concluded that the connection of city bus trips with train trips on the Riga - Jelgava route on weekdays is provided at a very good level on 6 out of 27 trips, which makes up 22% of the total number of trips, while 17 out of 27 trips, which makes up 63% of the total number of trips, can be characterized as good connections.

Figure 7
Number of city zones (A, B, C, D) to which city bus access is provided for train passengers from Riga on weekdays



Conclusions

1. Approximately 35% (~11,650 Jelgava residents) of all working Jelgava residents work in Riga, of which approximately 20% (~2,400 Jelgava residents) use the train to get to Riga. The approximate number of passengers transported by city buses on routes to the Jelgava railway station on a working day is 722 passengers, while the number of passengers transported from the Jelgava railway station on a working day is 703 passengers.
2. The connection of city bus trips with train trips on the Jelgava - Riga line on weekdays is provided at a very good level in 41% of cases (connections with 27 train trips were assessed), while 59% of train trips are considered well connected. The connection of city bus trips with train trips on the Riga - Jelgava line on weekdays is provided at a very good level in 22% of cases (connections with 27 train trips were assessed), while 63% of train trips are considered well connected.
3. The hypothesis put forward in the research has been partially proven, as Jelgava city bus services provide partial connectivity with regional train services.

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ASSESSMENT OF THE PROBLEMS OF SOCIAL-ECONOMIC ASPECTS OF SELF–EMPLOYMENT

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Abstract
Employment constitutes a fundamental indicator of economic development and growth; consequently, employment policy is integral to national and regional socio-economic strategies. Self-employment serves as a vital form of labour market participation, widely adopted in Latvia and other European Union (EU) member states as a mechanism for entrepreneurial initiation and labour market integration. According to Eurostat data, in 2023, the EU-27 recorded 26.0 million self-employed individuals, comprising 13.0% of the total employed population (199.6 million). Despite its widespread presence across EU member states, self-employment is associated with certain adverse characteristics. The self-employed status can be exploited to circumvent tax obligations and labour law compliance, predominantly benefiting employers by enabling labour cost reduction. However, such practices may significantly constrain self-employed individuals' access to social protection mechanisms, thereby adversely affecting their quality of life and overall well-being in the context of multiple social risk contexts, including incapacity, disability, and retirement. This research examines the facilitating and constraining factors influencing the socio-economic environment of self-employed individuals in Latvia, incorporating insights from experts in the field of self-employment. Based on the research findings, two prospective scenarios have been formulated to enhance the socio-economic conditions of self-employed individuals.
Keywords: self-employment, taxes, socio-economic aspects.

Introduction

In contemporary labour markets, flexible employment forms, including self-employment, are gaining increasing popularity among both employees and employers due to their various advantages. Self-employment provides greater autonomy and personal independence, facilitates labour market entry and retention, and enables individuals to generate additional income alongside their primary employment.

The scientific literature presents divergent perspectives on the role and significance of self-employment. Some scholars conceptualise it as a flexible form of employment that enhances labour market adaptability and economic dynamism (Davidsson & Henrekson, 2007; Millan et al., 2010; Purcell, 2000). Conversely, other researchers (McKeown, 2015) argue that self-employment, in certain cases, may represent a form of involuntary employment or even an 'escape' from traditional employment structures, often driven by precarious working conditions and employer-imposed constraints.

Self-employed persons or the self-employed in the sense of the present research are natural persons who perform the economic activity, i.e. self-employed individuals, **individual merchants (IK)**, farm owners (FO) and fishing undertaking owners (FUO) as well as royalty recipients.

Research hypothesis - by evaluating the factors influencing the socio-economic environment of self-employment in Latvia, it is possible to develop measures and scenarios that foster the development of self-employment.

The object of the research is the socio-economic environment of self-employment, the subject of the research is the possibilities of improving the legal status of self-employed persons, tax and accounting records, as well as social insurance. The research aim is to analyse the factors influencing the socio-economic environment of self-employment, to develop and evaluate scenarios that would promote the development of self-employment in Latvia. To achieve the aim of the research, the following tasks were set: 1) to identify the factors facilitating and inhibiting the socio-economic environment of self-employment; 2) to develop scenarios and proposals for improving the socio-economic environment of self-employment. The research was conducted between March and May 2023.

Materials and Methods

PEST analysis is used to group socio-economic factors. The research employs the expert survey method to ascertain expert opinions and evaluate factors influencing the socio-economic environment of self-employment in Latvia. The scenario method is applied to develop self-employment development scenarios in Latvia based on the information obtained in the research. The analytic hierarchy process (AHP) method is used to determine experts' assessments of the developed scenarios.

To achieve the research objectives, publications by Latvian and international scholars in international scientific databases, laws of the Republic of Latvia, regulations of the Cabinet of Ministers, planning documents, studies conducted by European Union institutions, informative reports from the Ministry of Welfare and the Ministry of Finance, data from the Central Statistical Bureau, the State Revenue Service, and Eurostat, as well as interviews conducted by the authors, have been utilized.

Results and Discussion

Statistical data indicate that self-employment plays a stable role in the labour market both in the EU member

states (where self-employed individuals accounted for 13.0% of total employment in 2023) and in Latvia (where the share was 13.3% in 2023). This demonstrates a consistent proportion of self-employment at both the national and European levels. Self-employed individuals are driven by various motivations to engage in this form of work.

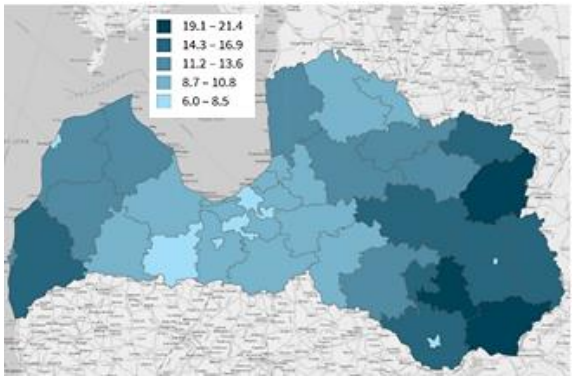
One of the motivations for self-employment is the reduction of taxable income and social security contributions, sometimes referred to as 'cost optimisation'. Here, self-employment is regarded as an exception in the labour market (Johansson, 2005; Szaban, 2018). According to some researchers (Vosko, 2006; Wall, 2015; Hughes, 2006), a defining feature of self-employment is its inherent instability, which they view as a negative aspect. The sources of this instability are linked to factors like lower social benefits, elevated risk, low income, and a lack of job security. On average, the share of self-employed individuals in Latvia and EU member states stands at 13.0%; however, in certain rural regions of Latvia, it reaches as high as 21.4%.

This disparity highlights the significant role of self-employment in rural development, as it fosters economic growth and provides sources of income. Self-employment contributes by creating new jobs for local residents and reducing unemployment, supporting the development of local products and services such as home - production, craftsmanship, and ecotourism, as well as promoting financial independence and reducing reliance on urban labour markets.

In 2023, the share of self-employed individuals among the employed population in Latvia was 13.3%. This figure varies across administrative territories, ranging from 6.0% in Olaine Municipality to 21.4% in Preiļi Municipality 'Figure 1'.

Figure 1

Percentage of self-employed workers among the employed population in Latvia's administrative divisions in 2023



Source: authors' construction based on CSO data, 2025.

The highest percentage of self-employed individuals within the employed population is found in the Latgale region: Preiļi Municipality (21.4%), Krāslava Municipality (19.5%) and Balvi Municipality (19.1%). In the Kurzeme region, the highest shares are recorded in Dienvidkurzeme Municipality (15.4%) and Kuldīga Municipality (13.6%).

Moreover, in Latvia, farms (farm owners FM) are predominantly small-scale and managed by their owners, who, according to regulatory provisions, are also classified as self-employed individuals. For example, in 2023, farms accounted for 20.0% of all registered enterprises in Preiļi Municipality and 16.4% in Balvi Municipality.

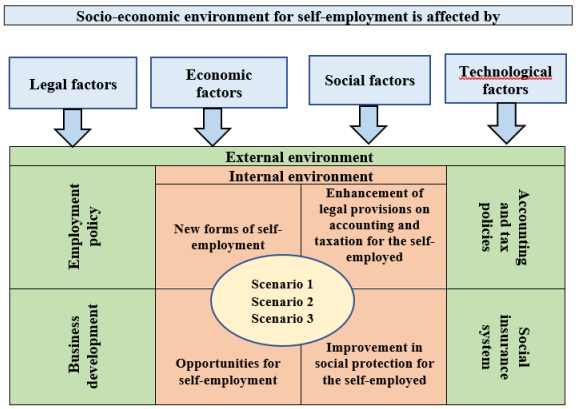
In 2023, 27,2 thousand self-employed individuals belonged to the occupational group *'Skilled agricultural, forestry, and fishery workers',* accounting for 23.0% of all self-employed persons. By 2024, this number had increased to 29,2 thousand or 24.3%.

This group includes individuals engaged in crop cultivation, harvesting, livestock production, forest management and conservation, fish farming and fishing, as well as hunting. Statistical data highlight the significant role of self-employment in rural regions, underscoring the need to promote self-employment in these areas by improving working conditions and support mechanisms.

Within the research, a conceptual structure for the internal and external environment was developed 'Figure 2'. Through a PEST analysis, it was identified that the socio-economic environment of self-employment is impacted by legal, economic, social, and technological factors.

Figure 2

The conceptual structure of the research's internal and external environment



Source: authors' construction.

The legal factors influencing self-employment include tax and accounting policy frameworks for self-employed individuals, conditions for accessing and obtaining funding, overall national employment policy, and the legal framework regulating self-employment.

The economic factors of self-employment reflect broader economic processes within the country that impact the well-being of self-employed individuals, the level of taxation they are subject to, and their participation in the labour market.

The social factors of self-employment pertain to cultural attitudes, ethical beliefs, shared values, lifestyle differentiation, demographics, education levels, and social protection.

The technological factors influencing self-employment are linked to advancements in technology that may transform the nature of self-employment. Technology drives innovation and reduces costs.

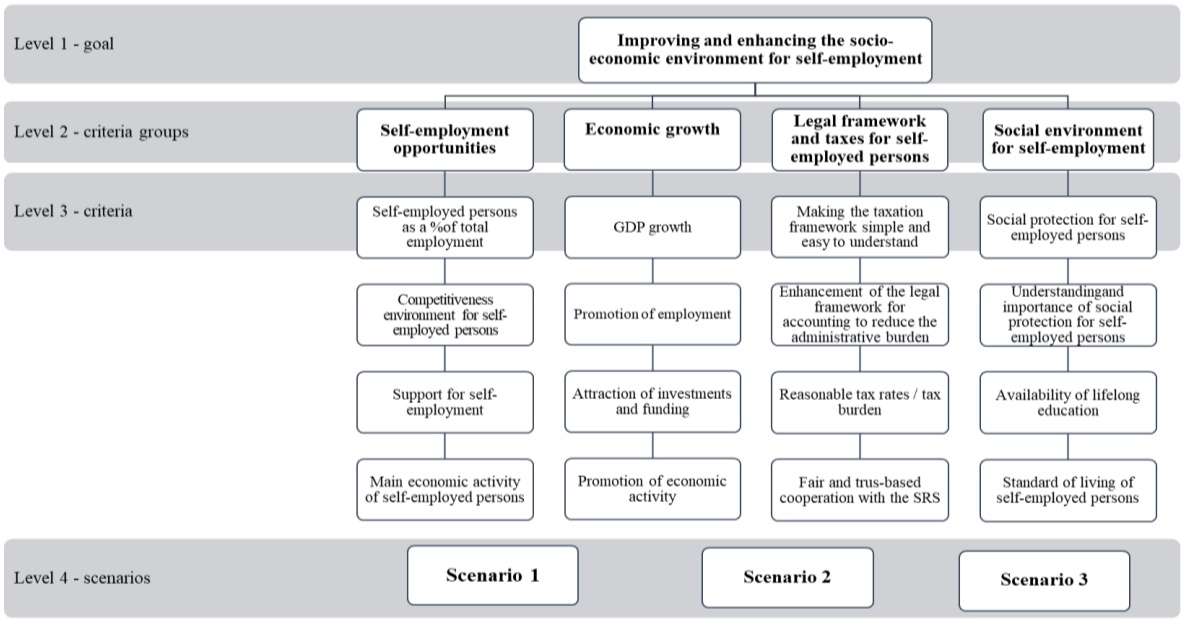
Given the significance of all these factors (legal, economic, social, and technological), to refine the scope of this research, one key factor from each category is selected: **the legal framework of self-employment** (legal factor), **the level of taxation** (economic factor) and **social protection** (social factor).

In March 2023, an expert survey was carried out to evaluate all relevant factors. Experts were invited to complete a questionnaire addressing the issue of 'Enhancing and improving the socio-economic environment as a necessity for promoting self-employment in Latvia'.

The purpose of the survey was to collect expert opinions on the deficiencies in Latvia's legal, tax, accounting, and social insurance systems and possible reforms. A total of seven experts participated, representing various fields and levels, including inspectors from the State Revenue Service, an accountant, a tax consultant, a professor, and a representative from the Ministry of Finance, all of whom deal with aspects of self-employment. The questionnaire was segmented into three main sections: an assessment of legal, economic, and social factors. Each section included multiple factor elements, which were evaluated on a scale from 1 to 5, where: 1 - unsatisfactory; 2 - rather unsatisfactory; 3 - rather satisfactory; 4 - satisfactory; 5 - very good. After evaluating the factor elements, respondents were prompted to share their views on the current regulatory framework, tax and accounting policies, and the social insurance system for self-employed individuals.

Figure 3

Criteria hierarchy for evaluating improvements and advancements in the socio-economic environment for self-employment



Source: authors' construction.

The legal factors affecting self-employed individuals in Latvia are viewed by experts as generally satisfactory. Among the four evaluated elements (procedures for registration and termination of self-employment; application of regulatory acts for accounting under the single-entry system; the accounting process itself under the single-entry system; and the possibility of using a simplified tax payment solution), the lowest-rated aspect was the application of regulatory acts for accounting under the single-entry system. Experts noted that the regulatory requirements are overly complex and numerous, making them difficult for self-employed individuals to navigate.

According to experts, the tax system for self-employed individuals (general tax regime, micro-enterprise tax, and reduced patent fee) is assessed as satisfactory. Among these tax regimes, the general tax regime was considered the most complex and rated as rather satisfactory, as self-employed individuals must have extensive knowledge of numerous regulatory acts to correctly calculate their taxes.

Experts rated the taxation of royalty recipients as rather satisfactory. However, there were differing views on whether recipients of royalties should be mandated to register as economic operators and select a suitable tax regime, or if they should stay unregistered and pay only royalty taxes. Experts

evaluate the social insurance system under both the general tax and micro-enterprise tax regimes as satisfactory. However, experts acknowledged that the calculation of mandatory state social insurance contributions under the general tax regime is complex. Self-employed individuals must calculate two types of social insurance contributions (31.07% and a 10% pension insurance contribution), and the State Social Insurance Agency may impose additional minimum social insurance contributions.

The Analytic Hierarchy Process (AHP), developed by American scientist T. L. Saaty (Saaty, 1980), was used to identify the most suitable development scenario for enhancing the socio-economic environment for self-employed individuals. To help experts understand the criterion groups and individual criteria, a document titled 'Description of criterion groups and individual criteria for the enhancement and improvement of the socio-economic environment of self-employment' was developed 'Figure 3'.

The authors present three potential scenarios for the improvement of the socio-economic environment for self-employed individuals in Latvia: **Scenario 1:** The existing tax and accounting system for self-employed individuals. **Scenario 2:** A revised tax and accounting system for self-employed individuals without a separate category for royalty recipients. **Scenario 3:** A revised tax and accounting system for self-employed individuals with a distinct category for royalty recipients. The subsequent section provides a detailed analysis of these potential scenarios for improving the socio-economic conditions of self-employment.

Scenario 1 represents the current system of accounting and tax calculation for self-employed individuals.

The objective of Scenario 2 is to categorise self-employed individuals based on income levels and professional activity. The core concept is to simplify both tax payments and accounting for self-employed individuals who generate additional income or have an annual income of up to €50,000 (before VAT registration). Description: the existing three tax regimes - micro-enterprise tax, personal income tax under the general regime, and the reduced patent fee - as well as the mandatory minimum state social insurance contributions, would be restructured as follows: the **micro-enterprise tax** would be replaced with a **self-employment tax**, applicable to self-employed individuals, **individual merchants (IK) and farm holdings (FM)** would continue to be taxed under the existing general tax regime with certain modifications; the **reduced patent fee** would be retained in its current form.

Recipients of royalties would register as self-employed individuals and pay one of the taxes available to self-employed persons, without distinguishing them as a separate category of royalty recipients, as planned from 1 January 2028.

As a result of rapid globalization and the growing opportunities offered by the internet, various platforms for generating additional income have become widely used in Latvia. Therefore, implementing a distinct tax regulation for this group is recommended. The authors propose dividing self-employed individuals into two categories: those providing services and those engaged in the production and/or sale of goods, applying different tax rates to the income of each group. A 25% self-employment tax would be applied to those offering services, such as working on digital platforms like Bolt and Wolt, as well as engaging in activities such as creative work, beauty services, private tutoring, childcare, cleaning services, language translation, event planning, tourism services, advertising revenue from various websites, car and equipment repairs, lawn mowing, and similar occupations.

For self-employed individuals engaged in producing and selling goods or renting personal property, a 15% self-employment tax rate is recommended. This group would consist of craftsmanship (such as jewellery making), the trade of handmade goods at local markets and fairs, product sales on platforms like Etsy, Printful, and Printify, mobile trading, guest accommodation through Airbnb and Booking.com, the sale of homemade food and beverages, selling tools and equipment on eBay, car rentals, and all other activities related to the trade of goods. This tax system would be available until the VAT registration threshold is met. The paid tax amount would be allocated in an 80/20 ratio, meaning 80% would be directed towards social insurance contributions and 20% towards personal income tax. If self-employment serves as a supplementary source of income, tax reliefs - such as allowances for dependents and the taxpayer's annual non-taxable minimum - could be applied to the primary place of employment without forfeiture. This system would provide self-employed individuals with coverage under five types of social insurance: state pension, disability, maternity, paternity, sickness, parental, and health insurance. However, they would not be insured against workplace accidents, occupational diseases, or unemployment. A mandatory requirement would be a separate settlement account or a business income account, with all transactions conducted via non-cash payments - either by bank transfer or through payment card terminals - thus reducing cash circulation. This strategy would decrease the administrative burden for self-employed individuals, as bookkeeping would no longer be required, and the number of reports submitted to the State Revenue Service would be reduced.

If a self-employed individual's annual income surpasses the VAT registration threshold, they must sign up for VAT as a self-employed person, individual merchant, or farm operator and follow the standard tax system. This system would largely remain unchanged, with some modifications - the social insurance contribution rate would be aligned with the rate for employees (34.09% in 2025) and this contribution would be mandatory based on the state-defined minimum wage, ensuring higher contributions to the

national social security budget and complete social protection for self-employed individuals. If a self-employed person wished to receive additional social insurance coverage, voluntary contributions above the minimum wage would be permitted. The State Revenue Service would conduct various informational campaigns (via social media, TV) to raise awareness of the importance of social insurance and its benefits. In this case, self-employed individuals would be entitled to comprehensive coverage across all seven types of social insurance, just like employees. This includes state pension insurance, disability insurance, maternity and paternity insurance, sickness insurance, parental insurance, health insurance, work accident and occupational disease insurance, as well as unemployment insurance. The progressive personal income tax rate would be retained. Additionally, self-employed individuals would have the flexibility to choose whether to conduct all transactions through non-cash payments using a dedicated bank account or to allow cash transactions while maintaining single-entry bookkeeping.

Scenario 3 – a new tax and accounting framework for self-employed individuals, differentiating those who earn royalties. Across various EU member states, individuals earning royalties are treated separately from self-employed individuals. In Latvia, a transition period has been established for authors, but from **January 1, 2028**, royalty recipients will be required to register as self-employed individuals and pay taxes themselves.

Table 1
Expert rating of criteria group

Criteria groups	*Experts*							*Average*
	1	*2*	*3*	*4*	*5*	*6*	*7*	
Self-employment opportunities	0.34	0.12	0.05	0.52	0.16	0.11	0.05	0.19
Economic growth	0.06	0.57	0.16	0.05	0.06	0.06	0.15	0.16
Legal framework and taxes for self-employed persons	0.16	0.13	0.57	0.30	0.54	0.31	0.57	0.37
Social environment for self-employment	0.44	0.17	0.22	0.12	0.24	0.53	0.23	0.28

Source: authors' calculations based on the expert survey, experts 7.

During the transition period, the **royalties payer withholds a 25% tax**, which is distributed as follows: **80% – social insurance contributions, 20% – personal income tax.**

Royalties recipients should be treated separately from self-employed individuals. Scenario 3 builds upon Scenario 2, with the key difference being that royalties recipients are not required to register as self-employed individuals unless their annual turnover from royalties exceeds €50,000. If their annual royalties income surpasses this threshold, they must register as self-employed individuals.

If royalties are paid by a collective management organisation for copyright and related rights, taxation and payment procedures remain unchanged.

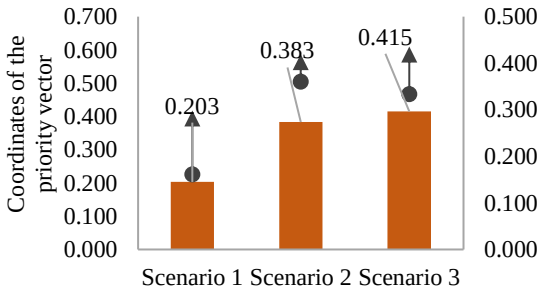
Under Scenario 3, royalties recipients remain subject to royalties tax until their annual turnover reaches €50,000. A 25% tax is withheld from royalties income, which is allocated as follows: **80% –social insurance contributions, 20% – personal income tax.**

The royalties recipient is insured under five types of social insurance: state pension insurance, disability insurance, maternity, paternity, and sickness insurance, parental insurance, and health insurance. However, they lack coverage for workplace accidents, occupational diseases, and unemployment, with no requirement for minimum social insurance payments. Income from royalties can be transferred to a personal bank account, eliminating the need for a dedicated business account. There is no requirement to maintain accounting records, as the payer of the royalties declares the relevant transactions, income, and withheld tax to the State Revenue Service. The expense norms specified in the Cabinet of Ministers regulations on the application of the *Personal Income Tax Law* (50% and 25%) are not applied. Conducting a hierarchical analysis of the enhancement and improvement of the socio-economic environment for self-employment, experts identified the criterion group 'Legal framework and taxes for self-employed persons' as the most significant among the four defined criterion groups. The average priority vector coordinate for this group is 0.37 (Table 1). Experts consider that the primary focus should be on the regulatory framework for self-employed individuals, which governs both accounting procedures and tax calculations. Experts number 3, 4, 5, 6, and 7 prioritised this criterion group, whereas experts number 1 and 2 identified different groups as their top priorities - namely, 'Self-employment opportunities' and 'Economic growth', respectively. When analyzing the current socio-economic conditions for self-employed individuals, experts offered the most feedback and

suggestions, particularly regarding accounting and taxation, with a focus on the legal-administrative environment and tax system. The following criterion group that requires adjustments to improve the socio-economic environment for self-employed individuals is the ‘Social Environment for the Self-Employed’, with an average priority vector coordinate of 0.28. Experts have considered ‘self-employment opportunities’ (0.19) and ‘economic growth’ (0.16) to be of lesser significance (Irmeja, 2023).

Figure 4

According to the expert, the most suitable scenario for advancing the socio-economic environment for self-employment



Source: the authors’ analysis based on the expert survey results, experts 7.

After evaluating the four criterion groups and sixteen criteria, experts have selected the third scenario, a new taxation and accounting system for the self-employed, separating royalties recipients as the optimal scenario, with a priority vector coordinate of 0.42. The second most optimal scenario is the second scenario – ‘a new taxation and accounting system for the self-employed, without separating royalties recipients’ -with a priority vector coordinate of 0.38. The first scenario, which involves the current taxation and accounting system for self-employed individuals in Latvia, was ranked third overall, with a priority vector coordinate of 0.20.

Conclusions

1. The percentage of self-employed individuals in Latvia’s employed population is slightly greater than the EU average, with figures of 13.5% and 13.0%, respectively, in 2023. In Latvia, this indicator varies by administrative territory, ranging from 6.0% in Olaine Municipality to 21.4% in Preiļi Municipality. In rural regions, self-employment has a significant impact on employment levels, with the highest proportion of self-employed individuals found in Preiļi Municipality (21.4%), Krāslava Municipality (19.5%), and Kuldīga Municipality (13.6%).
2. The socio-economic landscape for self-employment is shaped by legal, economic, social, and technological factors. Among these, experts evaluated the legal factor as somewhat satisfactory for self-employed individuals, highlighting the application of regulatory acts in accounting and the tax system for recipients of royalties. At the same time, the tax and social insurance systems for self-employed individuals were considered satisfactory, though experts highlighted the need for specific changes to tax regulations.
3. The research proposed two potential scenarios for enhancing the socio-economic environment for self-employment in Latvia: a new taxation and accounting system for self-employed individuals, either without distinguishing recipients of royalties or with a separate system for them. Experts identified the optimal scenario as the introduction of a new taxation and accounting system that specifically distinguishes recipients of royalties.

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ADDRESSING CYBERSECURITY CHALLENGES IN LATVIAN SMES: LEGAL, HUMAN, AND ECONOMIC DIMENSIONS OF DIGITAL TRANSFORMATION

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Abstract
In today's business environment small and medium-sized enterprises (SMEs) are constantly adapting to the era of digital transformation. The rapid integration of technology has catalysed digital transformation and engendered unprecedented challenges. The aim of this research is to ascertain the most pertinent cybersecurity risks for SMEs in the times of digital transformation. The study focus is on the cybersecurity standards, requirements and provision of support mechanisms established by the European Union and Latvian national legal frameworks. The empirical research analyses the human factor in cybersecurity for SMEs. The study revealed human, organisational, technological and security risks as significant cybersecurity risks for SMEs. The findings of the empirical study conducted reveal that continuous self-development, characterised by the acquisition of new skills and competencies, is conducive to the human resource perspective of digital transformation. Three fundamental objectives were identified to support the goals of cybersecurity and digital transformation. These are the availability of funding, public-private cooperation and education for enterprises. The study concludes that the development of robust legal and economic policies is fundamental to ensure the protection of SMEs in policy making, law enforcement and the ongoing digital transformation of the sector.
Keywords: cybersecurity, SMEs, economy, legal framework, risks.

Introduction

It is undeniable that digital autonomy and cyber security have now become a high strategic priority for the European Union (EU) and its Member States. In Latvia, the number of cyber-attacks has increased by 40% since 2022, and attacks on critical infrastructure as well as on public institutions have quadrupled; therefore, the level of cybersecurity threat could be considered to be high. It is often enterprises that are the target of cyber-attacks, thus both risking enterprises resources and becoming 'gateways' to access enterprises customers, including public authorities (Cert.lv., 2024). During the COVID-19 pandemic SMEs had to continuously adapt, including restoring Internet services, understanding cloud services, managing work remotely, etc. This created unprecedented challenges for SMEs, thereby increasing cyber threats and resulting cyber problems. Vulnerabilities in business are manifold. The rapid adoption of new technologies in the business environment such as cloud computing, artificial intelligence, blockchain, big data, etc. has not only accelerated the pace of digital transformation in SMEs but has also created a number of unprecedented challenges. During the digital transformation, SMEs could be more vulnerable and exposed to cyber-attacks. Moreover, it is cybersecurity that is crucial for business continuity, thereby resulting in the technological leap (Saeed et al., 2023). Cybersecurity risks range from data breaches to sophisticated cyber-attacks, with far-reaching and devastating impacts on business operations. Accordingly, a holistic understanding and strategic approach is essential to mitigate cyber threats (Benjamin et al., 2024). Therefore, this study aims to identify and analyse the cybersecurity risks and challenges for SMEs during their digital transformation from a legal and economic perspective.

Materials and Methods

The following research methods were employed to achieve the research aim: monographic and descriptive, which were based on a literature review to collect and analyse legal and economic literature on cybersecurity requirements of SMEs, risks and future challenges.

The research analysed research papers, conference proceedings, and reports by public authorities and performed a content analysis focused on cybersecurity risks in the SME sector. Based on the findings, the research developed a theoretical discussion, identifying the main risks affecting the cybersecurity of SMEs. The legal analysis method was employed to collect, organize and analyse regulatory legislation and policy documents at the national and EU levels (Hamzani et al., 2023).

Various methodologies are applied to make effective decisions. One such method is a questionnaire, which is considered one of the most effective research methods (QuestionPro, [n.d.]). The research used an empirical research method – a sociological survey –, and the results of the survey were analysed using statistical data analysis. Recent studies have demonstrated that enhancing security measures is only attainable through the advancement of digital competencies (Nyikes et al., 2022). The sociological survey was conducted with the aim to explore employees' evaluation of their digital literacy and to examine their motivation to acquire new knowledge and skills. The survey period was from April 2024 to June 2024, and a total of 152 respondents: 125 females and 27 males were interviewed, IBM SPSS software was used for statistical data analysis, while for calculation and analysis of statistical indicators – sampling and inferential statistical methods, including 'descriptive statistics', 'crosstabulation', and 'chi-square test' were used (Kristapsone, 2020).

Results and Discussion

1. Cybersecurity landscape for SMEs in the context of digital transformation

As regards the subject of cyber security, it should be mentioned that the Contact Committee of the EU explains the term cyber-attack as *'an attempt in cyberspace to endanger or destroy the confidentiality, integrity and availability of data or a computer system'* (Contact Committee, 2020). The term digital transformation is used to describe the introduction of digital solutions into business, which can lead to significant change and impact in a variety of areas, including business processes, customers, target markets and user experience (Saeed et al., 2023).

In the history of cyber-attacks, there are several famous cyber-attacks to note, one of the most dangerous being WannaCry, which blocked 200,000 computers in 150 countries using the Windows operating system in 2017. The result was encrypted data and a ransom demanded from the victim. In 2015, a cyber-attack on the Ukrainian electricity grid caused 230,000 people to experience a power outage. The cyber-attack involved phishing, whereby an employee receiving an email opened an infected Microsoft file with malware, thereby having irreparable consequences (Ahmad, 2023).

Arroyabe, Arranz and Arroyabe, Arroyabe have noted that SMEs often do not allocate enough resources to effective cybersecurity measures. The reason is a lack of understanding of the potential risks and the value of the investment. Therefore, best practices, regulatory requirements, complexity of cyber threats and organisational awareness are regarded as key drivers of cyber security in enterprises (Arroyabe et al., 2024). Ambreen, Jain, Yadav and Loonkar argue that raising awareness among SME decision-makers of the potential consequences of cyber-attacks on SMEs should be prioritised, with an emphasis on the responsibility of managers (Ambreen et al., 2024).

The 2024 Global Cyber Outlook focuses on two important areas of cyber security. First, it highlights the growing inequalities in cyberspace that have a significant impact on SMEs, noting several reasons such as early adoption of transformative technologies, limited access to cybersecurity services, legislation development, etc. Second, it highlights the impact of advanced technologies such as generative AI and large language models. Accordingly, a responsible approach to the introduction of advanced technologies is essential, involving the timely reinforcement of the systems supporting them (World Economic Forum, 2024a).

SMEs are recognised as a primary catalyst for economic growth and social development on a global scale. Wang points out that risks such as supply chain disruptions (technological, security and organisational) are typical for SMEs in the context of digital transformation. Thus, a set of measures such as the implementation of cybersecurity governance, security management tools, and supporting measures including hybrid training strategies to educate employees on the impact and potential of technology are essential to mitigate the risks (Wang, 2023). Romi points out that digital skills in the workforce are an essential aspect of regional economic development. Accordingly, digital competencies are necessary and imperative in using various digital opportunities such as ICT design and development, manufacturing, support and service, marketing, etc. (Romi, 2024). The 2024 Fortinet study concluded that to combat cyber-attacks, human resources need not only cyber security tools but also a certain set of skills. At the same time, the integration of innovative technologies based on a continuous build-up of knowledge and skills is an essential aspect of the fight against cyber threats (Fortinet, 2024). Annarelli and Palombi argue that the advent of digitalisation in business has accelerated a paradigm shift in the threat posed by cyberspace. Moreover, cyber resilience in the enterprise is fostered by, among other things, a continuous build-up of knowledge about the unique features of the latest digital technologies (Annarelli & Palombi, 2021).

A research study by Chidukwani, Zander and Koutsakis is dominated by concerns that cyber risks are evolving faster than digital technologies. As a result, problems are exacerbated by inexperience in the use of security technologies. In addition, SMEs' lack of resources to develop their networks also makes them easy targets for attackers. Therefore, social engineering is regarded as the most common form of attack against SMEs, including phishing attacks, hacking as data theft, malware, etc. (Chidukwani et al., 2022).

Luukkonen and Sönmez believe that phishing and social engineering are the main external threats that pose a potential attack on SMEs. They regard poor device and password protection, inadequate risk assessment and training, low skills and cyber hygiene culture as internal threats (Luukkonen & Sönmez, 2023).

Rawinadaran, Jayal, Prakash and Hewage have estimated that SMEs are most often confronted with three cyber security problems: first, malware attacks that cause damage to their networks and computer systems; second, phishing attacks; and third, ransomware attacks that lock down computer systems until a ransom is paid. Therefore, effective cyber security requires an understanding of the threats and their prevention (Rawindaran et al., 2023). Alahmari and Duncan revealed in their research study that 333 out of 612 SMEs in the UK were victims of a cyber-attack in 2018, thereby pointing out that cybersecurity risk management was essential for SMEs. They noted five sequential aspects as important, namely threats, behaviours, practices, awareness and decision-making (Alahmari & Duncan, 2020). Cybersecurity risks in digital transformation highlight the need for a regulatory framework with common cybersecurity

requirements, standards and liability thresholds addressing the specific needs of SMEs.

2. Scope and impact of the regulatory framework for cybersecurity for SMEs

2.1. EU legal regulations and their implications at the national level

One of the EU initiatives is to achieve the same high level of security for information systems across the EU, therefore the NIS Directive (European Parliament and..., 2016), adopted in 2016, introduced security measures and obligation to report security incidents. The improvements made were successful, yet given the volume, number and frequency of cybersecurity incidents, the risk of serious threats to the operation of networks and information systems is still increasing daily (Schmitz-Berndt, 2023). On 18 October 2024, the EU Directive NIS 2 replaced the original 2016 Directive, leaving Member States ill-prepared to face changing and emerging cybersecurity challenges (Vandezande, 2024).

The revised Directive, extends the regulation by the 2016 NIS Directive and sets stricter cyber security requirements for service providers (European Commission, 2024). For example, improving attack and risk management measures in SMEs if it is SMEs that supply products to larger enterprises. In this case, an attack on the supply chain can affect SMEs as well as larger enterprises (European Parliament and..., 2022). The requirements set by the Directive apply to 'essential' public and private entities such as food manufacturing, digital and postal services, etc., as well as 'important' entities such as banking, energy and manufacturing services, etc. (Ministry of Defence, 2023). Annexes I and II of the NIS2 Directive list in sequence both the essential and the important fields and the breakdown of fields to which the requirements of the Directive apply (European Parliament and..., 2022). The Member States are given an opportunity to specify which SMEs are essential or important for the economy or society of their Member State (DIGITALEUROPE, 2021), thereby identifying the fields or services that should be considered critical (The State Chancellery, 2025). Therefore, the requirements set by the Directive are also applicable, inter alia, to SMEs operating in the specified fields of activity.

To meet the requirements set by the NIS2 Directive and to implement the goals set by the Strategy in Latvia, the National Cyber Security Law (National Cybersecurity Law, 2024) came into force on 1 September 2024, replacing the previous Law on the Security of Information Technologies. The law applies to essential and important service providers operating in the energy, transport, health, banking and financial market industries and, based on a national initiative, also covers the security services industry and scientific institutions (National Cybersecurity Law, 2024). The requirements also apply to critical ICT infrastructures: bridges, hospitals, electricity infrastructure or port facilities. For example, an SME owning information technology systems in a critical industry needs to maintain the systems, or an SME that cooperates with larger enterprises operating in that industry. In this case, SMEs also have to comply with the requirements. The preamble to the NIS Directive 2 states that every EU Member State, including Latvia, should address the cybersecurity needs of SMEs in their cybersecurity strategies. Given the large number of SMEs in the business and industrial markets, it has been recognised that it is SMEs that face the greatest difficulty in adapting to working online and being targeted in supply chain attacks. Therefore, the strategies should include addressing such challenges and helping SMEs specifically (European Parliament and..., 2022). Based on the NIS2 Directive, as well as other legal acts, the Latvian Cyber Security Strategy 2023-2026 has been developed to contribute to cyber security in Latvia.

The most recent changes to strengthen security in the electronic environment are governed by the Cyber Resilience Act, which entered into force on 10 December 2024. It is the key piece of legislation to date (in addition to the NIS2 Directive referred to above and the Cybersecurity Act referred to below) in the EU aimed at protecting consumers and enterprises that have purchased hardware products with digital components or software (European Commission, 2025b). It is consumers who are faced with the choice of a digital product who will be able to make sure that cybersecurity is a general priority. According to the European Council, the requirements set by the Act are aimed at simplifying the identification of products with certain security features (World Economic Forum, 2024b).

Since the EU Cybersecurity Act came into force on 27 June 2019, this EU law also applies to SMEs. It aims to achieve a high level of cyber resilience and confidence by empowering ENISA with new powers needed to achieve its goals and objectives. The Agency's Advisory Group includes, among others, recognised experts from industry stakeholders, including SMEs (European Commission, 2024). In light of the above, for example, the Agency issued a report in 2021 'Cybersecurity for SMEs – Challenges and Recommendations'. ENISA has identified the following main cybersecurity challenges for SMEs: first, a low awareness of cybersecurity in general; second, insufficient protection of critical and sensitive information, budget problems, a lack of ICT cybersecurity expertise and personnel, a lack of appropriate guidelines, and challenges related to working online, electronic devices and low management support (European Union Agency…, 2021). The Agency's recommendations include measures such as employee training, regular software updating and incident response planning. Besides, to strengthen the overall security situation, each Member State is called upon to support SMEs by providing them with tailored resources, as well as to facilitate

information sharing (European Union Agency…, 2021). In addition, as stated by the European non-profit organization Small Business Standards (SBS), SMEs need to be provided with guidelines for understanding key legal acts relating to cybersecurity as well as the way they interrelate. For example, the Cyber Resilience Act and the NIS2 Directive. This is aimed, among other things, at reducing costs concerning potential outsourcing (Small Business Standards, 2023).

Although the report contains recommendations for the enhancement of cybersecurity, in March 2023, the Agency released a tool specifically designed to help SMEs to assess their levels of preparedness for cybersecurity. The tool performs two functions. First, a cybersecurity assessment, which determines the enterprise level of cybersecurity, considering its size, field, budget and other factors, and compares it with similar enterprises. The second function involves designing a personalised action plan, which in turn offers to create a cybersecurity improvement plan with particular steps based on current best cybersecurity practices (European Union Agency…, 2023).

2.2. Future AI-related challenges for SMEs

The digital transformation of SMEs has a major impact on any government policy; therefore, support systems are needed to implement AI in SMEs and overcome financial barriers (Schwaeke et al., 2024).

A legal act that should be specifically mentioned in relation to cybersecurity protection for SMEs is the first comprehensive legal act concerning artificial intelligence (AI) in the world (European Commission, 2025c), the AI Act, which will be fully applicable from 2 August 2026. For example, Article 62 of the Act requires the Member States to provide SMEs, including start-ups, priority access to a safe testing environment for new technologies and services, the so-called 'regulatory sandbox', and to promote understanding of the Act's provisions and the application through support and advice, training, the development of common information platforms, etc. (European Parliament and..., 2024). More specific requirements set by the Act, for example, relate to the development of standardised contractual clauses and other templates specifically for high-risk AI systems, which can be implemented by the European AI Office (European Parliament and..., 2024). It should be noted that the first provisions arising from the Act regarding prohibited AI practices that threaten fundamental rights and the security of citizens, as well as AI literacy, are applicable as of 2 February of 2025 (European Commission, 2025a).

Research shows a number of benefits of AI for SMEs. For example, higher efficiency, better decision-making, as well as overall customer satisfaction with marketing, risk management and human resources. However, effectively meeting the requirements specifically in the SME environment has been recognised as a challenge to address problems such as aligning decisions and processes, as well as gaining acceptance from the whole business team. It is the legal uncertainties associated with the introduction of AI into SMEs that necessitate a tool allowing the SMEs to be aware of the relevant regulatory framework (Schwaeke et al., 2024). For example, based on the Digital Decade 2023 report on the digital transformation performance of Latvia, it could be concluded that only 52% of SMEs in Latvia had achieved a basic level of digital intensity in 2022, which was relatively low compared with the EU average of 69% and the Digital Decade target of 90% (Ministry of Environmental..., 2024). In order to transpose the provisions of the AI Act for SMEs, it is necessary for the European Commission to provide guidance, while at national level the EU Member States will have to undertake extensive harmonisation and adaptation processes.

It is undeniable that in practice, the requirements for SMEs that the AI legal framework requires to be met are financially costly. However, the preamble of the AI Act states that it is the new medium-sized enterprises that need to have access to support measures to comply with the Act, not only due to a lack of legal resources but also due to a lack of training (European Parliament and..., 2024). The research study highlights that the cost ceiling for AI is determined both by the IT expertise required in this industry and by skilled human resources. The case law examined by the European Commission showed that SMEs undoubtedly incurred higher costs in implementing AI requirements than large enterprises did; however, since SMEs are accustomed to using third-party services, additional expenses should be considered business-as-usual (BAU) (Sommer et al., 2023).

2.3. Empirical research findings on the role of the human factor in SMEs

From an economic perspective, there are two main causes of challenges to overcome to achieve optimal cybersecurity standards in case of market imperfections. First, the fact that consumers themselves are largely unable to assess the overall level of cybersecurity of a digital product, thus not making a large monetary investment in a potentially safer option (Chiara, 2022**)**. Half a year ago, a research study found that there was a lack of research on whether various categories of SMEs might perceive investment returns differently (Wilson & McDonald, 2024). Second, a research study on the optimal level of investment in the cybersecurity market concluded that the level of investment was not considered optimal enough (Chiara, 2022**)**. In this respect, the available support and EU co-funding for SMEs in Latvia should be emphasized as a positive step towards providing the necessary support to SMEs at the national level. For example, at the end 2024, an EU grant support programme for enterprises of EUR 20,000-60,000 aimed to strengthen the cyber resilience of enterprises and promote the transformation of cyber security by

facilitating access to cyber security solutions. Accordingly, there were implemented pilot projects on technological solutions or developing and introducing cybersecurity technologies (The Cabinet of..., 2024). Since 2023 in Latvia, support for the digitalization of processes using grants available directly to SMEs has also been implemented through the Investment and Development Agency of Latvia. Funding of up to EUR 10,000 from the European Recovery Fund is granted for the development, implementation or transformation of digital services, products and software applications (Investment and Development…, 2023). For example, for the implementation of administrative, personnel management, sales, data management, transport and logistics, production, quality management etc. processes, the grant programme is planned to be implemented until 31 March 2026 (Investment and Development…[n.d.]).

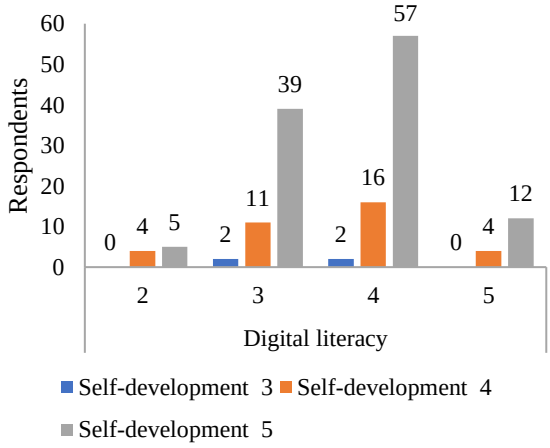
In connection with the aforementioned matter, a sociological study was conducted, the findings of which highlighted the importance of the human factor in cybersecurity. Employees must possess a set of skills, including digital literacy and the continuous renewal of skills and knowledge, in order to act as a cybersecurity shield for the enterprise. The objective of this empirical study was to investigate employees' self-assessment of their digital competence and assess their motivation to acquire new knowledge and skills. A total of 152 respondents were surveyed: salaried employees aged between 18 and 67, including 125 women and 27 men. The respondents were asked to give ratings on a scale from 1 (poor) to 5 (excellent). The question was as follows: 'How would you rate your digital skills'. A frequency analysis of the answers revealed that 49.3% of the respondents rated their digital skills at 4, which indicated some digital competence. At the same time, 34.2% of the respondents rated their digital skills as average (3) and only 10.5% rated their digital skills as excellent (5). Descriptive statistics revealed that the mean score of the respondents' digital skills: Mean = 3.64, Std. Deviation = 0.749, which indicated that the respondents' ratings did not significantly vary, and most of the responses fell into the category of values 3 and 4. At the same time, the results showed that Mode = 4, indicating that the most frequent rating of digital skills by the respondents was 4.

An analysis of the answers to the question: 'How important is personal development and learning new skills throughout your life to you' (see Figure 1, 'self-development') on a scale from 1 (not very important) to 5 (very important) revealed that based on the results of a frequency analysis, the vast majority of 74.3% gave a rating of 5, considering the acquisition of new knowledge very important, while 23% considered it important, and only 2.6% considered personal development and the acquisition of new knowledge less important. Descriptive statistics showed that the mean value of the respondents Mean= 4.72, Std. Deviation = 0.507; therefore, personal development throughout life was considered very important.

Analysing a relationship between the respondents' self-assessment of digital skills and the importance of learning new knowledge and based on the results of a chi-square test, the authors found that since $\chi^2 = 3.40 < \chi^2_{0.05} = 12.59$, df =6, Sign.=0.757 n=152, the null hypothesis could not be rejected; therefore, there were no statistically significant differences between the respondents' answers about digital skills and the importance of learning new knowledge. The results showed that we could not state that the respondents' self-assessments of their digital skills statistically related to their ratings of the need to acquire new knowledge throughout life. Based on the results of a cross-tabulation analysis, the following trend was identified: 113 out of 152 respondents rated learning and developing themselves throughout life as very important (5), 39 respondents (34.5%). Figure 1 rated their digital skills at 3 and 57 respondents (50.4%) gave a rating of 4 and 12 respondents gave a rating of 5. The following trend could be identified: the respondents who considered self-development, including lifelong learning, as very important, were more likely to rate their digital skills as medium and high.

Figure 1

Distribution of the respondents' self-assessment of digital skills according to the importance of knowledge acquisition, 2024



Source: authors' construction based on the results of a questionnaire survey and SPSS data analysis, 2024.

The sociological survey revealed that the vast majority of the respondents (74.3%) rated lifelong learning as very important. This could indicate the readiness of human resources for continuous renewal of skills. However, the average rating of digital skills was 3.64. It could be stated that the ratings of skills by the respondents were moderately high, which indicated not only the acceptance of innovative technologies but also their usage. Kruger and Dunning have explained

in their research study that people tend to overestimate their skills. Accordingly, the skills that increase competence in a specific field often coincide with the skills that are necessary to rate such competence in themselves and others (Dunning & Kruger, 1999). Although there were no statistically significant differences between the answers given by the respondents, the following trend was found: the respondents who rated lifelong learning as very important more often rated their digital skills as medium or high.

The sociological research analysis confirms the influence of the human factor in improving cybersecurity. It can be said that the majority of respondents rated their digital skills with an average score of 3.64, which is medium-high. In addition, 74.3% of respondents considered lifelong learning to be very important, confirming a high motivation to acquire new knowledge and skills. There was also a tendency for respondents who rated lifelong learning as more important to have higher self-rated digital skills.

Conclusions

1. SMEs are considered particularly vulnerable to cyber resilience. Insufficient financial and human resources, a lack of support systems and uncertainty regarding the interpretation of regulatory requirements in practice are among the main cybersecurity risks and threats to SMEs.
2. MEs are strategically important entities because SMEs can be market actors in the supply chain and be connected with larger enterprises at the municipal or national level. Therefore, it is necessary to pay increased attention to the application of proportionate requirements specifically to the cyber resilience SMEs arising from EU legislation.
3. Effective threat management in SMEs involves the management's understanding of and skills in dealing with threats, technology integration based on knowledgeable human resources and safe risk management. To achieve this, the results of the sociological survey revealed that 74.3% of the respondents considered lifelong learning to be very important. This indicated the readiness of human resources for a continuous build-up of their skills. As a result, the competence of employees will be increased, and consequently mistakes and lack of knowledge will be reduced, which will contribute to the cybersecurity shield in the enterprise.
4. EU and national institutions have already provided the necessary support for SMEs to adapt the requirements of legal acts to practice, e.g., financial resource opportunities, including grant programmes and cybersecurity assessment tools, etc. However, to guarantee uniform, secure and effective cyber resilience, as well as to meet the requirements set by the relevant legal acts, more effort is needed to guarantee real support in the long term.

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ASSESSMENT OF PUBLIC SPENDING ON SOCIAL PROTECTION FOR FAMILIES WITH CHILDREN IN THE EU MEMBER STATES

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Abstract
The enhancement of fertility rates and reduction of poverty among families with children are closely linked to the allocation of financial resources to social protection, particularly through social benefits and tax incentives. This allocation is an essential prerequisite for achieving sustainable national and rural development. The research aim is to assess public spending on social protection for families with children in the context of poverty reduction and fertility rates increase across the EU Member States. To achieve this, the research employs a comprehensive set of methodologies, including monographic and descriptive methods as well as analysis and synthesis, along with the graphic and statistical approaches (chain increase and correlation). The research concluded that the EU Member States invested 2.3% of GDP on average on child and family support in 2022, with Latvia spending below the EU average. None of the EU Member States achieved the 2.1 total fertility rate in 2015 and 2022 required for generational replacement. In Latvia, rural areas exhibit a slightly higher fertility rate than urban regions. The research findings show that countries with higher social protection expenditure as a percentage of GDP demonstrate lower incidence of children living in poverty. Throughout the period analysed, rural populations in the EU, particularly in Romania and Bulgaria, consistently face a higher risk of poverty. Moreover, spending on social protection for families with children does not directly impact fertility rates or poverty risk for single-adult households but significantly affect poverty risk for households with two adults and three or more children.
Keywords: social protection, fertility, poverty reduction, EU member states.

Introduction

The promotion of higher fertility rates and reduction of poverty among families with children are significantly influenced by the amount of financial resources allocated to social protection in the form of social benefits and tax incentives, which serve as a critical prerequisite for achieving sustainable national and rural development.

Latvia's strategic planning documents for several planning periods consistently underscore the importance of enhancing social security and increasing financial support for the social sector to reduce poverty among residents and foster fertility rates within the country (Latvijas ilgtspējīgas attīstības …, 2010; Par Sociālās aizsardzības …, 2021).

Reducing the risk of poverty and social exclusion is one of the EU's main objectives for 2019-2030 (Nabadzības risks un ..., 2025). Similarly, the National Development Plan of Latvia (2020) sets a target for 2027 aiming to reduce the poverty risk index for households with a single adult raising children to 24.5% and for households with two adults and three or more dependent children to 12%.

Support for social protection varies across the EU Member States, with a predominant reliance on the 'transfer-based' strategy mainly used by the Continental and Mediterranean countries. The main forms of support in these regions are benefits, service provision and tax incentives (Nygard et al., 2019).

Reducing social exclusion and poverty and promoting social justice in rural areas is one of the key challenges the world is facing today, as almost a quarter of the EU's population reside in rural areas (Kalinowski & Rosa, 2021).

As highlighted in the analytical report of the Cross-Sectoral Coordination Centre 'Latvian Families in Generations' (2018), social policy planners in Latvia, compared to other European countries, have the advantage of selecting various instruments to support fertility. This is particularly significant as Latvia is one of the countries where the population expresses a desire to have more children than they currently have.

Research hypothesis – the level of social protection spending for families with children varies across the EU Member States, affecting fertility rates in the country and contributing to the reduction of poverty.

The research aim is to assess public spending on social protection for families with children in the context of poverty reduction and fertility rates increase across the EU Member States.

The following research tasks are advanced to achieve the set aim:

1) to analyse social protection expenditure for families with children in the context of fertility promotion;
2) to study social protection expenditure for families with children in the context of poverty reduction.

Materials and Methods

Research methods: the monographic and descriptive methods, analysis and synthesis, the graphic method, statistical method (analysis of the chain increase, correlation).

The present research is based on a range of scientific publications, publicly available documents, information from databases and other sources.

The research period spans from 2015 to the most recent data available.

Results and Discussion

Assessing social protection in the context of fertility

Pezer indicates that social security systems of different countries are generally based on their economic situation and social policies. Social policies targeted

for families with children vary across countries but they are generally focused on improving child well-being, promoting fertility and reducing poverty (Pezer, 2022).

Social protection spending reduces the risk of poverty across all countries; though, to different degrees. Studies find that social protection expenditure has the greatest impact on poverty reduction, particularly in areas related to family, children and social exclusion (Halaskova et al., 2025).

The informative report 'On Demographic Policy Development' (2024) emphasises that an effective fertility strategy requires well-considered support for families with children ensuring long-term socio-economic security.

The EC departments have specified that Latvia's spending on social protection is insufficient to reduce poverty and income inequality (Par Sociālās aizsardzības..., 2021). The authors' analysis shows that the social policy target outlined in the previously mentioned guidelines to increase the share of total spending on social protection to at least 18% between 2021 and 2027 has been very modest and significantly below the EU average.

The analysis of the social protection spending across the EU Member States as a percentage of GDP shows that France, Denmark, Finland and Austria ranked as Top 5 countries from 2015 to 2019. Italy ranked in the Top 5 between 2020 and 2022. Despite Denmark's spending remaining above the EU average, it dropped out the Top 5 ranking from 2020.

Romania, Ireland, Malta, Bulgaria and the Baltic States consistently recorded the lowest levels of social protection expenditure as a percentage of GDP throughout the entire period. The EU average indicator for social protection spending stood at 28% from 2015 to 2019, slightly rising to 31.5% in 2020 before falling in the following years. In 2022, the figure returned to 28% again, suggesting that the overall social protection level in the EU Member States has not experienced a significant improvement (Expenditure on social ..., 2025).

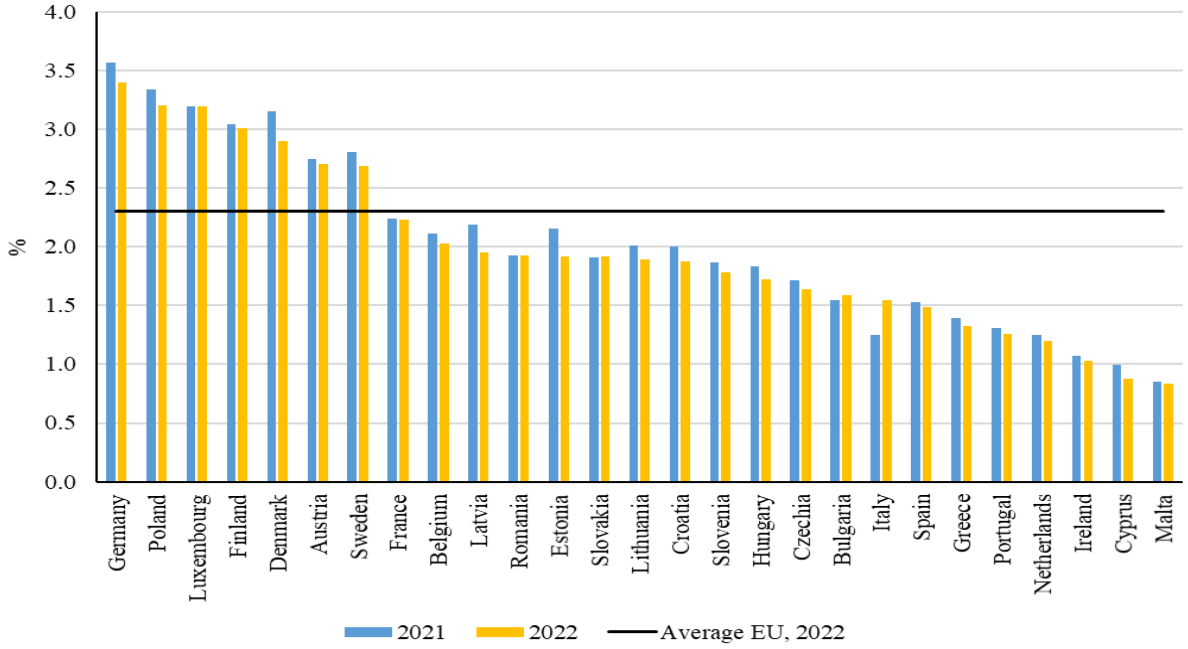
Social protection expenditure as a percentage of GDP tends to be higher in welfare countries and lower in Eastern European countries. However, Ireland serves as an exception due to its very high GDP ratio resulting from the activities of large multinational corporations in the country.

The analysis of the data on the share of public spending on support for families with children across the EU Member States allows concluding that, in both 2021 and 2022, the highest shares of support for families with children were observed in Germany, Poland, Luxembourg, Finland, Denmark, Austria and Sweden, ranging from 2.7% to 3.6% of GDP, while Latvia allocated 2.0% of its GDP to this support 'Figure 1'. A similar situation was observed also in 2020 (Mistre et al., 2023).

In 2022, the EU Member States allocated 2.3% of GDP on average in measures of policies to support families with children. Comparing the data across the Baltic States, Latvia dedicated a slightly higher share of GDP to social protection for families with children than Estonia and Lithuania in both 2021 and 2022. In Latvia, the share of expenditure as a percentage of GDP in 2022 decreased by 10.7% compared to 2021, yet it increased by 14.8% compared to 2020. Despite this increase, Latvia's spending still remains below the EU average (Mistre et al., 2023).

Figure 1

Social protection expenditure on families with children in the EU Member States in 2021 and 2022, (% of GDP)



Source: authors' construction based on Eurostat data - Expenditure on family ..., 2025, GDP and main ..., 2025.

Malta, Cyprus, Ireland, the Netherlands and Portugal recorded the lowest shares of social support for families with children as a percentage of GDP in both 2021 and 2022. It is widely acknowledged that national expenditure figures serve as general indicators of public policies in the area of social support for families with children (Pabalstu par bērnu ..., 2022).

The research authors align with the findings of Daglioglu and Bektas that family benefits may boost fertility rates, reduce family poverty, prevent children poverty and enhance national welfare (Daglioglu & Bektas, 2023).

Several studies indicate that there is no single determinant that may leave a significant impact on fertility rates. However, survey data show that financial security is also important for families with children (Informatīvais ziņojums 'Par..., 2024).

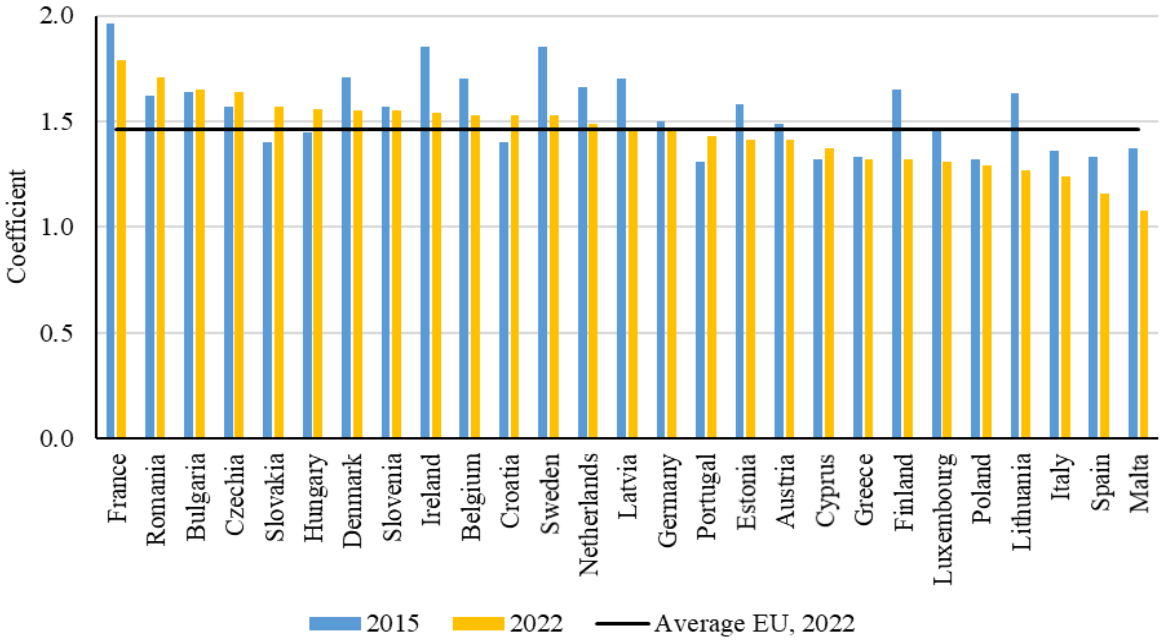
The correlation coefficient calculated by the authors for the period 2015-2022 reveals a strong negative correlation (r= -0.67) between fertility rates and the share of social protection expenditure on families with children as a percentage of GDP in Latvia. Despite a slight increase in the expenditure as a percentage of GDP on families with children between 2015 and 2021, fertility rates continued to decline. This suggests that fertility is influenced also by other factors, including the decreasing number of women of reproductive age (Iedzīvotāji pēc dzimuma ..., 2025).

The research authors believe that further increases in spending on support for families with children are necessary to reduce the negative fertility trend, as studies for the period 2011-2020 identified a moderately strong positive correlation between fertility rates and the share of social protection spending on families with children as a percentage of GDP (Mistre et al., 2023). Similarly Mežs (2013), analysing differences in population policies across the EU Member States, also indicates a correlation: the more financial resources invested in supporting families with children, the higher the fertility rate, and conversely.

The analysis of the total fertility rates across the EU Member States shows that in 2015, the highest rates were observed in France (2.0), followed by Ireland and Sweden (1.9), and Denmark, Belgium, the Netherlands, Finland and Latvia (1.7). The lowest fertility rates were recorded in Portugal and Poland, Cyprus, Spain, Greece, all with a rate of 1.3 'Figure 2'.

Figure 2

Total fertility rates in the EU Member States in 2015 and 2022



Source: authors' construction based on Eurostat data - Total fertility rate, 2025.

In 2022, France maintained the highest total fertility rate among the EU Member States equalling to 1.8. Romania and Bulgaria (1.7) also ranked among the Top 5 in 2022, indicating that fertility rates in these countries have improved slightly compared to 2015. The lowest total fertility rates in 2022 were observed in Malta (1.1), Spain and Italy (1.2), and Lithuania, Poland, Luxembourg, Finland and Greece (1.3), with many of these countries experiencing a downward trend in fertility rates.

However, despite Finland's social support being among the highest in the EU in both 2015 and 2022, the total fertility rate has fallen by 20% over these years. This signals on the necessity to provide in-depth research to better investigate this trend. Lindberg et al. suggest that Finnish family policy is primarily focused

towards high parental employment and low poverty (Lindberg et al., 2018). Similarly, Lithuania experienced a significant decline of 22% in its fertility rate. Vyšniauskienė & Brazienė (2017) argue that Lithuanian family policy is not supportive enough to families with children and there is a need to improve the legal framework for maternity, paternity and childcare as well as to increase support for young families.

Bokuna (2024), studying the situation in Poland, revealed that an increase in benefits for families with children has led to a modest increase in fertility in the short term.

However, Bariola & Collins (2021) point out that Denmark is known for its high levels of well-being thanks to its social democratic welfare model that reduces risk and insecurity. Though, in Denmark both the expenditure on social protection for families with children as a percentage of GDP and the total fertility rate have decreased in 2022 compared to 2015.

In Latvia, social protection spending for families with children as a percentage of GDP also decreased in 2022 compared to 2021, and the total fertility rate decreased by 6.4%, reflecting a negative trend.

It should be noted that none of the EU Member States has reached the total fertility rate of at least 2.1 in both 2015 and 2022 which is necessary for generational replacement.

Furthermore, a comparison of the total fertility rates in rural and urban areas of Latvia demonstrates a more favourable situation in rural areas than in urban ones (Table 1).

Table 1

Total fertility rates in urban and rural areas of Latvia in 2015-2023

Year	***Urban areas***	***Rural areas***	***Chain increase rate, %***	
			urban	***rural***
2015	1.70	1.70	-	-
2016	1.72	1.76	*1.2*	*3.5*
2017	1.69	1.70	*-1.7*	*-3.4*
2018	1.57	1.71	*-7.1*	*0.6*
2019	1.56	1.74	*-0.6*	*1.8*
2020	1.50	1.65	*-3.8*	*-5.2*
2021	1.53	1.68	*2.0*	*1.8*
2022	1.41	1.61	*-7.8*	*-4.2*
2023	1.29	1.53	*-8.5*	*-5.0*
2023/ 2015	-0.41	-0.17	*-24.1*	*-1.0*

Source: authors' calculations based on unpublished data CSB Latvia, 2025.

The decline in the total fertility rate is most pronounced in 2022 and 2023 with a particularly expressed decline in urban areas.

Assessment of social protection in terms of poverty reduction

The study 'Determination of Child-Raising Benefits in the Baltic Sea Region' (2022) emphasises that poverty remains one of the most discussed issues in social policy. The study results show that state support for social protection in the form of universal benefits can be an effective tool for reducing child poverty.

Benefits for families with children are typically implemented to mitigate child poverty, offset the financial burdens associated with child-raising and encourage higher fertility rates. Increased benefit levels are particularly effective in alleviating poverty, leading many countries to direct greater resources toward families with children who are most vulnerable to the risk of poverty. The research indicates that a one percent increase in public spending on social services per capita is associated with a reduction in the proportion of children at risk of poverty by approximately one percent (Pabalstu par bērnu ..., 2022).

The latest available data on the proportion of children at risk of poverty out of the total number of children under 18 in the EU Member States between 2015 and 2023 demonstrate the lowest proportion in Slovenia, Czechia, Denmark, Finland and the Netherlands (Table 2).

In turn, the highest proportion of children at risk of poverty during the period analysed was in Romania, Bulgaria, Spain, Greece and Italy.

In Latvia, this indicator has been below the EU average since 2016, and in 2023, the proportion of children at risk of poverty has decreased by 10.4 percentage points compared to 2015.

In general, the proportion of children at risk of poverty in the EU has fluctuated during the period analysed, with a tendency to decrease - by 2.6 percentage points or 9.5%, which can be assessed as a positive trend.

Therefore, the general conclusion suggests that countries with higher social protection spending as a percentage of GDP have fewer children at risk of poverty, and vice versa. However, this trend is not always straightforward to interpret, as shown, for example, in Slovenia, the Netherlands and Czechia.

Slovenia's social protection expenditure as a percentage of GDP was 1.8% in 2022, falling below the EU average indicator. Meantime, Slovenia reported the lowest percentage of children at risk of poverty within the EU Member States, with only 10.5% of children affected.

Progress related to the mitigation of child poverty in Slovenia can be attributed to a series of targeted measures that specifically address families with children. Slovenia's success in this area is largely due to well-directed social transfers designed to enhance social protection for families. These transfers include various forms of support aimed at assisting parents in multiple ways. For example, cash assistance is provided for every newborn to help cover essential costs, while a parental allowance is offered to mothers or fathers who do not have parental protection insurance. In addition, child benefits serve as supplementary income to assist with the maintenance,

upbringing and education of children. Parents of children requiring special care and protection in Slovenia are provided with an additional allowance, and some may be eligible for partial compensation for lost income, along with further relief measures. The importance of subsidised nursery places cannot be overstated, with free nursery places offered for a second child. Furthermore, subsidised school meals are available, contributing to the overall support system for children. Various allowances and relief measures are also extended to large families with at least three children (First Progress Report …, 2024).

Social transfers play a major role in preventing the risk of poverty; though, their impact on population income has slightly decreased compared to previous years (2023. gadā nabadzības ..., 2024).

Table 2

Proportion of children at risk of poverty up to the age of 18 in the EU Member States in 2015-2023, %

Country	***2015***	***2017***	***2019***	***2020***	***2021***	***2022***	***2023***	***2023/2015, pp***
Romania	53.4	48.7	39.1	40.7	41.5	41.5	39.0	-14.4
Spain	34	31.9	31	31.6	33.4	32.2	34.5	0.5
Bulgaria	47.5	42.4	35.8	35.5	33	33.9	33.9	-13.6
Greece	37.7	36.5	31.2	30.8	32	28.1	28.1	-9.6
Italy	34.1	30.8	27.1	28.9	29.7	28.5	27.1	-7.0
France	22.4	23.5	24.1	23.6	22.5	27.1	26.6	4.2
Luxembourg	23.3	21.5	25.4	24.2	29.4	24	26.1	2.8
Slovakia	24.7	22.7	21	18.4	19.7	24.7	25.3	0.6
Malta	27.8	23.6	23.7	22.3	23.2	23.1	25.2	-2.6
EU	**27.4**	**25.1**	**22.8**	**24**	**24.4**	**24.7**	**24.8**	-2.6
Hungary	40.3	33.5	24.1	21.7	23.3	18.1	24.4	-15.9
Ireland	29.2	26	25.1	22.4	23.5	22.3	24.3	-4.9
Germany	19.3	18.6	15.4	22.3	23.7	24.4	23.9	4.6
Austria	22.2	22.7	20.1	21.9	22.8	21.6	22.7	0.5
Portugal	31.2	24.6	21.9	21.9	22.9	20.7	22.6	-8.6
Lithuania	34.8	31.3	25.8	23.1	21.6	22.4	21.7	-13.1
Sweden	19.7	19.4	23	20.2	19.7	19.9	21.6	1.9
Latvia	**30.7**	**25**	**18.7**	**19.7**	**20.1**	**19.8**	**20.3**	**-10.4**
Belgium	24.1	24.2	23	22	20.5	19.6	19	-5.1
Estonia	22.2	18.8	19.7	17.4	17.4	16.6	18.3	-3.9
Croatia	25.2	24.5	19.1	18.4	18.6	18.1	17.3	-7.9
Poland	26.8	17.8	16.2	16.1	16.5	16.7	16.9	-9.9
Cyprus	22.9	21.7	20.3	19.0	19.2	18.1	16.7	-6.2
Netherlands	17.1	16.4	15.4	15.8	14.9	13.9	15.9	-1.2
Denmark	16.2	15.1	13.8	13.4	14	13.8	15.3	-0.9
Czechia	17.8	14.3	13.0	12.9	13.3	13.4	15.0	-2.8
Finland	14.5	15.0	13.8	14.5	13.2	14.9	13.8	-0.7
Slovenia	16.6	15.6	11.6	12.1	11	10.3	10.7	-5.9

Source: authors' construction based on Eurostat data – Persons at risk of poverty ..., 2025.

The analysis of maternal and social deprivation across the EU Member States shows that people in rural areas are slightly more exposed to poverty than those in urban areas within the entire period analysed, especially rural population in Romania and Bulgaria. Yet, the trend is downward. For example, in Romania, approximately 46% of the rural population were at risk of poverty in 2022, with this figure decreasing to 38.4% in 2023 (Material and social ..., 2025).

Finland and Slovenia among the EU Member States had the lowest poverty risk index for single-adult households with children in 2020 and 2021; while in Slovenia, the poverty risk index increased by 10.1 percentage points or 61.2% in 2022 compared to 2021. Romania, Poland, Hungary and Germany also report a low poverty risk index for single-adult households in 2022 'Figure 3'.

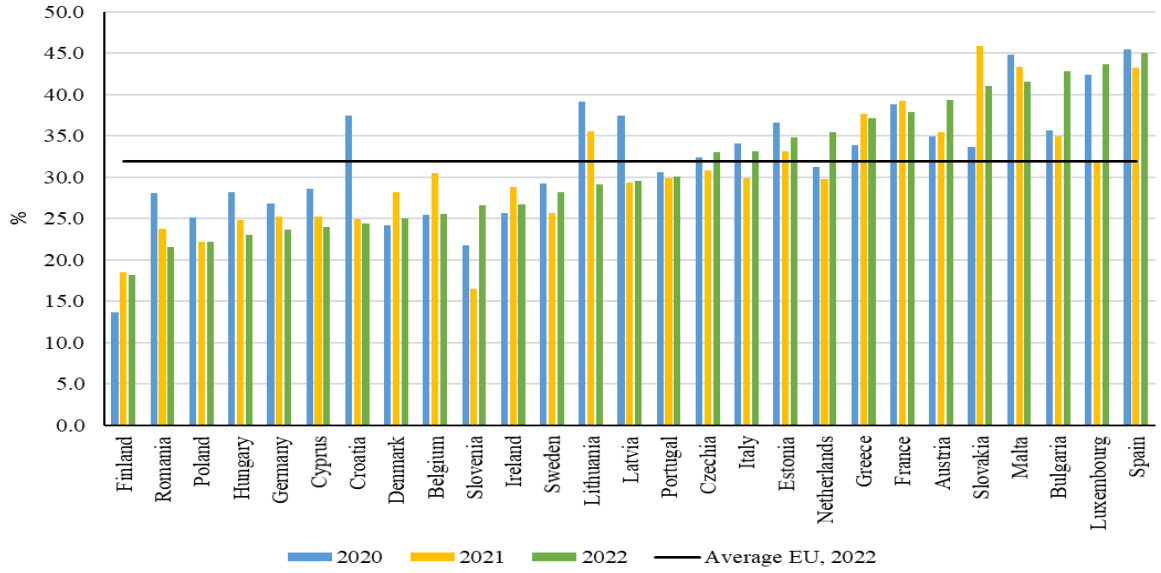
Malta, Spain and Luxembourg have the highest poverty risk indices over the entire period analysed. Similarly, in Latvia, the poverty risk index was above

the EU average (37.5%) in 2020, reflecting a negative trend due to the increased risk of a single-adult households to provide for the family. The situation improved significantly in 2021 (29.4%) and 2022 (29.6%), however, the index slightly rose to 30.4% in 2023 (Nabadzības risks un ..., 2025).

It should be noted that Latvia may face difficulties achieving the target of 24.5% set in the National Development Plan of Latvia for 2021-2027 (2020). The situation in the EU has not changed essentially on average (2020 - 32.9%, 2021 - 31.8% and 2022 - 31.9%).

Figure 3

Poverty risk index for households with one adult with dependent children in the EU Member States in 2020-2022, %



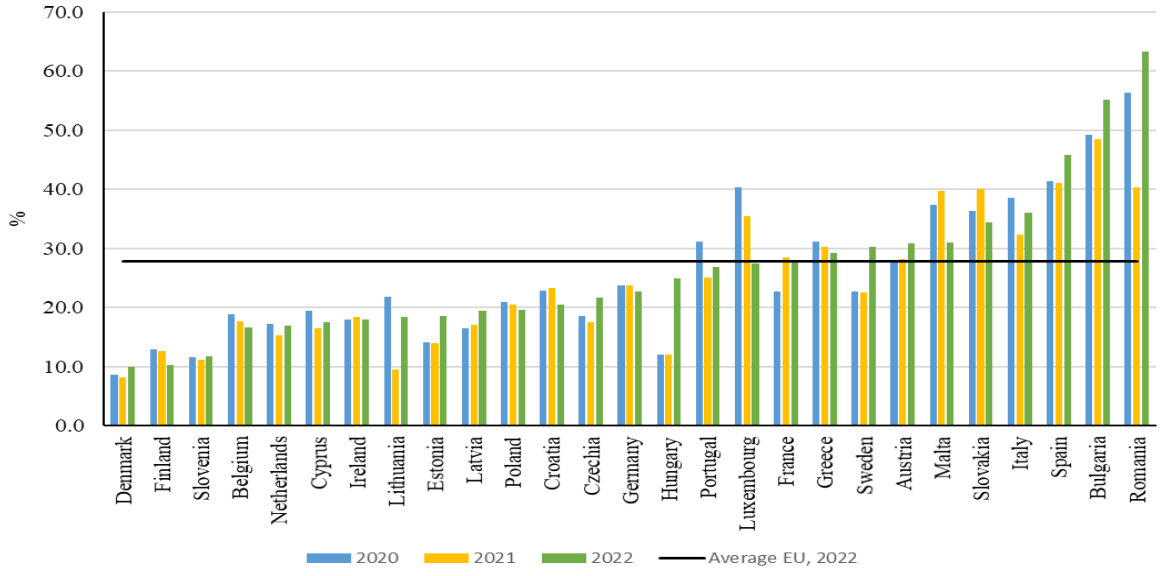
Source: authors' construction based on Eurostat data - At-risk-of ..., 2025.

The situation in some EU Member States is particularly critical, since the highest poverty risk index exceeds 40%, suggesting that special support is needed for single-adult families.

An analysis of the poverty risk index for households with two adults and three or more dependent children shows that most EU Member States (17 countries) are below the EU average between 2020 and 2022, suggesting that this type of households is at lower risk of poverty than households with one adult raising children 'Figure 4'.

Figure 4

Poverty risk index for households with two adults with three or more dependent children in the EU Member States in 2020-2022, %



Source: authors' construction based on Eurostat data - At-risk-of ..., 2025.

The poverty risk index for such households across the EU ranged between 26.2% and 27.8% on average from 2020 to 2022, with an increasing trend observed. Denmark, Finland and Slovenia consistently reported the lowest risk of poverty for these households over the entire period analysed. In 2022, the Baltic States demonstrated a similar poverty risk index for this type of households, ranging from 18.4% to 19.5% and ranking among the Top 10 EU Member States with the lowest poverty risks for such households. Throughout the period analysed, the highest poverty risk index for this type of household was in Bulgaria, Romania and Spain.

In Latvia, despite the increase in income from wage employment, the risk of poverty for households with two adults and three or more dependent children has increased over the period analysed, and it continued to increase also in 2023, reaching 20.8% (Nabadzības risks un ..., 2025). It should be noted that Latvia may face difficulties to reach the target of 12% set in the National Development Plan of Latvia for 2021-2027 (2020) if this trend continues.

Family benefits are recognised to reduce overall poverty, especially in families with two, three or more children and single mothers with children (Lew et al., 2021). In most countries, children benefits and social assistance are the most effective tools in reducing poverty (Leventi et al., 2019). Family allowances are indispensable for lone parents, even if they are employed (Nieuwenhuis, 2021).

According to the Bank of Latvia expert forecast, even small, direct interventions to financially support families have direct benefits and reduce the risk of poverty. Moreover, the data from the Central Statistical Bureau of Latvia show that the number of third and subsequent children in the families of Latvia has been increasing in recent years (Tautas ataudzes stratēģija ..., 2022). This shows that Latvia needs to continue its targeted family support policy to achieve the desired results.

Conclusions

1. In 2022, the EU Member States invested 2.3% of GDP on average in policies to support children and families. In Latvia, this figure is below the EU average; yet, it is slightly higher than in Estonia and Lithuania.
2. The total fertility rate in 2015 and 2022 in none of the EU Member States has reached at least 2.1, which would ensure generational replacement. The total fertility rate in rural areas of Latvia is slightly higher than in urban areas.
3. In countries where social protection spending as a percentage of GDP is higher, the number of children at risk of poverty is lower and vice versa.
4. In the EU, on average, households with two adults and three or more dependent children have a lower risk of poverty than households with one adult and dependent children; although it demonstrates a tendency to increase.
5. Spending on social protection for families with children in the EU Member States has no direct impact on the fertility rate or the risk of poverty in households with one adult raising children. However, it does have an impact on the risk of poverty in households with two adults with three or more dependent children.

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USING EUROPEAN UNION CO-FINANCING IN ENTREPRENEURSHIP FOR DEVELOPMENT OF RURAL AREAS IN THE LATGALE REGION

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Abstract
Latgale region in Latvia has various opportunities for starting/expanding businesses, promoted by both - state support programs and European Union (EU) financial instruments. The aim of the research project 'Entrepreneurship development in Latgale region, modernization of production/service provision with the help of the LEADER programme projects' by the Latvia University of Life Sciences and Technologies (LBTU) Agency Malnava College was to analyse how entrepreneurs had used EU co-financing in rural areas. Project participants – teaching staff and the 2nd year students of the Short-Cycle Professional Higher Education Study Program 'Entrepreneurship in Agriculture'. Implementing the LEADER approach, local development initiatives support sustainability of rural communities. Research tasks and methods: online survey of entrepreneurs; analysis of the EU LEADER programme business projects in four municipalities; semi-structured interviews with entrepreneurs. The main results of the research: within the selected four municipalities of Latgale region in total 197 projects of the LEADER programme were implemented providing local rural entrepreneurs access to approximately 3.64 million euros EU co-financing, which had allowed them to build/ reconstruct agricultural production buildings, purchase modern equipment, develop/ diversify production etc. The main problems of entrepreneurs – securing their own pre-financing, complicated bureaucracy, insufficient knowledge of project management etc.
Keywords: entrepreneurship, agriculture, Latgale region, EU LEADER programme.

Introduction

Entrepreneurship in agriculture is associated with the use of natural resources, seasonality, climate, and other natural conditions, which can directly affect business results. In Latvia, the study of the Institute of Agricultural Resources and Economics 'The Impact of Agriculture and Forestry on Rural Space – Economic and Social Aspects' indicates that agriculture and forestry have historically formed the basic sectors of rural territory with a significant impact on the socio-economic development of the country and regions. Both sectors literally consume rural territory – land and forests, which are used in agriculture as a resource, turning them into marketable and aesthetic values – production and landscape – and creating jobs and income for the people involved (Institute…, 2024).

The Latvian Doctor of Agricultural Sciences, Professor K. Špoģis has stated that agriculture is a business, entrepreneurship, and any well-educated farmer can work well in any of Latvia's regions, in Zemgale, Vidzeme, Kurzeme, and in Latgale. The scientist emphasized that with each passing day the differentiation in agriculture will be felt even more sharply. The Professor also pointed out that not necessarily everyone living in the countryside should and would become an entrepreneur. However, those who will become farmers should also be successful entrepreneurs and therefore must study intensively and continuously, as well as receive all possible support from the state and society (Špoģis, 1998).

The aim of the study is to analyse how entrepreneurs in Latvia can develop their business in agriculture by attracting co-financing of EU funds, including the LEADER programme. The study has a theoretical and practical part. The research involved the project of LBTU agency Malnava College named 'Entrepreneurship development in Latgale region, modernization of production/ service provision with the help of the LEADER programme projects', implemented in cooperation with partners – non-governmental organizations 'Ludza District Partnership', 'Preili-Livani Municipalities Partnership 'Kūpā' and 'Rezekne District Partnership'. The research was done in Livani, Ludza, Preili and Rezekne municipalities from 2016 to 2024. The research was conducted by two lecturers and three students from the short professional higher education program 'Agricultural Entrepreneurship' at LBTU Malnava College to introduce students to both scientific work and the research topic – the LEADER program. Research period: from October 1, 2024, to June 30, 2025.

Materials and Methods

The study used a variety of materials: scientific literature, publications and statistical data from the state institutions, as well as unpublished materials from non-governmental organizations. Research methods: the online entrepreneur survey and semi-structured interviews were done, and information on EU LEADER co-financed projects were collected.

First of all, the scientific literature on entrepreneurship as capital, on the specifics of business, especially in agriculture, was collected and analysed within the framework of the theoretical study. Several authors emphasize that in the 21st century, capital is the knowledge and skills of people, which are essential in business, as it, in turn, is considered one of the indicators of national development. Promoting entrepreneurship in the agricultural sector is one of the most suitable options for promoting agribusiness and increasing the added value created by agricultural exports (Fatemi, 2020). In the literature, one can find the phrase – agribusiness is a profitable marriage of

agriculture and business. Most farmers consider agriculture to be a combination of philosophy and lifestyle, therefore, in its broadest sense, agribusiness combines philosophy, lifestyle and business, creating ideals that provide a goal and objectives to strive for (Muzari, 2015). Entrepreneurship is a key factor for the survival of smallholder agriculture in an ever-changing and increasingly complex global economy. Agribusiness is defined as sustainable, community-oriented and direct marketing of a variety of agricultural products and inputs. Farmers-entrepreneurs are passionate about their agricultural business and are willing to take calculated risks to make their farms profitable and their businesses grow (Kahan, 2012).

Nowadays, pressure for sustainable development is increasing, so research in this area is needed, including sustainable value creation practices and entrepreneurs' efforts to achieve this goal, especially in the agricultural sector (Sargani et al., 2020). In modern business, the sustainability factor, for example, is emphasized for agricultural start-ups as a catalyst for economic growth and environmental sustainability, so such companies need to find an appropriate and sustainable business ecosystem to ensure their long-term operation and survival (Aliabadi et al., 2022).

The practical part of the study is based on the analysis of the project funding related to agriculture and fisheries from EU funds in Latvia – the European Agricultural Guarantee Fund (EAGF), the European Agricultural Fund for Rural Development (EAFRD) and the European Maritime and Fisheries Fund (EMFF). The development of the LEADER programme was studied within the framework of the EAGF and EAFRD in Europe and Latvia.

Results and Discussion

LEADER – translated from French (Liaison Entre Actions pour le Développement de L'Economie Rurale) means 'targeted and coordinated actions for the development of the rural economy'. It is one of the EU funded programmes providing co-financing in rural territories of the European Union. It is a local development instrument used for 30 years to engage local actors in the design and delivery of strategies, decision-making and resource allocation for the development of their rural areas (The State…, 2023). It is implemented by around 2,800 Local Action Groups (LAGs), covering 61% of the rural population in the EU and bringing together public, private and civil-society stakeholders in a particular area *(situation as of the end of 2018, EU-28)*. In the rural development context, LEADER is being implemented under the national and regional Rural Development Programmes of each EU Member State. LEADER principles are based on Community-Led Local Development Strategies (CLDS), and they provide an opportunity to implement ideas for local development initiatives of rural communities, including entrepreneurship and rural development within the framework of the EU Common Agricultural Policy (European…, n.d.). LEADER 2014-2020 has proven its relevance, effectiveness, and added value for integrated and sustainable rural development at local level across Europe. By spending a very small proportion of the total European Agricultural Fund for Rural Development (around 7% or 7 billion euros over the period) to set up 2,784 LEADER local action groups in EU Member States, the programme has been able to develop complex and locally adapted solutions to rural development challenges in many contrasting rural contexts (Publications…, 2022).

In Latvia, in 2008, legislation approved to establish LAGs, so that local communities could use LEADER projects in their territories, including the support for entrepreneurship (Rural…, n.d.). By 2021, the largest share, or 41.3%, of the supported (supervised and approved) projects had been implemented by entrepreneurs (Ltd., farms and cooperatives), 31.3% had been supported by non-governmental organizations, slightly less by state and local government institutions (27.6%) and 0.1% by other recipients of support. The implementation of Community-led Local Development Strategies has made a significant contribution to achieving the employment target of the RDP 2014-2020 – thus, 119 new jobs have been created by 2020 (it is planned to create more than 1,000) (Ministry…, 2022). In 2023-2027, 58.5 million euros were used for this purpose, which is 7% of the total funding of the European Agricultural Fund for Rural Development in Latvia (Rural, n.d.). Regional Development Indicator Module (RAIM) calculates the financing of EAGF, EAFRD and EMFF. The total funding of these three funds (2015-2023) was 4,842 billion euros. In the distribution by Latvia's planning regions, most of financing was used in Vidzeme region (27.2%), followed by Kurzeme (25.0%), Latgale (22.7%), Zemgale (20.1%) and 5.0% in Riga planning region (State, n.d.). In the territories around Riga, the capital of Latvia, the impact of LEADER on rural development is less significant, this does not mean that it is not needed in the development of these territories. The proximity of the capital significantly affects employment opportunities, availability of services, the proportion of agriculture as a sector and its role in the economic processes of the territory (Ministry…, 2022).

In Latgale planning region, it was 1.1 billion euros of the total financing in Latvia (State…, n.d.). Since 2014, the LEADER approach has been operating as Community-Led Local Development, the main difference from the previous period is more integrated approach and more diverse financial model – the possibility of implementing LEADER from other EU funds. Unlike the traditional top-down approach in the management of EU funds, it is based on a bottom-up approach. It enables local residents to take the

initiative by entrusting the process to LAGs, to establish partnerships between public, private and non-governmental sectors and to operate in a specific territory, developing and implementing CLDS. 126 million euros were used to finance the programme during the 2014-2020 programming period (until 2022) (The Sate…, 2023). Economic, environmental, social and governance factors relate to sustainability in business (Bormane & Tiuncika, 2024). Thus, it is concluded that the implementation of the LEADER programme projects in accordance with the goals and needs of local communities has a positive effect on sustainable development in rural areas. Non-governmental organizations 'Ludza District Partnership', 'Preili-Livani Municipalities Partnership 'Kūpā'' and 'Rezekne District Partnership' have developed the LEADER programme project competitions in their territories; they also advise local communities on project development, and evaluate the submitted project applications in order to further forward them to the Rural Support Service for approval and funding (Ludza…, n.d.; Preili-Livani…, n.d.; Rezekne…, n.d.).

In 2023, there were 16,736 economically active enterprises in the market sector in Latgale region, or 10% of the total number in Latvia, and the number of enterprises per 1,000 inhabitants was 69 enterprises, which was 21 units less than the average in Latvia (90). In Table 1, data of the four analysed municipalities of Latgale region are included. Since the territories analysed in the study differ significantly in terms of their area and population, it is difficult to compare the data. For example, Rezekne Municipality has 4.5 times larger area and 2.7 times more population than Livani Municipality (Official…, n.d.).

Table 1

Some indicators of Latgale region in 2023

Territories / indicators	***Economically active enterprises in the market sector***			***Territory, km²***	***Population***
	number	***% of total***	***per 1000 inhabitants***		
Latgale region, incl.	16,736	100.0	69	14,546.85	245,053
Livani Municipality	815	4.9	79	622.57	10,411
Ludza Municipality	1,363	8.1	65	2,411.36	21,257
Preili Municipality	1,702	10.2	107	1,413.42	16,037
Rezekne Municipality	1,940	11.6	68	2,810.90	28,805

To implement the first task of the research project, the authors studied how entrepreneurs of Latgale region develop their businesses in sectors related to agriculture and rural development, using EU funding.

The funding per capita of the three funds in Figure 1, depicts that the largest amount of funding was in Preili Municipality, followed by Rezekne, Ludza and Livani municipalities.

The online Google Forms survey was conducted with the aim to involve entrepreneurs in Latgale, especially in the municipalities of Livani, Ludza, Preili and Rezekne, with the support of project partners – non-governmental organizations. The survey was anonymous, confidential, and all data was used only in aggregated form. The survey period was from December 2024 to February 2025, and 56 respondents participated in it. It should be admitted that, unfortunately, the entrepreneurs were not active despite the fact that the information was widely spread on social networks. More than a half of the surveyed farms were established between 2001 and 2020, mostly up to 100 ha in size, and they are mainly engaged in crop production and livestock farming. Almost 93% of the farms have used personal financing for development; almost 84% have received subsidies from the EU and the state budget, 28 or half of the respondents have received support from other EU programmes, while 12 indicated that they have used the LADER programme. The respondents pointed out several difficulties in developing projects for EU programmes, including LEADER: providing pre-financing, insufficient knowledge in developing project applications. At the same time, several respondents answered that there were no difficulties. Positive moments for the development of farms: purchase of machinery and equipment, expansion of the farm, additional jobs for local residents and increased production volume, as well as new experience in project development.

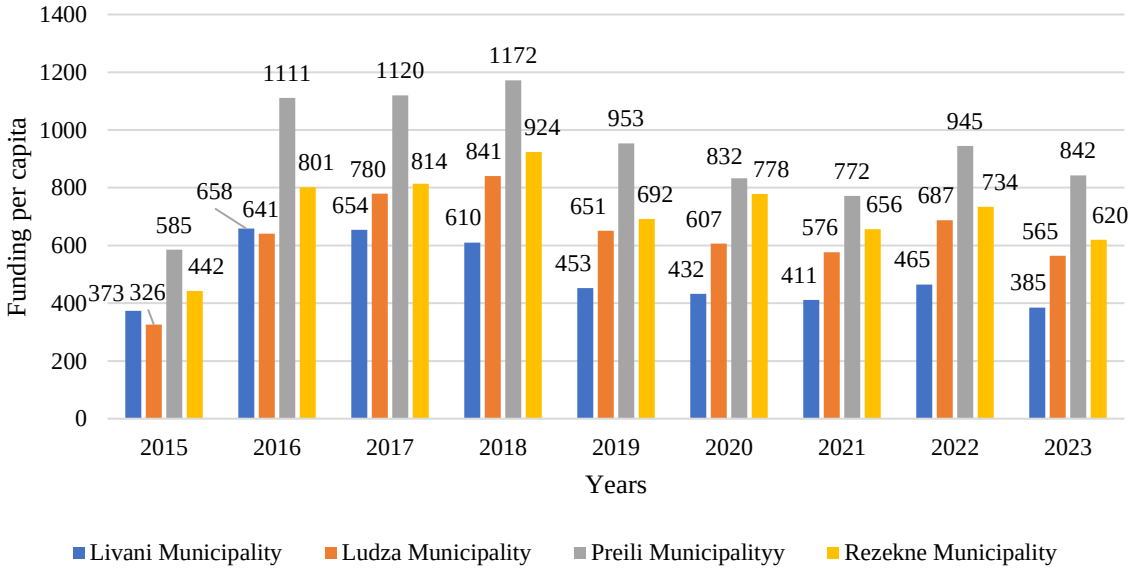
The LEADER programme was mainly chosen by relatively small farms that did not have an opportunity to purchase larger plots of land to expand their economic activities in the countryside. The programme provides an opportunity to manage existing land resources more intensively, providing services to others, as well as offering locally produced products.

Entrepreneurs have most often used the LEADER programme for the provision of services – 139 projects, while there were 58 projects for the start/ development of production. Services offered in tourism, logging, agricultural machinery and car service, as well as catering, beauty care, organization of sports and recreational events, etc. Production is

related to the cultivation and processing of food raw materials, woodworking, cosmetics, etc. The differences by year can be explained by the deadlines for the project competitions announced by the LEADER programme in each area.

Figure 1

Funding of the European Agricultural Guarantee Fund, the European Agricultural Fund for Rural Development and the European Maritime and Fisheries Fund in Livani, Preili, Ludza and Rezekne municipalities in 2015-2023, euros per capita

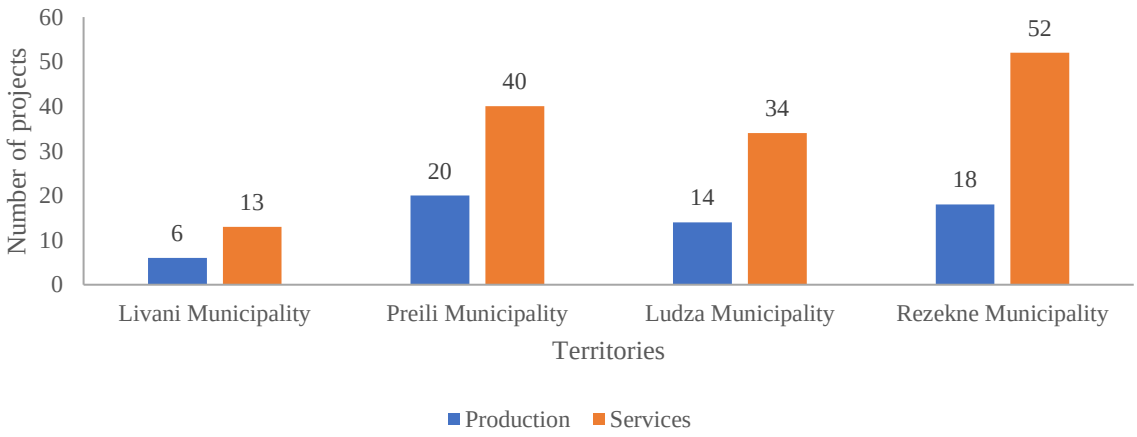


The second task of the project was to analyse LEADER program entrepreneurship projects in rural areas of Livani, Ludza, Preili and Rezekne municipalities. Therefore, with the support of partner organizations, information collected from these four territories in 2016-2024, identified 197 projects for a total amount of 3.64 million euros (public financing). The distribution across the four research areas is shown in Figure 2. Unlike the data in Figure 3, it includes additional projects in Livani Municipality (in 2016 and 2024), Rezekne Municipality (in 2016) and Preili Municipality (in 2024). The number of supported projects in rural territories of the municipalities are as follows: 19 in Livani, 60 in Preili, 48 in Ludza and 70 in Rezekne.

Services are offered in tourism, logging, agricultural machinery and car service, as well as catering, beauty care, organization of sports and recreational events, etc. Production is related to the cultivation and processing of food raw materials, woodworking, cosmetics, etc.

Figure 2

Number of LEADER projects in Livani, Preili, Ludza and Rezekne municipalities in 2016-2024, including production and services



The differences by year are explained by the deadlines for the project competitions announced by the LEADER programme in each territory.

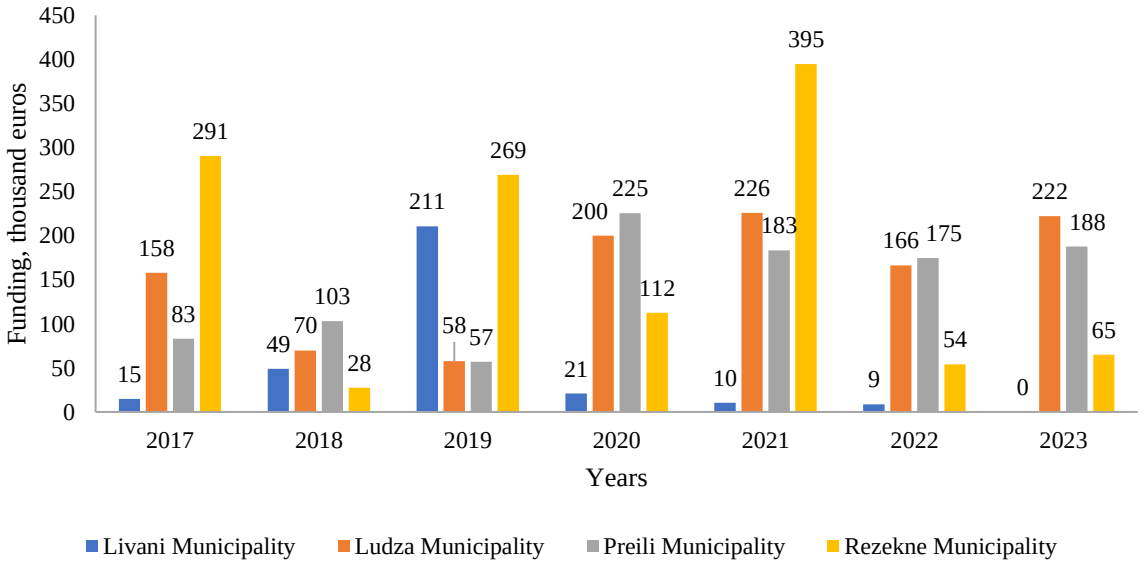
As mentioned earlier, the territories analysed in the study differ significantly in terms of area and population, making it difficult to compare the number of LEADER projects and the amount of public funding.

At the same time, insights were obtained into the interest, participation and results of entrepreneurs in the respective territories.

Since the LEADER programme projects were not implemented in all research territories – municipalities in 2016 and 2024, information for the period from 2017 to 2023 was analysed in detail, see Figure 3.

Figure 3

Public funding of the EU LEADER programme projects for entrepreneurship in Livani, Preili, Ludza and Rezekne municipalities in 2017-2023, thousand euros



The authors of the study have come to the conclusion that the impact of public funding – co-financing of LEADER business projects – on farm operations and, more broadly, on the development of rural areas could be assessed if the available funding was larger and on more favourable terms, see Figure 3.

The study of Swedish scientists concludes that a large part of LEADER activities take place on the margins and with limited resources, which cannot be a structurally transformative force for European rural areas. There is a risk that LEADER can be perceived as a therapeutic or symbolic policy, whose participants take the situation for granted. Local action group participants see small projects, insignificant added value, mutual trust and partnerships as essential elements to achieve even structural changes in life and development opportunities in rural areas (Johansson & Holmquist, 2024).

The third task of the research – semi-structured interviews were conducted with 12 entrepreneurs by telephone and in person in February, 2025. Since Malnava College is located in Ludza Municipality, entrepreneurs from relatively nearby farms were interviewed – five in Rezekne Municipality (farms founded from 1991 to 2020) and seven in Ludza Municipality (farms founded from 1994 to 2018) areas. As with the online survey, there were also difficulties in conducting interviews, because many entrepreneurs were unwilling or did not have time to do the interviews. According to the developed semi-structured interview methodology, eight questions with several sub-questions were formulated and all the invited entrepreneurs were asked the same questions to make it possible to compare and analyse the answers provided.

The size of farms was from one to 60 ha, currently up to 2,300 ha in one farm. The different answers were received to the question: 'What was your motivation to create your own farm?' They were as follows: under the influence of parents and continuing family traditions (4); to create one's own company – an idea during the Covid-19, changing the occupation in order to earn extra money (4); to work in the countryside – agriculture, in nature (2); to create products with added value (1) and to develop the business by developing projects (1). Business activities on farms are mostly carried out in 2-3 sectors, the main sectors of the interviewed were as follows: grain farming (8); forestry (4); livestock farming (initially 4, currently 2); tourism (2); crop production and beekeeping (1 each); grain processing and home production (1 each). If in the early stages of farms, only one person was employed (in 7 farms) and 2-3 family members supported the activity, now the farms employ 2-3

employees (in 9 farms) and even 22 employees (in one farm).

When asked 'Have your ideas, plans, and dreams about farming been realized?' the following answers were provided: 'yes, a stable production company has been established', 'there is a joy in what has been achieved', 'the goal has been achieved', etc. (8), partially realized (4). To the question: 'What are the main achievements?' the following answers were received: expanded and developed economic activity, increased revenue, stable processing and market position (8), implemented projects (2), practical experience (1), as well as healthy thinking and respect for the laws of nature (1). Since none of the interviewees expressed a strictly negative stance, the authors of the study conclude that entrepreneurs are generally satisfied with the activities carried out. The entrepreneurs received most support on farms from their family (9), the Latvian Rural Advisory Centre and the Rural Support Service (9), a private consultant, a project developer (3), Altum financing (2), a bank loan (2), as well as the head of the local municipality (1). Financial support from the state and/or local government was indicated in 11 responses, including four projects financed by local governments (grants), five – state-subsidized diesel fuel, two – loan interest repayment. These responses demonstrate the significant participation of Latvia's rural support organizations, as well as state and local governments, in the development of farms.

Since one of the objectives of the research project was to identify the EU LEADER programme co-financing in rural areas, several questions were on this topic. All 12 respondents indicated that their farm had received financial support from the LEADER projects of 10 to 90 thousand euros each, including five farms that had received funding 2-3 times.

All the respondents indicated that the support of the LEADER programme is important and necessary, as it allows them to gain new experience and provides an opportunity to develop and expand their business, especially for small farms. At the same time, one response indicated that there was a negative experience because the implementation of the project could not change the circumstances that arose due to objective circumstances.

When asked about the most pressing problems currently faced by the farms, the following main answers were received: lack of funding, decreasing project support, high prices (5), shortage of labour and construction workers (3), complicated procurement and reporting procedures, as well as supervisory institutions (3). Respondents expressed their proposals that could help solve the problems: 'do it yourself and follow the information' (4), advance payment in projects, EU co-financing and new sources of financing (3), stable agricultural policy and prices (2), less bureaucracy and greater trust in entrepreneurs (2), educational seminars in project development and implementation (1).

At the end of the interview, entrepreneurs were invited to add/express their thoughts. These were: not being afraid to implement ideas, assessing one's strengths and being patient, entrepreneurship (5), long project approval time and complicated procedure for making changes, difficult to find suppliers, high prices (3), bureaucracy needs to be reduced (2), difficult experience in proving for oneself (1), etc., but satisfaction – three work places were created (1). After the interview, each entrepreneur was thanked for their time and answers to the questions that provided a broader and more comprehensive picture of the research topic.

A study on the economic impact of the LEADER programme in Romanian rural communities recommends that policymakers increase the financial support offered, focusing on the least developed communities, in order to have a real impact on the economic development of the beneficiary rural communities. Furthermore, it takes time for the economic impact of the LEADER programme to be visible (Opria et al., 2023). The authors of the article agree with this opinion, as the research conducted also proved it.

Conclusions

1. Entrepreneurship in agriculture is related to the use of natural resources and natural conditions, which can directly affect business results. At the same time, it is possible to attract additional financial resources from EU funds to create and develop business.
2. The LBTU agency Malnava College research project showed the biggest difficulties in the EU LEADER programme projects in four municipalities (Livani, Ludza, Preili and Rezekne) of Latgale region in Latvia – insufficient knowledge in developing project applications; ensuring one's own co-financing (self-financing), price changes from project development to implementation, too long project review time, etc. The positive aspects: new experience in project development, purchase of machinery and equipment, farm expansion, additional jobs for local residents, increased production volume, etc.
3. The LEADER programme is chosen by relatively small farms because it provides an opportunity to manage the existing land resources more intensively, providing services to others, as well as offering locally produced products.
4. In order to increase the interest of Latgale entrepreneurs in the LEADER programme funding for business development, it would be necessary:
- to provide more information about LEADER opportunities for rural development, including popularizing examples of good practice and the most successful project implementers;
- Latgale non-governmental organizations should raise

the issue of pre-financing and self-financing of farms in the LEADER projects at the national level, as well as to continue to The LEADER programme was mainly chosen by relatively small farms that did not have an opportunity to purchase larger plots of land to expand their economic activities in the countryside. The programme provides an opportunity to manage existing land resources more intensively, providing services to others, as well as offering locally produced products.

Entrepreneurs have most often used the LEADER programme for the provision of services – 139 projects, while there were 58 projects for the start/ development of production. Services offered in tourism, logging, agricultural machinery and car service, as well as catering, beauty care, organization of sports and recreational events, etc. Production is related to the cultivation and processing of food raw materials, woodworking, cosmetics, etc. The differences by year can be explained by the deadlines for the project competitions announced by the LEADER programme in each area.

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STREET RENAMING AS CULTURAL RESISTANCE: DECOMMUNIZATION AND IDENTITY IN RURAL UKRAINIAN SETTLEMENTS

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Abstract
This study examines the renaming of streets in rural communities of Ukraine, which represents one of the essential aspects of the decommunization process initiated by a series of 2015 laws banning the use of communist and National Socialist totalitarian regime symbols. Henri Lefebvre's theory of the production of space is employed to analyze how street renaming in rural areas of Ukraine is not just an administrative procedure but a transformative practice actively generating new social meanings and values. Additionally, the study applies Pierre Bourdieu's concept of social space and symbolic power to demonstrate how street renaming disrupts the established symbolic order and challenges Soviet/Russian narratives entrenched in toponyms. Renaming streets with references to Ukrainian military heroes, historical personalities, national events, and cultural symbols enables rural communities to assert their hierarchy of values and alter the dynamics of symbolic power in both the symbolic and physical spaces. In this study, we applied a controlled NLP classifier based on a transformer language model, adapted for thematic classification tasks, to analyze 23,536 changes in the names of rural streets. All changes were encoded into 10 thematic categories. The results indicate that despite the dominance of neutral or descriptive names, a significant portion of renaming falls into the category of names that identify culture. In western regions, names honoring historical and cultural figures, as well as elements (symbols) of national/cultural identity, are more common. Notably, a small number of all renaming is dedicated to commemorating those who lost their lives as a result of the ongoing war, underscoring the active participation of rural communities in the decommunization process in post-colonial conditions.
Keywords: cultural resistance, identity, decommunization, decolonization, machine learning.

Introduction

The official legislative process of decommunization in Ukraine began in 2015 following the adoption of several laws aimed at dismantling communist symbols and renaming objects with Soviet-regime names (Gerchanivska, 2024). Before these legislative acts, Ukraine had already experienced efforts to distance itself from its communist past, particularly after the collapse of the Soviet Union in 1991 (Kobchenko, 2016). However, it was the 2015 decommunization laws that significantly accelerated the transformation of street names across the country, and by 2016, 51,493 streets had already been renamed (Ukrainian Institute of National Memory, 2016). After the full-scale invasion by Russia, this process gained momentum, with about 76% of Ukrainians in 2022 supporting the idea of renaming streets with Russian-related names, while a 2024 study demonstrated that the majority of Ukrainians (88%) positively viewed naming streets after fallen soldiers, military personnel, and veterans (Rating Group, 2022, 2024).

This toponymic transformation is not only a matter of administrative decisions but also a form of symbolic resistance, an official attempt to reshape Ukraine's cultural and value hierarchy and establish a new historical and cultural narrative. Renaming streets represents an important symbolic step, showcasing the break with the Soviet past and the embrace of Ukrainian identity (Chuprinova et al., 2024). These measures are particularly crucial in rural areas, where Soviet names often lingered the longest. Affirming local Ukrainian identity through new street names can be regarded as a grassroots act of cultural resistance. This context underscores the importance of street renaming in Ukraine's cultural and historical memory post-2015, laying the foundation for studying how these changes occur at the local level.

The significance of decommunization in Ukraine is closely tied to decentralization reforms, which empowered local communities to actively participate in renaming streets and other public spaces. Granting autonomy to local self-government bodies provided the institutional framework for villages and towns to make decisions about renaming streets. This expansion of powers allows villages and towns to construct their own spaces and reflect their historical and cultural contexts (Salnikova et al., 2021). These reforms shifted citizen engagement in spatial planning, resulting in a reorientation from purely material issues to addressing social, political, and professional needs (Salnikova & Khanin, 2022).

Considering the context of decommunization, an important question arises: How do the practices of renaming streets in rural settlements in Ukraine serve as indicators of cultural resistance? Most existing studies on post-Soviet toponymic changes focus on urban centers and the 'politics of memory', often emphasizing official narratives and commemoration at the urban level (Demska & Levchuk, 2020; Gnatiuk, 2023). By contrast, the rural dimension of decommunization remains understudied, creating a gap in the scholarly understanding of Ukrainian identity transformation. Rural communities were not passive executors of decrees; in many cases, they actively participated in selecting new names that aligned with local culture, historical and cultural memory, or national sentiments. These renamings at the village level are indicators of grassroots identity changes, demonstrating how citizens interpret the legacy of Soviet cultural dominance and resist it. Thus,

the research problem lies in uncovering the patterns and meanings behind these village-level street name changes. Specifically, this research ***aims*** to examine how street renaming becomes an act of cultural resistance, a way for local communities to symbolically reject colonial (Soviet) narratives and assert their own. Analyzing street names before and after renaming enables tracing the process of rethinking cultural and national identity. The focus on rural areas offers a new approach to analyzing decommunization by showcasing how the struggle for historical and cultural memory unfolds in everyday practices. Thus, the research connects cultural practices at the micro level with the broader aspect of cultural resistance in Ukraine.

Materials and Methods

The First Post-Soviet Renaming (early 1990s): unlike Ukraine, which started the process with some delay, other post-Soviet republics quickly renamed their public spaces after gaining independence in 1991. Immediately following the fall of Soviet rule, countries such as Poland, Latvia, and Romania dismantled communist monuments and restored pre-Soviet names to streets, cities, and landmarks (Ochman, 2025).

This first wave of renaming and monument removal represented more than just administrative changes—it was a conscious movement away from the communist past. Names and places that once reflected Soviet ideological dominance were stripped of their sacrality and reinterpreted to reflect national identity and historical continuity. It is worth noting that Lithuania, Latvia, and Estonia already had their own national identities, recognized their belonging to a nation, and viewed their culture as superior to that of the Russian occupier (Annus, 2011). Thus, in the Baltic capitals (Riga, Tallinn, and Vilnius), this process began swiftly. Streets and squares that had previously borne the names of Soviet figures were among the first to be renamed. These changes signified not just the erasure of the Soviet past but a broader redefinition of urban identity. This interaction between physical space and symbolic meaning forms the basis for the theoretical reinterpretation of renaming practices as acts of resistance (Czepczyński & Sooväli-Sepping, 2015).

The research is based on sociological and postcolonial theoretical frameworks, which view the renaming of streets as a symbolic struggle over space and identity. Henri Lefebvre's theory of the production of space provides an important theoretical premise: space is not merely a neutral background but a social product that is continuously shaped and contested by social factors (Lefebvre, 1991). From this perspective, naming and renaming streets is part of the production of social space; each name conveys specific values and histories into the space. The authority to name space is inherently political. Here, we employ Bourdieu's (1989) concept of symbolic power, which argues that the right to name and classify the social world is a significant form of power that can create and sustain symbolic hierarchies and shape perceptions of reality (Patterson, 2006). In the context of Ukraine's decommunization, the state's ability to rename 'Lenin Street' to 'Heroes of Ukraine Street' illustrates this symbolic power, establishing a new vision of history and identity with official legitimacy. At the same time, Bourdieu's concept of habitus suggests that local populations possess internalized dispositions and memories that mediate how they respond to such changes (Wacquant, 2005). Renaming is a two-way process: it is imposed top-down as an act of power, but it is also interpreted, utilized, or even resisted by ordinary people in everyday life. A postcolonial perspective enhances this analysis, enabling Soviet names to be viewed as instruments of imperial narrative and renaming as an act of decolonization. In many ways, the decommunization of toponyms in Ukraine parallels classical postcolonial affirmations of space: the removal of markers of the former empire to establish an autonomous cultural identity (Latysh, 2023).

This study is significant on multiple levels. Empirically, it contributes to a detailed understanding of the decommunization process in Ukraine at the grassroots level and reveals how small communities actively participate in the reconfiguration of national and cultural memory. While decommunization is often discussed in terms of laws and public debates, our focus on street names in villages uncovers the everyday face of historical changes, how national policy is implemented (or localized) in rural areas. This research perspective expands knowledge about memory and identity in post-Soviet societies. The study also advances the discourse on decommunization and decolonization. By considering the renaming of Ukrainian streets as an example of postcolonial identity assertion, we emphasize the continuity between the removal of Soviet symbols and the broader shedding of colonial legacies (Gnatiuk, 2018).

The combination of Henri Lefebvre's and Pierre Bourdieu's spatial theories with postcolonial theories allows us to examine how the renaming of streets in rural Ukraine functions as a form of cultural resistance and rethinking of identity. The use of computational sociology methods in the research, particularly machine learning, underscores the importance of these spatial practices in reconstructing value hierarchies within local communities. Analyzing street renaming as conscious acts of decolonization, the study highlights the role of everyday practices in asserting sovereignty and shaping national identity, especially in the context of war. This research contributes to a comprehensive understanding of how local actions, such as renaming streets, serve as crucial aspects of cultural struggle and development, reflecting manifestations of identity and values in rural areas.

The analysis utilizes a robust dataset obtained from geodata.online, a platform offering up-to-date address data for Ukraine. This dataset includes 23,536 renamed streets across 8,580 settlements, covering all regions of the country. The initial stage involves cleaning and processing the data using OpenRefine (https://openrefine.org/), an open-source tool. OpenRefine facilitates the detection and correction of inconsistencies, duplicates, and formatting errors, ensuring the standardization of street names and their suitability for further analysis. At this stage, the Key Solution Method was implemented using the Keying Function (Fingerprint). This approach enabled the creation of unique identifiers for street names, improving the process of identifying duplicates and ensuring data merging.

Following the data cleaning process, similar records were merged using several advanced methods. Initially, the Nearest Neighbour Method was applied in combination with the Levenshtein Distance function with a radius of 1–2 (used for block sizes ranging from 15 to 8) to merge nearly identical street names. Another Nearest Neighbour Method was also applied using the PPM (Prediction by Partial Matching) Distance function with a radius of 1, which proved particularly effective for block sizes of 15 and smaller. Additionally, the Key Collision Method was applied using the Beider-Morse Function to detect phonetic similarities and eliminate any remaining discrepancies.

After the data merging, a text classification method was employed to distribute street names into thematic groups. This classification is performed using a machine-learning-based classifier grounded in natural language processing technology. The classifier is designed to identify and group street names by themes such as historical/cultural figures, cultural elements, descriptive names, military-related names, and more. To enhance the reliability and accuracy of the classification, an iterative verification process was implemented, during which assigned categories were reanalyzed and adjusted. This algorithm not only reduces misclassifications but also gradually improves the overall quality of categorization.

All calculations and computational procedures were conducted using the R programming language. The overall methodology, combining automated processing with systematic quality monitoring and specialized merging methods, ensures that the subsequent analysis of street renaming in rural Ukraine is based on a reliable and accurately classified dataset.

Results and Discussion

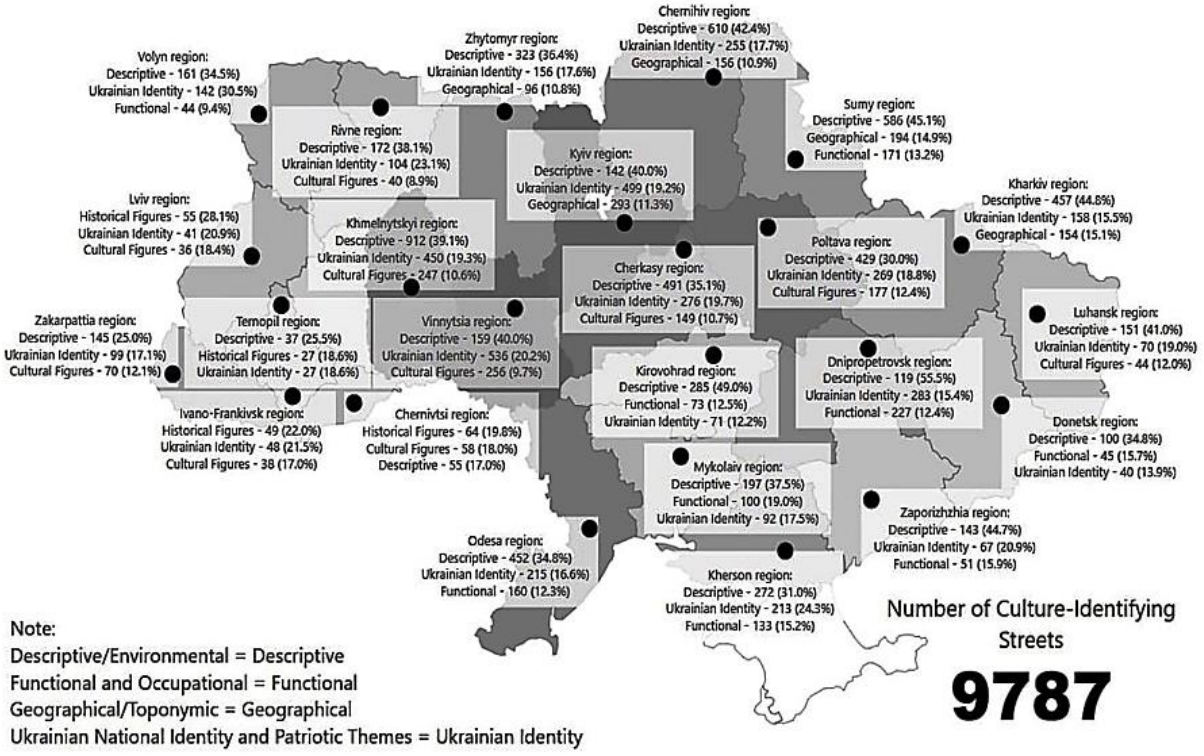
The classification of street names after renaming covers the following categories:

5. **Military and defense units:** Streets named after specific military units, brigades, battalions, or significant military formations in Ukrainian history *(e.g., 127th Brigade, 129th Territorial Defense Brigade, Aidar, Azov)*.
6. **Commemorative dates and events:** Streets dedicated to significant historical events or important dates *(e.g., 1st of May, 24th of August, 9th of March)*.
7. **Descriptive/environmental:** Streets named based on their physical features, landscape characteristics, natural elements, or appearance *(e.g., Chestnut, Sunny, Pine)*.
8. **Historical figures:** Streets named in honor of individuals significant in Ukrainian or world history, politics, or science *(e.g., Mykhailo Hrushevskyi, Ivan Mazepa, Academician Vernadskyi)*.
9. **Cultural figures:** Streets named after prominent figures in literature, art, music, theater, and culture *(e.g., Lesia Ukrainka, Ivan Franko, Taras Shevchenko)*.
10. **Functional-professional:** Streets named after professions, industrial functions, or the practical purpose of the locality *(e.g., Builders, Railway, Energetics)*.
11. **Russian-Ukrainian war:** Streets named after civilians and soldiers who died as a result of the Russian-Ukrainian war (from 2014 to the present) *(e.g., Heroes of the ATO, Heroes of the Armed Forces of Ukraine, Ruslan Marchenko)*.
12. **Geographic/toponymic:** Streets named after cities, regions, rivers, mountains, or other geographical objects *(e.g., Carpathian, Western, Dnipro)*.
13. **Religious and spiritual:** Streets associated with religious or spiritual themes, institutions, saints, religious leaders, or traditional religious holidays *(e.g., Holy Intercession/Trinity, Saint Nicholas)*.
14. **Ukrainian national identity and patriotic themes:** Streets symbolizing Ukrainian national identity, unity, independence, as well as significant symbols or markers of Ukrainian identity *(e.g., Independence, Unity, Ukrainian Renaissance)*.

The analysis revealed that the most commonly renamed streets were Centralna (Central) (5.31%), Myru (Peace) (4.41%), Vyshneva (Cherry) (3.81%), Soniaczna (Sunny) (2.24%), and Sadova (Garden) (2.22%), reflecting a neutral nature in their original names. Regions leading in the number of renamed streets include Vinnytsia region – 2,650 streets (11.3% of the total), Kyiv region – 2,604 streets (11.1%), Khmelnytskyi region – 2,330 streets (9.9%), Dnipropetrovsk region – 1,837 streets (7.81%), and Chernihiv region – 1,437 streets (6.11%). On average, each region accounts for 981 streets, with a median of 730. The minimum number of renamed streets was in Ternopil region – 145 (see Table 2).

The higher frequency of street renaming in eastern and central regions compared to western regions can be explained by historical differences in Soviet influence and colonial legacy. Eastern and central Ukraine experienced more extensive and prolonged Soviet rule, which led to a greater prevalence of Soviet symbolism in public spaces.

Figure 1
Distribution of Street Name Categories by Region



This necessitated large-scale renaming initiatives. In contrast, western regions were relatively less affected by Soviet influence and, therefore, had fewer Soviet-era street names that required renaming (Gnatiuk, 2018).

Most street renamings were driven by the use of descriptive characteristics or elements of the environment (38.8%), while names reflecting national identity or patriotic themes accounted for 18.4% (see Table 1).

Table 1
Categories of Renaming Distribution

Category of Renaming	***%***
Descriptive/Environmental	38.8
Ukrainian National Identity and Patriotic Themes	18.4
Functional-professional	10.3
Geographical/Toponymic	9.3
Cultural Figures	8.4
Historical Figures	6.2
Russian-Ukrainian War	4.6
Religious and Spiritual	2.7
Commemorative Dates and Events	1.1
Military and Defensive Units	0.4

The analysis of renaming data highlights both general trends and regional differences across Ukraine. The predominant trend is the frequent choice of descriptive street names. For example, in the Dnipropetrovsk region, descriptive names account for 55.5% of the renamings, whereas in the Kyiv and Vinnytsia regions, this figure is around 40%. This trend indicates that local communities often prefer practical, easily recognizable names that reflect local geography or natural landmarks.

At the same time, street names emphasizing Ukrainian national identity and patriotic themes often rank either first or second in various regions, comprising 15% to 24% of the total renamings. This reflects deliberate efforts to strengthen national identity and symbolically distance modern local spaces from their colonial legacy. In regions such as Ivano-Frankivsk and Lviv, the 'Historical Figures' category is particularly prominent, accounting for 22.0% and 28.1% of renamings, respectively. This trend underscores regional priorities in commemorating individuals important to Ukraine's historical narrative.

Other categories, including cultural figures and functional or professional names, while not dominant overall, demonstrate the influence of local historical and cultural identity on the renaming process. These data suggest the renaming process is largely driven by practical and neutral aspects. However, efforts to incorporate national, cultural, and historical symbolism are important, as this reflects a broader strategy of rethinking and reconstructing public spaces in a post-Soviet context, see Figure 1.

Due to the low representation of certain categories, we grouped them into two broader groups. The first group includes street names that are culturally, historically, and socially significant, while the second group includes neutral names:

• Names that identify culture: Military and defense units, commemorative dates and events, historical figures, cultural figures, the Russian-Ukrainian war, religious and spiritual themes, Ukrainian national identity, and patriotic themes.
• Names that neutralize ideology: Descriptive/ environmental, functional-professional, geographic/ toponymic.

The distribution for the two grouped categories of street renaming (Culture-Identifying and Ideologically-Neutral) is 58.4% / 41.6%, respectively. The data analysis emphasizes regional differences in the approaches of local communities to the decommunization process. The Culture-Identifying category encompasses efforts aimed at embedding cultural, historical, and patriotic symbolism into rural spaces. For example, in the Ivano-Frankivsk region, 81.2% of renamed streets reflect identity-oriented values. Conversely, in the northern and eastern regions, the Ideologically-Neutral category prevails. In the Dnipropetrovsk region, 75.3% of renamed streets fall into the neutral category, indicating a preference for practical, non-ideological approaches to renaming (see Table 2).

Overall, regional differences in street renaming strategies across Ukraine can largely be explained by the various historical, political, and cultural contexts highlighted by Gnatiuk (2018). According to the author, renaming processes reflect different regional approaches deeply rooted in the historical narrative, political preferences, and collective memory of each region. In the western regions (such as Lviv, Ivano-Frankivsk, and Chernivtsi), the predominance of street names in the Culture-Identifying category reflects the cultural-historical continuity with the Ukrainian People's Republic (UPR) and, to some extent, the Ukrainian Insurgent Army (UIA). These regions actively use renaming as a tool to emphasize national heritage and strengthen a distinct national and cultural identity. In contrast, in the northern (Sumy region) and eastern regions (notably, Dnipropetrovsk region), the predominance of neutral names (descriptive or common toponyms) supports the author's observation about efforts aimed at depoliticizing toponymy. In these areas, neutral and less controversial symbols, such as references to local geography, have historically been preferred to ease political or ideological tensions in communities with diverse ethnic compositions and electoral preferences.

Table 2
Categories of Renaming Distribution by Region (N – Ideologically-Neutral; C – Culture-Identifying)

Region	***Main***	***Count***	***%***	***Region***	***Main***	***Count***	***%***
Ivano-Frankivsk	N	42	18.8	Mykolaiv	N	333	63.4
	C	**181**	**81.2**		C	192	36.6
Volyn	N	241	51.7	Odesa	N	739	57.0
	C	225	48.3		C	558	43.0
Vinnytsia	N	1454	54.9	Poltava	N	703	49.1
	C	1196	45.1		**C**	**728**	**50.9**
Dnipropetrovsk	N	1384	75.3	Rivne	N	234	51.9
	C	453	24.7		C	217	48.1
Donetsk	N	176	61.3	Sumy	N	951	73.2
	C	111	38.7		C	349	26.8
Zhytomyr	N	502	56.5	Ternopil	N	61	42.1
	C	386	43.5		**C**	**84**	**57.9**
Zakarpattia	N	259	44.7	Kharkiv	N	724	70.9
	C	**321**	**55.3**		C	297	29.1
Zaporizhzhia	N	217	67.8	Kherson	N	518	59.1
	C	103	32.2		C	359	40.9
Kyiv	N	1551	59.6	Khmelnytskyi	N	1313	56.4
	C	1053	40.4		C	1017	43.6
Kirovohrad	N	407	69.9	Cherkasy	N	723	51.7
	C	175	30.1		C	675	48.3
Luhansk	N	212	57.6	Chernivtsi	N	93	28.8
	C	156	42.4		**C**	**230**	**71.2**
Lviv	N	23	11.7	Chernihiv	N	889	61.9
	C	**173**	**88.3**		C	548	38.1

Given that the distribution of street names across the two categories varies by region, a Chi-squared test of independence was conducted to determine whether there is a significant association between regions and naming groups (see Table 3). The resulting p-value < 2.2e-16 was significantly lower than the commonly accepted significance threshold (0.05), allowing the rejection of the null hypothesis of independence. Thus, certain regions statistically significantly favor Culture-Identifying street names compared to Ideologically-Neutral ones.

Table 3
Pearson's Chi-squared test

	Values
χ^2 (Chi-squared)	1067.9
Degrees of Freedom (df)	23

To further explore regional differences, standardized residuals from the Chi-squared test were analyzed, which allowed the identification of the following patterns:

15. *Regions with significantly higher prevalence of Names that Identify Culture* (positive residuals > 2): Lviv region (13.32), Ivano-Frankivsk region (12.05), Chernivtsi region (10.88), Poltava region (7.36), Zakarpattia region (6.81), and Cherkasy region (5.24). Positive residuals in these regions indicate a frequency of street names that identify culture higher than expected, predominantly observed in western regions. This pattern suggests a strong regional tendency toward cultural identification, reflecting historical, political, and sociocultural influences.
16. *Regions with significantly lower prevalence of Names that Identify Culture* (negative residuals < -2), indicating a greater prevalence of 'neutral' names: Dnipropetrovsk region (-15.33), Sumy region (-11.09), Kharkiv region (-8.28), Zaporizhzhia region (-3.43), Chernihiv region (-2.74), and Mykolaiv region (-2.36). These regions demonstrate significantly lower cultural identification through street names, with a pronounced preference for Ideologically-Neutral names, particularly in the Dnipropetrovsk and Sumy regions. However, despite this tendency toward neutrality in some regions, the street renaming process in Ukraine is closely tied to the formation of cultural and national identity. Street names serve not only functional purposes but also represent symbolic meanings that reflect collective and historical memory.

Street renaming in Ukraine acts as a form of cultural resistance, analogous to how language choice functions as resistance on digital platforms (Burdin, 2023). In a study on the Ukrainization of YouTube content, the preference for Ukrainian-language videos was interpreted as an active form of cultural resistance against the dominance of Russian content. Similarly, the selection of new street names affirms cultural and national identity. While the majority (58.4%) of renamed streets have neutral names, a significant 41.6% exhibit distinct cultural, historical, or social themes, reflecting an awareness of heritage and identity in the renaming process. Notably, nearly 5% of all renamed streets were dedicated to honoring fallen heroes and civilian victims of the ongoing Russian-Ukrainian war, embedding collective memory of these sacrifices into rural public spaces. This practice of commemoration, replacing Soviet-era street names with those of Ukrainian soldiers, national figures, and war victims, represents a vital element of cultural memory and a significant step toward decolonization (Verbytska, 2015). Like the conscious choice of language, renaming streets with cultural, historical, or social significance serves as a form of self-expression. This practice not only represents a hierarchy of societal values but also actively contributes to constructing and representing identity.

The ongoing processes of decommunization and decolonization in Ukraine have resulted in deliberate removal of Soviet/Russian toponyms and their replacement with names emphasizing Ukrainian culture, history, and wartime sacrifices. This shift reflects society's efforts to cleanse public spaces of colonial symbols from the past. While most renamed streets now have neutral names, many symbolically reconstruct resistance, challenging the cultural and symbolic dominance previously rooted in Soviet-era naming practices.

Importantly, the renaming of streets using national and patriotic themes, prominent historical and cultural figures, heroes, and civilians highlights the critical role of local initiative in these collective efforts to confront the colonial past. Even within the framework of a national decommunization program, local communities and authorities retain the discretion to choose new names independently. Thus, numerous rural communities emphasize their distinct regional identity and history through their naming choices. This bottom-up approach underscores that collective memory in Ukraine is shaped not only by centralized decisions but also by local values and priorities.

Honoring heroes, recognizing historical tragedies, and selecting culturally significant names contribute to strengthening collective memory at the community level. However, evident regional differences—where some regions adopt symbolic, memory-related names while others prefer practical, neutral ones—demonstrate that there is no universal strategy for decolonizing rural spaces. These differences reflect the unique historical, political, and social narratives of each region.

Conclusions

1. Renaming streets in rural Ukraine serves as a significant form of cultural resistance. The use of cultural, historical, and social themes in new street names reflects a rejection of colonial Soviet narratives and affirms culture and national identity. Rural communities actively participate in this process, choosing not only neutral names but also those that reflect culture, collective memory, and patriotic sentiments, emphasizing the local nature of resistance.
2. The process of renaming streets in rural areas reflects both national trends and regional differences. Despite the predominance of descriptive and neutral names (58.4%), a considerable portion of names (41.6%) hold cultural, historical, and social significance. This duality highlights that the renaming process combines practical considerations with deliberate symbolic actions that integrate Ukrainian culture and history into everyday life.

3. Regional differences, revealed through statistical analysis, reflect historical, cultural, and political characteristics in Ukraine. Western regions, such as Lviv, Ivano-Frankivsk, and Chernivtsi, predominantly choose Names that Identify Culture, emphasizing historical continuity with the UNR and UPA. In contrast, northern and eastern regions favor neutral and depoliticized names, reflecting regional strategies aimed at reducing ideological tensions.
4. The renaming process actively contributes to the formation of collective memory and national narrative, particularly in honoring the memory of Ukrainian soldiers, civilian victims of the Russian-Ukrainian war, and prominent historical or cultural figures. Approximately 5% of renamed streets commemorate individuals who died in the war, embedding this knowledge into collective and historical memory.
5. Street renaming in rural Ukraine symbolizes societal efforts toward decommunization and decolonization. Local communities play a crucial role in shaping their own symbolic space. This reflects that collective/historical memory and identity construction in Ukraine are closely tied to local dimensions.
6. Overall, the process of renaming streets with the involvement of rural communities contributes to the development of rural spaces. It not only enhances social cohesion but also fosters the formation of collective/historical memory and encourages active community participation in constructing their own cultural and symbolic space.

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PHD STUDENTS' INTERDISCIPLINARY COLLABORATION IN EAP

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Abstract
In recent years, science has become increasingly interdisciplinary and collaborative due to the complex global challenges that must be addressed in the 21st century. Interdisciplinary collaboration in research leads to creativity and innovation by combining various perspectives, areas of expertise, and approaches from different scientific fields. For PhD students conducting their doctoral research, learning to collaborate across disciplines is crucial. The present research aims to investigate the role of interdisciplinary collaboration integration into the study course of English for Academic Purposes (EAP) for PhD students. The article describes the main peculiarities and aims of the EAP course in higher education, outlines strategies for integrating interdisciplinary collaboration, examines the benefits and challenges within the curriculum. The authors conducted qualitative interviews with PhD students from various disciplines. The results of the interviews presented both the advantages and challenges of interdisciplinary collaboration. Based on these findings, a survey was conducted with PhD students to assess whether interdisciplinary collaboration during classroom activities facilitated learning outcomes in the EAP course. The results of this survey demonstrated an overwhelmingly positive students' opinion, and the majority of respondents agreed that it benefitted their learning outcomes, for example, it helped them discuss research ideas more effectively in English, improved problem-solving, developed academic English oral and writing skills, and increased confidence in working with peers from different disciplines. Thus, the study suggests that to prepare the next generation of researchers for academic success in the modern research environment, interdisciplinary collaboration should be integrated into an EAP course.
Keywords: English for Academic Purposes (EAP), interdisciplinary collaboration, academic communication skills, research skills development.

Introduction

Collaboration is widely acknowledged as one of the most important skills of the 21st century as there is a growing need for society to think and work collectively for common goals to strive for success and achieve high results (Riaz & Marium, 2023).

Learning through collaboration or Collaborative Learning (CL) is an educational approach that has gained significant attention in the last few decades. It involves creating an environment for students where they work together in small groups, mutually searching for understanding and meaning, sharing knowledge, and exchanging multiple perspectives to achieve a common goal, complete a task, or find a solution to a problem (Smith & MacGregor, 1992).

The underlying principle of collaborative learning is reaching consensus through cooperation, as opposed to competition in which group members try to outperform each other (Slavin, 2014; Gijlers et al., 2009). Collaboration is a 'philosophy of interaction' and a personal lifestyle that suggests a way of dealing with people that respects and highlights individual group members' abilities and contributions (Laal, 2013).

The impact of collaborative learning in the higher education context is thoroughly discussed in scientific literature. Scholars consider it a promising pedagogical approach in tertiary education instruction and they highlight that collaborative work on an academic task can be more powerful than traditional methods of pedagogy because it motivates students to become more active and more involved in participation in the learning process (Quenee, 2017; Lin, 2015; Ruijuan et al., 2023).

Collaborative learning represents a move away from the traditional teacher-centered or lecture-based environment. Educators who use a collaborative approach view themselves not as experts and knowledge transmitters, but as facilitators, guides, and creators of active learning experiences for their students. Students, in contrast, take a central role, they actively construct their knowledge through participation in group work and collaboration (Baloche & Brody, 2017).

Collaborative learning in essence is a constructivist approach that incorporates the principles of Cognitive Constructivism and Social Constructivism (Taggart & Wheeler, 2023). Cognitive constructivism emphasizes the role of individual experience in the process of meaning-making. Students actively construct knowledge based on their present stage of cognitive development, integrating new information into their existing understanding of the world and their past experiences (Piaget, 2002). Social Constructivism focuses on learning through social interactions. According to this theory, learners encounter a variety of viewpoints when they participate in discussion and collaboration, and this process stimulates them to engage with new ideas and refine their understanding. Consequently, knowledge is developed by relationships, culture, and environment (Vygotsky, 1980).

Collaborative learning in higher education comprises a wide range of instructional methods that can be adapted to meet different learning goals and contexts. They include cooperative learning, problem-based learning, team-based learning, peer tutoring, study groups, project-based learning, game-based learning, and learning communities. All these methods focus on student active engagement in the learning process and encourage exploration and practical application of the course content, rather than merely relying on teacher-led instruction (Barkley et al., 2014, Kuwabara et al., 2020). Based on constructivist principles, these

approaches highlight the importance of student interaction, exploration, and reflection as integral components of the learning process (Suthers, 2012).

The main elements of collaborative learning are broadly defined and thoroughly described in the research literature, they include: positive interdependence (students rely on each other to achieve a common goal), face-to-face promotion of interactions (students help and encourage one another to learn), individual accountabilities or personal responsibilities (every student contributes meaningfully), interpersonal or small-group skills (such as effective social skills, conflict resolution, leadership, trust-building) and group processing (where groups reflect on their performance and evaluate it to facilitate further collaboration) (Johnson & Johnson, 1999, 2018). By incorporating these elements into the learning process, the teacher can prepare students for collaborative work in academic, professional, and research environments.

Interdisciplinary collaboration in research

Numerous studies have highlighted the value of interdisciplinary collaboration in research. It is defined as addressing 'an issue from a range of disciplinary perspectives, where the contributions from the various disciplines are acknowledged and integrated to provide a holistic or systemic outcome' (Lyall et al., 2011). Interdisciplinary collaboration is acknowledged as the cornerstone of contemporary research, which is vital for addressing the complex global challenges faced by society today (Gaikwad, 2024; Baker, 2015; Cheruvelil & Soranno, 2018).

Modern real-world problems are multifaceted, their understanding and solving require the integration of the collective intelligence of diverse experts from various disciplines into research (Rask & Shin, 2024). Incorporating knowledge and experience from diverse fields enables researchers to contribute unique insights, uncover new dimensions, and address complex issues from multiple perspectives (Carr et al., 2018). This collaborative approach surpasses the boundaries of individual domains, enriches problem analysis with quality and depth, and enhances creativity, and new insights. Consequently, interdisciplinary research often leads to innovation, groundbreaking discoveries, and transformative solutions and drives scientific progress (Wagner, 2019; Warren & Warren, 2023).

Despite its importance, there is little research on how interdisciplinary collaboration can be integrated into the EAP course at the university to enhance learning outcomes and advance students' research. Therefore, the present research aims to investigate the role of interdisciplinary collaboration integration into the study course of English for Academic Purposes (EAP) for PhD students. This article describes the main peculiarities and aims of the EAP course in higher education, outlines strategies for integrating interdisciplinary collaboration, examines the benefits and challenges within the curriculum, and presents students' views on its impact on their learning outcomes.

Materials and Methods

Peculiarities and aims of the EAP course

In contrast to general English courses, the study course 'English for Academic Purposes' at Latvia University of Life Sciences and Technologies focuses on developing linguistic and communicative skills necessary for research. This course is designed for local and international PhD students from diverse disciplines and programs at LBTU, such as Agricultural Engineering, Agriculture, Food Science, Landscape Architecture, Agrarian and Regional Economics, Environmental Engineering, Civil Engineering, and Information Technologies. English proficiency levels of PhD students range from B2 to C1.

This one-term course (6 ECTS) takes place at the beginning of doctoral studies and emphasizes oral presentations, scientific writing, research vocabulary building, and the search and selection of relevant information using authentic research literature. Throughout the EAP course, doctoral students become familiarised with the European Research Area and acquire the formal styles used in journal publications and conference contributions. Different forms of writing, including literature reviews, research proposals, conference submissions, formal correspondence, and annotated bibliographies are covered, and students actively acquire a specialised vocabulary of 250 key terms in English.

The EAP course includes practical classes, seminars, and workshops. Various teaching methods, including case studies, debate, discussion, textual and vocabulary work encourage student collaboration, communication, creativity, and critical thinking. This course focuses on the practical application of academic English in research and professional settings, fostering not only knowledge and skills but also confidence and autonomy in English-speaking academic contexts, as well as the capability to plan and execute research activities in an English-speaking environment.

To explore the role of interdisciplinary collaboration within the EAP course, the authors employed qualitative and quantitative sociological research methods to collect and analyse data, including semi-structured qualitative interviews and a quantitative survey.

Integrating interdisciplinary collaboration into EAP

For PhD students working on their PhD thesis, learning to collaborate across various disciplines is especially important. Integrating interdisciplinary collaboration into the EAP course presents an opportunity not only to improve PhD students' academic English language skills but also to enhance their ability to engage in productive and meaningful discussions about research within diverse scientific fields. Since group work is an integral part of the study process, working in small, diverse groups, students can

explore interdisciplinary connections, deepen their understanding of how research fields intersect, and contribute to solving complex problems.

In order to promote interdisciplinary collaboration, several instructional strategies were integrated into the EAP curriculum, such as Interdisciplinary Insights, Research Proposal Presentations and Interdisciplinary Feedback, Interdisciplinary Case Study, and Reflection on Interdisciplinary Collaboration. PhD students were deliberately assigned to groups with diverse academic fields, each group consisted of 4-6 participants. Below is a description of these strategies.

Interdisciplinary Insights

Students brainstormed and explored how advancements in their fields overlap and contribute to solving shared problems. Identifying connections between their fields, they explained how combining knowledge from various disciplines could lead to innovative solutions. Students discussed the mutual benefits of interdisciplinary collaboration and how combining different perspectives can enhance their research. For example, students found out that Landscape Architecture and Civil Engineering can collaborate to design urban environments that integrate natural landscapes with infrastructure to create sustainable, resilient cities; students also came up with a solution that Food Science and Environmental Engineering can work together to solve food waste issues by creating sustainable food processing techniques and waste management solutions.

Research Proposal Presentations & Interdisciplinary Feedback

Each student presented their research, after which the groups analysed all proposals and discussed common themes and approaches. Then, using the Questions, Praise, Suggest format group members provided their feedback to their peers. They prepared three open-ended questions for clarification. Then the group discussed the strengths of each presentation and offered constructive suggestions for improvement or alternative approaches. Finally, students summarised and presented their group work for the whole class using a table or a mind map in order to represent the diversity of ideas visually.

Interdisciplinary Case Study

The cases that students worked on required opinions from multiple fields. Examples of cases included: reducing city traffic jams with smart technology, designing a sustainable urban agriculture system, and creating a zero-waste restaurant concept. Groups analysed a case they were assigned, brainstormed solutions, and created a plan, employing ideas from various fields. Then groups presented their solutions to the whole class showing the integration of various disciplines, receiving feedback and suggestions. Finally, each group reflected on how the interdisciplinary approach enhanced problem-solving and summarised key takeaways.

Reflection on Interdisciplinary Collaboration

Students wrote a reflective paragraph in which they explored whether interdisciplinary collaboration benefitted their research. Students analysed if working with colleagues from different fields provoked new perspectives on their work and if answering questions from groupmates with different expertise led to deeper insights and enhanced their research. This process encouraged them to think outside their specific academic fields and fostered a more holistic approach to their work.

Results and Discussion

The present research aimed to investigate the role of interdisciplinary collaboration integration into EAP. The study was conducted in two stages. First, students' opinions about the benefits and challenges of interdisciplinary collaboration in the EAP course were explored. Second, the impact of interdisciplinary collaboration on students' learning outcomes was investigated. Below is a detailed description of these stages.

Identifying advantages and challenges of interdisciplinary collaboration in EAP

To explore students' views on the benefits and challenges of interdisciplinary collaboration in the EAP course, qualitative interviews were conducted in 2024 and 2025 with PhD students of various disciplines, including Agricultural Engineering, Agriculture, Food Science, Landscape Architecture, Agrarian and Regional Economics, Environmental Engineering, Civil Engineering, and Information Technologies. In total, 60 PhD students were involved in interdisciplinary collaboration as part of the EAP course and then reflected on their experiences. The most common benefits identified were grouped into five categories: broadening perspectives and exploring interdisciplinary connections, facilitating creativity and innovative solutions, receiving feedback for improvement, improving communication skills, and enhancing presentation skills. Students' comments provide valuable insights into each of these aspects.

Broadening perspectives and exploring interdisciplinary connections

Collaborating with peers from different academic fields encouraged students to view their research from new angles and find connections between disciplines. It helped them relate their research to broader themes and real-world issues, and thus they enhanced its significance, practical application and made it more accessible to a wider audience. Students' comments:

S23: 'Interdisciplinary collaboration has broadened my perspective on my research, highlighting aspects like economic viability, sustainability, and risk-sharing mechanisms'.

S7: 'Listening to research from colleagues in other fields helped me see how my work connects to broader themes like environmental stewardship and social cohesion'.

S15: 'Engaging with peers from diverse disciplines widened my viewpoint and inspired me to consider factors I hadn't thought about before'.

S43: 'Peers from environmental sciences helped me

connect my work on sustainable practices with broader ecological goals'.
S58: 'Comments from colleagues underscored aspects such as economic resilience, ecotourism potential, and enhanced resource management - an angle I hadn't initially considered'.
S60: 'Suggestions about considering societal impacts made my research more comprehensive and aligned with real-world issues'.

Facilitating creativity and innovative solutions

Working in interdisciplinary groups created an environment that promoted creativity and the generation of fresh ideas. The students were encouraged to combine knowledge and experience from diverse academic fields and explore unconventional solutions to complex problems more effectively. Students' comments:
S2: 'The best deals often come from people who worked in other industries on a daily basis. We just have to listen to each other and find an opportunity to answer the questions asked'.
S13: 'When different people come together with their unique experience and knowledge, they can contribute to the common work'.
S27: 'Sometimes, working in one field for a long time makes the big picture disappear. Outsiders can give a fresh perspective or come up with a new idea'.
S14: 'Interdisciplinary collaboration encourages creative problem-solving, as it integrates multiple viewpoints into innovative approaches'.
S6: 'Interdisciplinary teamwork motivated me to approach my research creatively and explore unconventional solutions'.

Receiving feedback for improvement

Receiving constructive criticism from peers with different expertise students were inspired to review and evaluate their work critically. This feedback often pointed out areas for improvement they overlooked, helping refine such aspects as research focus, methodology, and presentation. Students comments:
S3: 'Suggestions to incorporate more visual data helped me improve the clarity of my research presentations'.
S12: 'Constructive feedback made me realize that my presentation lacked clarity in certain areas, encouraging me to refine my arguments'.
S27: 'Answering questions from peers prompted me to revisit and improve my methodology and focus'.
S1: 'Questions from colleagues made me step back for a moment and reflect on the importance of the topic to myself'.
S4: 'Interdisciplinary feedback revealed areas of my research that needed further exploration and refinement'.
S59: 'Answering questions helped me identify weaknesses and rethink the scope of my study'.

Improving communication skills

Collaborating with peers from various academic disciplines enhanced students' ability to communicate their research to an audience unfamiliar with their specific field. They were forced to simplify language, define terms, and explain concepts in an understandable way. This process not only improved students' ability to engage with diverse audiences but also improved their overall communication skills. Students' comments:
S13: 'Questions from the audience allow you to look at your topic from the outside and try to explain things that you know in a simple and understandable way to others'.
S34: 'Answering questions from colleagues with different expertise forced me to explain my research more clearly, revealing gaps in my knowledge'.
S45: 'Discussing my work with students from other disciplines taught me to use more accessible language and focus on clarity'.
S28: 'This collaboration challenged me to articulate complex ideas in ways that could be understood by non-specialists'.

Enhancing presentation skills

Students were encouraged to improve their presentation style and focus on clarity, engagement, and effective visual design. Also, listening to others' presentations inspired students to improve their own delivery and enhance the impact of their research. Students' comments:
S2: 'Observing and evaluating others' presentations was particularly beneficial, both in terms of presentation design and presentation skills'.
S27: 'I realized the importance of being clearer and speaking more slowly when I present'.
S34: 'Watching how passionate others were about their research inspired me to present my own work in a more engaging way'.
S55: 'Feedback on my presentation design and delivery helped me create more visually appealing and impactful slides'.

However, engaging in interdisciplinary collaboration about research in EAP the students also faced several challenges such as uneven contributions, stress and anxiety, language barriers, time and effort, and difficulties in finding common ground.

Uneven contributions

Some students noted that not all team members were equally engaged in providing feedback or participating in discussions:
S18: 'Sometimes, some team members didn't participate much, which slowed down our discussions and made the collaboration less effective'.
S55: 'It was frustrating when some peers did not contribute as much, and the workload was not evenly shared'.

Stress and anxiety

Presenting research in an interdisciplinary setting was stressful for some students, especially when they felt their work was less advanced or when they faced criticism:
S14: 'During the presentation, due to anxiety, I found myself reading the whole script of my speech'.
S26: 'It was slightly stressful, as I had to present my

research, which is still in its early stages compared to some of my colleagues'.

S43: 'I felt nervous presenting my ideas in front of peers with more experience. Sometimes, I had difficulty expressing my thoughts clearly, and this led to misunderstandings during discussions'.

Language barriers

Language barriers added difficulty in both presenting research and understanding feedback:

S3: 'Due to my limited knowledge of a foreign language, I pay more attention in class to preparing for a presentation with as few mistakes as possible rather than focusing on others' ideas and advice'.

S22: 'I often felt unsure when listening to complex feedback in the foreign language. It was hard to respond appropriately'.

Time and effort

Interdisciplinary collaboration required additional time and effort to bridge knowledge gaps and understand diverse perspectives:

S4: 'Answering questions from colleagues unfamiliar with veterinary medicine challenged me to clarify my research aims and methodologies, which was time-consuming'.

S7: 'As an economist, I often use terms that I consider understandable without providing sufficient explanations, and my colleagues sometimes struggled to fully grasp my presentation'.

S35: 'In a short time, I had to evaluate their work, in which they are experts, despite having limited information on the subject'.

Despite the challenges of interdisciplinary collaboration integration into EAP, most students acknowledged its overall benefits and viewed this experience as valuable for personal and academic and professional growth.

Investigating the impact of interdisciplinary collaboration on learning outcomes in EAP

Based on these findings, a survey was conducted in 2025 involving 40 PhD students to investigate the impact of interdisciplinary collaboration on their learning outcomes. The respondents completed a Likert-type questionnaire in which they ranked 15 suggested statements about the EAP course as SA (strongly agree), A (agree), N (neutral), D (disagree), and SD (strongly disagree). The results obtained were analysed by SPSS, they are shown in Table 1 below.

Table 1
Student perceptions on the impact of interdisciplinary collaboration on their learning outcomes in EAP

#	*Statement*	*Valid percent*					*Mean*	*St. dev. (σ)*
		SA	*A*	*N*	*D*	*SD*		
1	Interdisciplinary collaboration made problem-solving easier.	51.7	25.0	21.7	1.7	0.0	1.7333	.86095
2	The collaborative experience was meaningful to me.	18.3	51.7	28.3	1.7	0.0	2.1333	.72408
3	Collaborating with peers has boosted my English oral presentation skills.	40.0	46.7	13.3	0.0	0.0	1.7333	.68561
4	I have enhanced my ability to discuss research ideas effectively in English.	43.3	45.0	11.7	0.0	0.0	1.6833	.67627
5	I am more confident collaborating with individuals from diverse disciplines now.	28.3	38.3	33.3	0.0	0.0	2.0500	.79030
6	I have developed stronger communication and interpersonal skills through teamwork.	5.0	66.7	25.0	3.3	0.0	2.2667	.60693
7	Collaborating with others inspired me to explore new ideas and directions in my research.	20.0	51.7	23.3	5.0	0.0	2.1333	79119
8	I have developed more effective academic writing skills in English.	41.7	41.7	16.7	0.0	0.0	1.7500	.72778
9	My ability to use discipline-specific vocabulary in English has improved.	21.7	53.3	25.0	0.0	0.0	2.0333	.68807
10	Peer questions constructively challenged my assumptions.	30.0	43.3	20.0	6.7	0.0	2.0333	.88234
11	Discussions with peers inspired critical thinking about my research.	15.0	28.3	40.0	13.3	3.3	2.6167	1.00998
12	Collaboration helped me understand my strengths and weaknesses in English.	13.3	58.3	20.0	6.7	1.7	2.2500	.83615
13	I feel more capable of reading and analyzing academic texts in English.	11.7	28.3	40.0	13.3	6.7	2.7500	1.05163
14	I am now better at managing time and coordinating tasks in a research team.	0.0	8.3	20.0	55.0	16.7	3.8000	.81926
15	I feel more comfortable taking leadership roles in collaborative projects.	5.0	15.0	28.3	31.7	20.0	3.4667	1.12697

Research findings highlight that respondents agreed that interdisciplinary collaboration in the EAP course positively affected their learning outcomes, assessments strongly agree and agree are domineering.

For example, almost 90% of students strongly agreed or agreed that interdisciplinary collaboration helped them discuss research ideas more effectively in English (43.3% strongly agree, 45.0% agree), which resulted in the lowest mean score (1.68) and a standard deviation of 0.68. Also, most of the students either strongly agreed or agreed that interdisciplinary collaboration made problem-solving easier (51.7% strongly agree, 25.0% agree), which resulted in a low mean score of 1.73 and a standard deviation of 0.86. Over 85% of students strongly agreed or agreed that collaborating with peers boosted their English oral presentation skills (40.0% strongly agree, 46.7% agree), with a mean of 1.73 and a standard deviation of 0.69. Almost 85 % of respondents strongly agreed or agreed that they developed stronger academic writing skills in English (41.7% strongly agree, 41.7% agreed), which led to a low mean score (1.75) and a standard deviation of 0.72. Also, most students acknowledged improved confidence in collaborating with individuals from diverse disciplines (28.3% strongly agree, 38.3% agree), with a mean of 2.05 and a standard deviation of 0.79.

However, some statements showed less agreement. For example, responding to the statement 'I am now better at managing time and coordinating tasks in a research team' only 8.3% agreed, while over 70% either disagreed or strongly disagreed, which resulted in the highest mean of 3.8 and standard deviation of 0.82. Also, responses to the statement 'I feel more comfortable taking leadership roles in collaborative projects' showed less consensus: 5% strongly agreed, 15% agreed, and 51.7% disagreed or strongly disagreed. The mean for this statement was 3.47 with a standard deviation of 1.13, which shows that there were different opinions.

Conclusions

1. Interdisciplinary collaboration in the EAP course plays a crucial role in developing PhD students' academic English language skills and preparing them for complex research challenges.
2. Students can approach complex problems with a wider perspective when they participate in interdisciplinary discussions, exchange alternative viewpoints, present research proposals, and collaborate on case studies. Consequently, their research quality is enhanced and their ability to communicate effectively in English in an academic environment is promoted.
3. The benefits of interdisciplinary collaboration in EAP were identified in the study, they include: broadening perspectives and exploring interdisciplinary connections, facilitating creativity and innovative solutions, receiving peer feedback for improvement, improving communication skills, and enhancing presentation skills. However, there were also some challenges such as uneven contributions, stress and anxiety, language barriers, time and effort, and difficulties in finding common ground.
4. Research findings highlight that interdisciplinary collaboration in the EAP course positively affected students' learning outcomes. It helped them discuss research ideas more effectively in English, enhanced problem-solving, boosted academic English oral and writing skills, and increased confidence in working with peers from different disciplines, which is crucial for conducting research in interdisciplinary contexts. However, the limited impact on time management and taking leadership roles in interdisciplinary collaborative research show areas for further EAP curriculum improvement.

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ENABLING CIRCULAR ECONOMY THROUGH INDUSTRIAL SYMBIOSIS PLATFORMS: A QUINTUPLE HELIX AND EDUCATIONAL PERSPECTIVE

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Abstract
Current economic development is experiencing a significant transformation in the European Union. For the last decade, it has become explicitly clear that the linear business model is no longer valid, as it leads to such factors as overconsumption, overproduction, natural resource scarcity, and extensive waste generation. The circular economy is seen as one of the practical solutions, offering a range of business models that can overcome these issues. This research examines the transformative potential of Industrial Symbiosis in the transition to a Circular Economy by applying the Quintuple Helix approach. The research aims to identify different tools and enablers for Industrial Symbiosis adoption, emphasising the role of digital platforms and educational initiatives that promote resource sharing and cross-sectoral collaboration. The methods used within this research are evaluating secondary data, including policy document analysis and small and medium company surveys. The study enhances stakeholder awareness and skills in implementing Industrial Symbiosis principles by assessing the educational gaps and a range of digital tools that different Stakeholders can apply in various manners, thus still fostering Industrial Symbiosis. Research findings highlight the importance of stakeholder education and technology-driven solutions in overcoming Industrial Symbiosis implementation challenges. Interdisciplinary learning promoting and integrating sustainability and circular economy aspects in study curricula can result in more qualified employees possessing the ability to see the big picture and comprehend the benefits of cross-sectoral cooperation and resource efficiency on local, regional, and national levels.
Keywords: circular economy, industrial symbiosis, digitalisation.

Introduction

It is becoming more and more evident that Circular Economy business models will have a long-term impact on the present economic model and that the countries will have to adopt new ways of thinking and management, in particular when tackling resource efficiency and recovering the value of by-products and materials before becoming waste (Yazan & Fraccascia 2019; Ghisellini et al., 2016; EC, 2014). The researcher considers Industrial Symbiosis a significant mind shift and facilitator for such a transition (Kiesnere et al., 2024). It requires certain preconditions to be met, but for such a geographically small country as Latvia, this could become a country-wide Project or a set of Sandboxes across the country. Social, economic, and environmental modifications of current legislation, business practices, mindsets, and infrastructure might be required to implement Industrial Symbiosis in real-time. Considering current trends within the European Green Deal and the latest Clean Industrial Deal, setting targets such as an increase of circular material use rate from 11.8% in 2025 to 24% by 2030, Industrial Symbiosis may be an efficient way for the national economies to move forward. Therefore, Industrial Symbiosis may be an efficient pathway for national economies, including Latvia, to advance toward a more circular and resource-efficient economy. This research aims to explore and design effective mechanisms for enabling Industrial Symbiosis in Latvia, focusing on digital platforms and educational tools that promote cross-sectoral collaboration, resource efficiency, and sustainable development. The author identifies the following main objectives of the research:

- To identify key enablers and barriers to Industrial Symbiosis adoption in Latvia.
- To evaluate the role of digital technologies and educational initiatives in facilitating Industrial Symbiosis.
- To analyse case studies and existing Industrial Symbiosis platforms to identify best practices.
- To develop a conceptual framework integrating Industrial Symbiosis within Latvia's national circular economy agenda.

Present research has identified three main research questions:

1. What tools and practices are most effective for enabling Industrial Symbiosis in the context of Latvia's bioeconomy?
2. How can digitalisation and education support cross-sectoral engagement in Industrial Symbiosis?
3. What are the practical steps and preconditions needed to scale up Industrial Symbiosis across Latvia?

Industrial Symbiosis concept

Industrial symbiosis is an innovative concept that promotes resource sharing and waste exchange among industries, leading to sustainable and efficient operations, thus contributing to the Waste Framework Directive by focusing on the best possible waste treatment option – waste prevention. This research is relevant and novel because it addresses the growing need for more sustainable practices in the manufacturing sector and the necessity to optimise resource consumption by producing more with fewer virgin materials. Furthermore, Industrial Symbiosis contributes to the circular economy by promoting the reuse and optimisation of resources, reducing waste generation and greenhouse gas emissions. The research on Industrial Symbiosis is crucial in understanding and promoting the transition towards a more sustainable and

integrated industrial system. The latest research discusses the surge of Industrial Symbiosis development in Europe and highlights its importance in fostering circular and sustainable practices in the manufacturing sector and beyond (Uvarova et al., 2020; Jiao & Boons, 2021). The research on Industrial Symbiosis is topical as it provides an updated overview of the activity in Europe, mapping key networks and studying prevailing typologies, size, geographical distribution, and resources traded. It also identifies obstacles and challenges facing Industrial Symbiosis development in Europe, such as weak economic incentives, geographical variations in incentives and drivers, and legislative complexities that hinder cross-border transport (Lawal et al., 2021). The research on Industrial Symbiosis provides valuable insights into the potential of this approach to contribute to the transition to a Circular Economy. It is crucial in understanding and promoting the transition towards a more sustainable and integrated industrial system. In the global arena, it is also important to seek solutions to foster Industrial Symbiosis and avoid barriers to its implementation. With this respect, the researcher also considers a 'sandbox approach' to be a very beneficial tool for the stakeholders to be on the same page and avoid potential administrative burdens and potential fines from the regulatory authority. The sandbox approach, often utilised in business and technology contexts, involves creating a safe and controlled environment for testing new ideas, products, or services before full-scale implementation (Johnson et al., 2008; Spitsin et al., 2024). It provides organisations with a structured framework to experiment with innovative solutions and assess their feasibility, functionality, and potential impact without risking disruptions to existing operations or stakeholders (Islam, 2024).

When assessing Latvia's case, specific examples of industrial symmetry may be found, but they are pretty small-scale and mainly limited to resource exchange between just two companies. However, the current assessment of statistical data, particularly Latvian ratios in material consumption and resource efficiency, shows the urgent necessity for improvement. Latvia's resource efficiency was about 0.93 Eur/per capita in 2020. In contrast, the EU average was 2.19 Eur/per capita, and according to the latest data, the figures have reached 0.94 Eur/kg and 2.7 Eur/kg, respectively (CSP, 2024; Eurostat, 2024). At the same time, material consumption reaches approx. 16t/capita, whereas the EU average is 14 t/capita. The 8th Environment Action Programme aims to significantly reduce the EU's material footprint, meaning the amount of raw material extracted to produce goods and services. The per capita material footprint remained stable from 2010 to 2022 and dropped by 4.5% in 2023. Raw material extraction was 14.1 tonnes per capita in 2023, which is considered unsustainable and above the global average (EEA, 2024). This leads to the conclusion that Latvia uses many primary resources ineffectively. The researcher sees that Industrial Symbiosis may be a tool to improve the aforementioned ratios, implement the Circular Economy business model into practice, and boost Latvian companies' competitiveness in the EU and Global market.

Table 1

Assessment of a sample of physical and digital Industrial Symbiosis Cases

Industrial Symbiosis Name	***Type of Symbiosis***	***Country of Origin***	***Years in Operation***	***Key Performance Indicators (KPIs)***	***Additional Information***
Kalundborg Eco-Industrial Park	Physical resource exchange (water, energy, materials)	Denmark	Since 1970s	Over 30 symbiotic exchanges; significant reductions in CO_2 emissions; increased resource efficiency.	One of the earliest examples of industrial symbiosis, with long-standing partnerships between companies.
Kemi-Tornio Industrial Symbiosis	Physical resource exchange (materials, energy)	Finland	Since early 2000s	Involves over 700 companies; over 5,000 resources registered; over 2,500 synergy opportunities identified.	Developed to increase energy and resource efficiency in the region. Activities include joint use of utilities, collective waste management, combined transport, and shared facilities.
Finnish Industrial Symbiosis System (FISS)	Facilitated resource exchange and co-development	Finland	Since 2013	Over 30 workshops conducted in 14 regions; over 700 companies involved; over 5,000 resources registered; over 2,500 synergy opportunities identified.	FISS is based on active facilitation of symbioses and co-development. It brings together regional actors in a network to promote new business opportunities, re-use of waste, and reduction in the use of natural resources.

Industrial Symbiosis Name	***Type of Symbiosis***	***Country of Origin***	***Years in Operation***	***Key Performance Indicators (KPIs)***	***Additional Information***
Śmiłowo Eco-Industrial Park	Physical resource exchange (materials, energy)	Poland	Since 1982	Utilizes 300,000 tons of meat waste/year; produces 110,000 tons of meat and bone meal biofuel; uses 120,000 tons of pig manure as fertilizers; produces 460,000 GJ of bioenergy; eliminates 92,000 tons of CO_2 emissions.	The park covers the entire lifecycle of products, from plant cultivation to animal feed preparation, livestock breeding, meat processing, and waste utilization for biofuel and fertilizers.
Sfridoo Marketplace®	Digital marketplace for secondary resources	Italy	Since 2017	Thousands of material transactions; numerous companies participating in waste repurposing.	A SaaS platform for listing, buying, and selling industrial by-products.
ENEA Industrial Symbiosis Platform	Digital matchmaking for industrial waste utilisation	Italy	Since 2011	Connected 250 companies; facilitated over 2,600 resource exchanges.	Conducts resource audits and connects companies for sustainable waste utilisation.
Life M3P	An online matchmaking platform for industrial waste	European Union (Italy, Belgium, North Macedonia, Spain)	2016–2019	Optimised resource use in manufacturing; reduced landfill waste.	Focused on lowering virgin raw material consumption through industrial waste exchange.
SYNERGie® Platform	Digital industrial symbiosis tool	International	Since 2005	Over 100,000 resources listed; connected 34,000+ organizations across 23 countries.	Developed by International Synergies Limited, it is used globally for industrial matchmaking.

Materials and Methods

The present research focuses on secondary data analysis and monographic research to identify efficient solutions for Industrial Symbiosis in the digital era. In addition, the study covers a preliminary assessment of a survey disseminated in five countries among businesses related to Industrial Symbiosis. The quintuple helix framework allows researchers to look at the research topic from different angles and identify the most effective solutions that further need to be disseminated in the educational process. As the author is concerned, taking into consideration the global shift for businesses towards circular economy business models as well as a sustainable business practice in the long run, the topic of Industrial Symbiosis as well as digitalisation aspects must be integrated as cross-sectoral knowledge base not only for specific study programs but on a broader scale. Table 1 summarises sampled industrial symbiosis cases in both physical and digital marketplaces to broaden general awareness of types of symbiotic cooperations.

Results and Discussion

Incorporating digital technologies into Industrial Symbiosis frameworks can revolutionise cross-sectoral cooperations by improving data exchange, process optimisation, and overall network efficiency (Su et al., 2023). Digital technologies enhance Industrial Symbiosis by developing specific match-making solutions, i.e. identifying symbiotic opportunities (Makropoulos et al., 2024), as well as allowing for real-time information exchange (Akrivou et al., 2022) and supporting companies through different digital platforms (Cecelja et al., 2015). Industrial Symbiosis also allows information and communication Technology to step in and combine with the Internet of Things to create more resource-efficient production and management systems (Grant et al., 2010). During the desk research, using secondary data and monographic research method, a range of digital technologies have been identified as the ones that can significantly impact Industrial Symbiosis digitalisation:

Digital Platforms and Information and Communication Technology (ICT) Systems

Digital platforms and ICT systems can become centralised hubs for data exchange among companies and industries. These platforms offer real-time information exchange regarding available resources and arising waste streams and highlight potential synergies, enhancing collaboration and decision-making processes. One example worth mentioning here is the CORALIS project, which stresses the importance of standardised sharing protocols and common ICT platforms to improve company mutual trust, process efficiency, and innovation implementation within Industrial Symbiosis networks (Krom et al., 2022; Riesner et al., 2025).

Blockchain Technology

Blockchain technology is another considerably innovative solution offering a decentralised and secure method for saving transactions and tracking resources managed within Industrial Symbiosis networks. It is also being seen as enabling the technology of Industry 4.0 to disseminate industrial symbiosis practices (Ciano et al., 2025). Blockchain can enhance transparency, traceability, and mutual trust among participating companies (which is especially important if the companies have not cooperated in the past and come from different industry sectors, regions, or even countries) by providing bulletproof records of resource exchanges. This technology allows for overcoming challenges linked to data confidentiality and integrity, which often become a cornerstone of why many companies are very reserved in engaging in Industrial Symbiosis (Parikshit et al., 2023; Aquilani et al., 2020).

Digital Twins

Digital twins are virtual representations of physical assets, processes, or systems that enable real-time data adjustment, monitoring, and simulation. In the framework of industrial symbiosis, digital twins can be applied to model a company's or an industry's resource flows, forecast outcomes of potential synergies, and optimise the company's operations. This tool allows for the development of the Sandbox approach by securing a controlled environment and possibilities to ensure real-time monitoring (Bandara & Buics, 2024; Mammun et al., 2021). The most common ways to apply digital twins are:

- Urban Planning: to simulate traffic, energy consumption, and infrastructure development, as well as city expansion planning and efficient existing resource management.
- Healthcare: to apply personalised treatment planning and predictive diagnostics.
- Manufacturing: to monitor equipment operation, forecast and divert failures, and optimise operations, thus reducing standstill time and operational expenditures.
- Retail: to optimise store layouts and enhance customer experiences.

Internet of Things (IoT) and Sensors

Diverse IoT devices and sensors allow for real-time data collection on resource consumption, waste generation, and identification of specific environmental conditions. This data can be further processed to monitor internal and external processes, detect inefficiencies in the latter, and identify opportunities for improvement as well as for symbiotic exchanges. The data flow from IoT devices, which is being performed in real-time, supports dynamic and proactive decision-making and enhances the responsiveness of Industrial Symbiosis networks (Mallawaarachchi & Jayakodi, 2023).

Data Analytics and Artificial Intelligence (AI)

Sophisticated data analytics and the application of specific AI algorithms can process large datasets to identify patterns, predict trends, and, as a result, optimise resource management strategies. In the Industrial Symbiosis context, efficient application of these technologies can identify potential synergies, forecast the benefits of cross-sectoral company collaborations, and support strategic planning on the company, regional, or even national levels. The integration of AI into the Industrial Symbiosis daily routine can lead to more efficient and sustainable cooperation networks that would be guided by data-driven decisions as well as the identification and implementation of symbiotic relationships (Hamidur, 2022; Chatzidimitriou et al., 2021). Table 2 provides the results of a comparative analysis of the existing digital technologies in Industrial Symbiosis that have been assessed above.

Table 2

Benefits and Drawbacks of Digital Technologies in Industrial Symbiosis

Digital Technology	***Benefits***	***Drawbacks***
Digital Platforms and ICT Systems	+ Enhance communication and data sharing among participants + Facilitate the identification of symbiotic opportunities + Improve coordination and efficiency	− Standardisation and interoperability required − Potential resistance to technology adoption − Dependence on reliable digital infrastructure
Blockchain Technology	+ Ensure data security and transparency + Build trust among participants + Provide immutable records of transactions	− High energy consumption − Complexity in implementation − Scalability concerns

Digital Technology	***Benefits***	***Drawbacks***
Digital Twins	+ Enable real-time monitoring and simulation + Optimize resource flows and processes + Predict outcomes of potential synergies	– High initial setup costs – Continuous data input required – Complexity in creating accurate models
IoT and Sensors	+ Provide real-time data collection + Monitor environmental conditions + Detect inefficiencies promptly	– Data privacy and security concerns – High costs of deployment and maintenance – Potential data overload without proper analytics
Data Analytics and AI	+ Identify patterns and predict trends + Optimize decision-making processes + Enhance strategic planning	– Large datasets for accuracy required – Potential biases in algorithms – Skilled personnel to interpret results needed

When applying the Quintuple helix approach to the results of this research, one can identify the digital tools that each of the Stakeholders can apply and identify overlaps that can lead to applying one or another technology. Based on the literature research on the tools used by different stakeholders, the author has developed Figure 1, which depicts the correlation of the digital tools with the Quintuple Helix stakeholders, which will be further approbated during the follow-up research.

Figure 1

Digital tools application by Quintuple Helix Stakeholders

Digital Technology	Government	Industry	Academia	Civil Society	Environment
Digital Platforms and ICT Systems	Policy-making, regulation, public data platforms	Supply chain management, resource exchange platforms	Research collaboration, data sharing	Community engagement, transparency	Environmental monitoring, sustainability reporting
Blockchain Technology	Secure transactions, policy enforcement	Supply chain transparency, smart contracts	Research on secure data exchange	Consumer trust, fair trade verification	Tracking resource flows, reducing waste
Digital Twins	Urban planning, infrastructure simulation	Production optimization, waste reduction	Research on predictive analytics	Public engagement in city planning	Ecosystem modeling, climate impact assessment
IoT and Sensors	Smart cities, regulatory compliance	Process automation, real-time monitoring	Experimental testing, research data collection	Citizen science, real-time awareness	Pollution tracking, biodiversity monitoring
Data Analytics and AI	Policy analysis, forecasting	Market predictions, efficiency optimization	Machine learning research, knowledge discovery	Public sentiment analysis, behavioral insights	Climate modeling, predictive sustainability metrics

In addition, the author has assessed the results of a survey on Industrial Symbiosis among small and medium companies in five different countries – Latvia, Norway, Slovenia, Poland, and Italy. The number of respondents in the interim stage, as the survey period is still in process, is 72. The author would like to highlight three main aspects that the survey has revealed. First, regarding overall awareness of Industrial Symbiosis, it can be noted that 43% of respondents had not heard of the concept of Industrial Symbiosis before the survey; 38% selected the 'somewhat familiar' option, and only 19% stated that

they are very familiar with the concept.

Another aspect that arose from the survey is the knowledge gaps identified by the companies:

- 56% - Understanding industrial symbiosis and circular economy basics;
- 56% - Identifying resource-sharing opportunities;
- 50% - Benefits of IS/CE for cost savings and business growth;
- 47% - Digital tools that support IS (e.g., tracking waste, finding partners);
- 41% - Complying with environmental regulations.

This result reveals an impressive knowledge gap and a call to action for the Higher Education Institutions and trainers. Even though the surveyed companies stated a lack of general knowledge on the topic in the first place, the assessment of these gaps proves that the companies are ready and would be interested in knowledge-building as it may result in economic efficiency, value creation, and cost optimisation for OpEx. This led to the necessity to offer market-specific stand-alone on-demand courses on circular economy and Industrial Symbiosis. This also signals that this knowledge may be lacking in the overall education system. Taking into consideration the latest developments in terms of sustainability, circular economy, European Green Deal, etc., it is becoming more and more important to revise the study program curricula and implement the latest trends on the aforementioned topics not only in specific study programs, but horizontally into all study programs to broaden the general society knowledge on these topics, so it is further transferred and applied in the business sector.

Conclusions

The present research explored how digitalisation and education can be key enablers for industrial symbiosis implementation in Latvia's transition toward a circular economy. By applying the Quintuple Helix model and analysing secondary data alongside preliminary survey insights from SMEs across five countries, several important conclusions emerged:

1. Digital technologies - including platforms, blockchain, IoT, digital twins, and AI - demonstrate strong potential to facilitate resource-sharing, enhance transparency, and optimise symbiotic cooperation across sectors. However, effective implementation depends on overcoming interoperability, data security, and digital infrastructure challenges.
2. The Quintuple Helix model proved helpful in identifying how different stakeholders - academia, industry, government, civil society, and the environment - can apply or benefit from IS-related digital tools. This intersection strengthens policy integration, innovation uptake, and cross-sectoral learning.
3. The survey results confirmed that many SMEs lack awareness and practical knowledge about Industrial Symbiosis, particularly regarding digital tools, environmental compliance, and circular business opportunities. This underscores the urgent need for targeted educational initiatives and training.
4. Integrating Industrial Symbiosis into higher education and vocational programs is essential to fill knowledge gaps, foster sustainable mindsets, and create a future workforce supporting a circular and digitally enabled economy.

Future research will focus on testing digital tools in educational 'sandboxes' and developing modular training materials to support Industrial Symbiosis implementation in practice and foster its popularity within Latvian policy planning, municipalities, society, and business sectors.

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A COMPARATIVE STUDY OF THE IMPORTANCE OF MATHEMATICS AND CAREER NEEDS IN ENGINEERING STUDIES

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Abstract
Mathematics is a fundamental skill in many fields of engineering and technology. Mastering it provides the necessary analytical and problem-solving skills that are essential for successful performance in engineering, data analysis, or other technical professions. Mathematical skills are widely used in building models, performing calculations, and analysing data, which are important for making sound technical and business decisions. Based on expectancy-value theory, which examines how the practical importance of a task influences an individual's motivation to learn and achieve, the study focuses on how students evaluate the importance of mathematics in relation to their future career needs, as the usefulness of mathematics in a profession can influence students' motivation to study the subject more deeply and more fully. A clear understanding of the practical applications of mathematics enables students to see the direct relevance of their studies to future career opportunities, thereby increasing their motivation and engagement in the learning process. The study was conducted at four universities in two countries - Latvia and Estonia. The results of the study indicate a moderate positive correlation between the practical application of mathematics knowledge in engineering and students' perceptions of its role in cognitive development, which is essential for engineering professionals. The integration of mathematics into engineering programs significantly affects students' perceptions of its usefulness: the more actively mathematics is used in the engineering curriculum, the more students see its value in promoting engineering skills.
Keywords: expectancy value theory, mathematics, motivation.

Introduction

Continuous reforms and changes are taking place in the education system in Latvia, Estonia and the whole of Europe. The structure, pace of implementation and role of these reforms in the growth of young people are the subject of constant debate and controversy. One of the most widely discussed subject blocks is the exact sciences, their necessity, quality and intensity of teaching (from various aspects) (Kopeika & Zvirgzdiņa, 2020). This discussion occurs despite the widely accepted fact that a good knowledge of mathematics and the ability to apply it comprehensively is a fundamental element in the professional work and growth of specialists in various fields, especially in engineering. For example, mathematics is fundamental in engineering, providing tools and methods for modelling and solving technical problems. It allows for the development of precise models for system dynamics, for example, in automotive and electrical engineering projects, using differential equations, statistics, and linear algebra. Mathematics also provides methods for encoding physical laws, which are crucial when analysing the behaviour of materials and energy in the context of thermodynamics and quantum physics. Additionally, systems theory uses mathematics to describe and analyse system behaviour, employing stability and control theories necessary for designing safe and efficient control systems. These methods are vitally important, ensuring system safety and efficiency under changing conditions (Kreyszig, 2011; Niss, 2017).

Engineers must use mathematical models to represent real-world systems. Mathematics helps engineers analyse these models, predict outcomes and make informed decisions (Tunesk, 2022; Saranya, 2023).

The proficiency of engineers in utilizing mathematical tools is fundamentally linked to their professional efficacy and success. This proficiency underpins their capability to conduct precise calculations and implement technical simulations that are critical in designing, testing, and optimizing various engineering systems (Johnson, 2017; Smith & Brown, 2019).

Unfortunately, it must be acknowledged that the awareness of this for a large part of school youth is absent or only partial. Researchers from Latvia and Estonia, in order to find out the current situation more accurately, assess, understand whether and how significant the differences are between the attitudes of young people from both countries, as well as whether this attitude has changed during their studies, when conducting a student survey, were interested not only in skills and assessments, but also in the emotional side of the situation.

Materials and Methods

The research methodology is based on the expectancy value theory, developed by Jacquelynne Eccles and her colleagues. Expectancy-value theory is a psychological model that explains motivation and behaviour as a function of an individual's expectations for success and the value they place on achieving a goal.

This theory is based on the belief that individuals' choices, persistence, and performance can be explained by their beliefs about how well they will perform an action and the extent to which they value that action (Eccles et al., 1983; Wigfield, 1994). Eccles et al. (1983) developed an expected value model of performance and choice and studied it in the field of mathematics achievement, assuming that expectations and values directly influence achievement choices, as well as performance, effort, and persistence. This theory is widely applied in educational psychology to understand and enhance student motivation by addressing their expectations for success and the values they associate with educational tasks. Expectancy-value theory highlights the dual importance of competency-related beliefs and values in explaining student motivation. Theory argues that, for example, the decision to major in engineering with the goal of becoming a civil engineer is determined by a variety of factors (Eccles et al., 1983).

The expectancy-value theory is a pivotal framework in understanding how students assess the significance of educational content in relation to their future career needs. It explores two primary components: expectations of success and the value of tasks (Wigfield, & Eccles, 2000; Eccles & Wigfield, 2002):

• The theory considers how students' confidence in their ability to successfully complete a mathematics course boosts their willingness to engage and persist in the learning process. When students believe they have the necessary skills and knowledge to handle mathematical challenges, their motivation to learn increases;

• This aspect encompasses utilitarian value, intrinsic value, relational value, and avoidance of negative consequences. Specifically, the utilitarian value, which looks at how mathematics can aid in achieving career goals, is a crucial motivational driver. For example, when students see a direct link between mathematical skills and the requirements of their chosen profession, such as engineering or technology, their interest and determination to acquire these skills increase.

Using this theory can enhance educational practices by fostering student engagement and motivation in the learning process, helping them achieve their career and personal growth goals. Utilizing the framework of expectancy-value theory, this research delves into how students perceive the relevance of mathematics for their prospective professional paths. The perceived practicality of mathematics in various careers significantly shapes students' enthusiasm and commitment to mastering the subject. A clear understanding of the practical applications of mathematics enables students to see the direct relevance of their studies to future career opportunities, which in turn enhances their motivation and participation in the educational process.

The empirical part of the study includes a survey of engineering students at the authors' universities. The questionnaire was created based on the theoretical considerations mentioned above, as well as considering the authors' observations. The invitation to complete the questionnaire was sent electronically through the universities e-learning system. Four universities took part in this study: Riga Technical University (RTU), Estonian University of Life Sciences (EMU), Latvia University of Life Sciences and Technologies (LBTU), TTK University of Applied Sciences (TTK UAS) and Estonian University of Life Sciences (EMU).

The study sample consisted of 283 engineering students: 174 from Estonia and 109 from Latvia. Data were collected in the spring semester of the 2024–2025 academic year.

Results and Discussion

When evaluating the preparation of young people for studies, initially it seems that the systems in both countries are similar - in secondary school one can study mathematics at 2 levels, i.e. Mathematics I, after which the final exam is taken (in Latvia, the so-called 'Optimal Level' exam), and Mathematics II, also ending with an exam (in Latvia the so-called 'Higher Level' exam). Without examining the curriculum' s specific content, the various elements appear to be largely equivalent. But in order for a young person to be able to apply for a competition for a budget place in engineering sciences at the university as the minimum condition is, at the end of high school, he was successful in mathematics (level Mathematics I is enough) and, by 2024, there was a requirement that he has passed the Centralized Exam, at least 20% (these conditions apply only to mathematics – the rest of the positions will not be discussed in this article), while in Estonia the conditions are stricter, so, if a young man has not studied Mathematics II, regardless of the results obtained in Mathematics I, he must take an entrance exam.

Starting from the 2025/26 school year, the complex entrance exam, which includes mathematics, physics and some tasks related to the chosen specialty, is also introduced at RTU in several of the most demanded programs, regardless of whether the young person has mastered mathematics at the first or second level in high school. Hopefully this practice will expand.

Estonia's education system is widely recognized for its strong digital infrastructure, high student performance, and innovative policies. The system comprises pre-primary, basic, secondary, vocational, and higher education (OECD, 2023a). Digital education is a major priority, with extensive online resources, e-learning platforms, and data-driven policy-making (OECD, 2023b). Higher education is internationally competitive, with a focus on globalization and attracting foreign students (Fedotov, 2024).

In Estonia, completing upper secondary (high school) education requires students to undertake a curriculum of at least 96 courses over three years, with each course consisting of 35 academic hours. In mathematics,

students can choose between two levels: narrow (8 courses) and extensive (14 courses). To graduate, they must pass three state examinations: Estonian language, mathematics, and a foreign language. The mathematics exam is available at both levels - narrow and extensive - allowing students to select the one that best aligns with their coursework and future academic goals. Estonian teachers have the flexibility to choose their teaching methods, with a strong emphasis on student participation and independent research. They are encouraged to incorporate tasks that develop critical thinking, including research projects requiring information retrieval from various sources, including foreign languages. Additionally, schools have autonomy in selecting educational literature, ensuring alignment with national standards, while the state provides financial support to acquire necessary learning materials.

Both Latvia and Estonia place a significant emphasis on mathematics as critical to engineering and technical fields, but Estonia's system appears to be more rigorous in ensuring depth of knowledge, possibly reflecting its broader educational goals of high student performance and international competitiveness. Students who have not taken Mathematics II must pass an entrance exam, irrespective of their performance in Mathematics I.

This requirement underscores Estonia's emphasis on a robust mathematical foundation. The educational system in Estonia is known for its strong digital infrastructure and a high level of student autonomy in learning, supported by innovative teaching methods that encourage critical thinking and independent research.

Considering the situation, the initial hypothesis is that applicants studying in Estonia value the role of mathematical knowledge both in engineering studies and in subsequent work, more highly since there are higher requirements when starting their studies at university.

To begin with, let's evaluate the answers to the question: Why do you think it is necessary to study Higher Mathematics at university? [A specialist with an understanding of mathematics is able to easily complete tasks that require logical thinking].

Since the 4th year students were an insignificant part of those surveyed, in terms of numbers, the results only from the answers of first, second- and third-year students were analyzed.

Evaluating the results shown in Tables 1-3, it is evident that the proportion of students who perceive mathematical skills and thinking as a tool for solving various problems - especially those requiring logical thinking - increases throughout their studies, (see Table 4). Notably, at two of the universities, this proportion reached up to 100% of the responses.

There is a logical explanation for this situation – already during their studies, young people, while doing term papers, taking engineering courses in their specialty and working on different jobs related to their specialty, are increasingly faced with the fact that mathematics is not only a work tool to be able to solve a problem. By learning new topics in mathematics, trying to see what problems they could be used to solve, how to do this more rationally and simply, a person develops logical thinking, the skills of evaluating several parallel scenarios and predicting further steps.

Table 1

Why do you think it is necessary to study Higher Mathematics at university? [A specialist with an understanding of mathematics is able to easily complete tasks that require logical thinking]. (Answers of 1st year students)

	RTU (%)	***LBTU (%)***	***EMU (%)***	***TTK (%)***
Completely agree	54	18	38	38
Agree	29	27	25	31
Partially agree	17	37	25	31
Disagree	0	18	12	0

Table 2

Why do you think it is necessary to study Higher Mathematics at university? [A specialist with an understanding of mathematics is able to easily complete tasks that require logical thinking]. (Answers from 2nd year students)

	RTU (%)	***LBTU (%)***	***EMU (%)***	***TTK (%)***
Completely agree	64	33	35	50
Agree	18	38	29	8
Partially agree	18	15	29	21
Disagree	0	14	7	21

Table 3

Why do you think it is necessary to study Higher Mathematics at university? [A specialist with an understanding of mathematics is able to easily complete tasks that require logical thinking]. (Answers from 3rd year students)

	RTU (%)	***LBTU (%)***	***EMU (%)***	***TTK (%)***
Completely agree	100	25	67	33
Agree	0	50	33	12
Partially agree	0	0	0	44
Disagree	0	25	0	11

It should be noted that the hypothesis that Estonian students will value these skills higher than Latvian representatives when preparing diligently for studies and taking entrance exams should be rejected.

Table 4
The proportion of students who completely agree or agree that a specialist with an understanding of mathematics can easily complete tasks that require logical thinking

	RTU (%)	***LBTU (%)***	***EMU (%)***	***TTK (%)***
1st course	87	45	73	69
3rd course	100	75	100	46

A significant majority of students agree that mathematics is essential for developing key skills such as creativity, logical thinking, and accuracy.
When looking at the issue, do employers value employees with good math skills. It must be admitted that the students` rating, although slightly, but is lower than the previous one. However, while further studying at the university an increasing the number of students recognize that employers value employees with good math skills (see Table 5-7).

Table 5
Why do you think it is necessary to study Higher Mathematics at university? [Employers highly value employees with good math skills] (Answers of 1st year students)

	RTU (%)	***LBTU (%)***	***EMU (%)***	***TTK (%)***
Completely agree	21	8	37	25
Agree	29	33	25	50
Partially agree	46	36	25	25
Disagree	4	23	13	0

Table 6
Why do you think it is necessary to study Higher Mathematics at university? [Employers highly value employees with good math skills] (Answers from 2nd year students)

	RTU (%)	***LBTU (%)***	***EMU (%)***	***TTK (%)***
Completely agree	37	19	36	42
Agree	45	24	43	22
Partially agree	9	52	21	29
Disagree	9	5	0	7

Based on the responses from students, there is a clear and strong consensus on the necessity of mathematics for future engineers.
Many students recognize that solving engineering problems creatively and successfully requires a solid foundation in mathematics (Table 8). For instance, around 44% of students at EMU and 27% of students at RTU strongly agree that mathematics is a crucial brain trainer for engineering tasks.

Table 7
Why do you think it is necessary to study Higher Mathematics at university? [Employers highly value employees with good math skills] (Answers from 3rd year students)

	RTU (%)	***LBTU (%)***	***EMU (%)***	***TTK (%)***
Completely agree	67	0	67	33
Agree	33	100	33	22
Partially agree	0	0	0	12
Disagree	0	0	0	33

Table 8
Why do you think it is necessary to study Higher Mathematics at university? [It is a brain trainer to be able to successfully and creatively solve various engineering problems]

	RTU (%)	***LBTU (%)***	***EMU (%)***	***TTK (%)***
Completely agree	59	25	62	38
Agree	13	35	27	36
Partially agree	24	30	11	18
Disagree	4	10	0	8

Understanding various relationships that future engineers need to comprehend is also widely supported. For example, 59 % of students at LBTU and 25% of students at RTU strongly agree that mastering mathematical concepts is essential to understanding engineering relationships. A number of topics taught in specialization courses are based on mathematical regularities. Many students across the institutions acknowledge this. EMU and RTU students, for instance, show a high level of agreement on this (around 83% at EMU and 91% at RTU) (Table 9).

Table 9
Why do you think it is necessary to study Higher Mathematics at university? [A number of topics taught in the specialization courses are based on mathematical regularities]

	RTU (%)	***LBTU (%)***	***EMU (%)***	***TTK (%)***
Completely agree	43	26	59	30
Agree	48	32	24	32
Partially agree	7	28	14	28
Disagree	2	14	3	6

Learning mathematics promotes the development of creativity and accuracy in future specialists (Table 10), with EMU showing around 71% of students who agree strongly, and RTU showing 95% support for this view.

Table 10

Why do you think it is necessary to study Higher Mathematics at university? [Learning mathematics promotes the development of creativity and accuracy in future specialists]

	RTU (%)	***LBTU (%)***	***EMU (%)***	***TTK (%)***
Completely agree	43	19	46	36
Agree	52	33	25	28
Partially agree	4	30	22	24
Disagree	0	17	7	12

Students agree that specialists with a strong understanding of mathematics are able to easily complete tasks requiring logical thinking. RTU shows the highest percentage of strong agreement at 46%, followed by TTK with 21% of students agreeing that a mathematical background is vital for logical thinking.

A large part of the students' answers based on the previous work experience of the young people, because despite the fact that the young people have only recently graduated from high school, the majority are already participating in the labor market and working in paid employment in parallel with their studies.

There is a widespread acknowledgment that employers value employees with strong math skills. LBTU students report 28% agreement, and RTU sees 46% of students believing that employers highly appreciate mathematical skills.

This summary reinforces the strong belief among students that mathematics is a necessary and valuable tool for both academic and professional success in engineering. The data from the tables supports this notion, showing that students across all institutions agree on the importance of mathematics in developing essential skills for the future.

Based on Expectancy-value theory, when students see a direct link between mathematical skills and the requirements of their chosen profession, their interest and determination to acquire these skills increase.

A key observation from the research results is that institutions where students frequently apply mathematical concepts in engineering contexts tend to have higher agreement that mathematics acts as a cognitive enhancer. RTU and TTK, where 60-65% of students report frequent use of mathematics, also have the highest percentage of students who believe that mathematics enhances their problem-solving and creative thinking abilities (80-85%). Conversely, at EMU, where only 52% of students report frequent use of mathematics, a relatively higher proportion (22%) remain neutral or disagree with the assertion that mathematics functions as a brain trainer.

These results (Table 11) suggest that as the frequency of mathematics use in practice increases, perceptions of its usefulness for cognitive development increase. This aligns with prior research indicating that actively engaging with mathematical concepts strengthens analytical reasoning and problem-solving abilities, essential for engineering professionals.

The findings indicate that the integration of mathematics in engineering curricula significantly influences students' perception of its usefulness. Programs that explicitly apply mathematics in engineering contexts may reinforce students' understanding of its cognitive benefits. This raises an important pedagogical consideration: if mathematics is not actively utilized in an engineering curriculum, students may be less likely to recognize its value in fostering critical thinking skills.

Table 11

Mathematics usage and perception across institutions

Institution	***Frequent Use of Mathematics in Engineering (%)***	***Occasional Use of Mathematics (%)***	***Rarely/Not Used (%)***	***Agree Mathematics is a Brain Trainer (%)***	***Disagree/Neutral on Brain Trainer (%)***
RTU	65	25	10	80	20
LBTU	58	30	12	85	15
EMU	52	35	13	78	22
TTK	60	28	12	82	18

Conclusions

1. The results show that the students believe that mathematics is a necessary and valuable tool for both academic and professional success in engineering. demonstrating that students from all educational institutions agree on the importance of mathematics in developing essential skills for the future.
2. The institutions where students frequently apply

mathematical concepts in engineering contexts tend to have higher agreement that mathematics acts as a cognitive enhancer. This is confirmed by the results of the study, namely RTU and TTK, where 60-65% of students report frequent use of mathematics, also have the highest percentage of students who believe that mathematics enhances their problem-solving and creative thinking abilities (80-85%).

3. The proportion of students who admit that mathematical skills and thinking are a tool for solving various problems as easily as possible, in the solution of which logical thinking must be involved, only increases during their studies.

4. The findings indicate that active engagement with mathematical concepts enhances analytical thinking and problem-solving skills, which are crucial for engineers.

5. Expectancy beliefs are crucial to the expectancy–value theory seeing the perceived usefulness for future goals as critical for student's motivation.

6. Future research could further investigate the causal relationship between the extent of mathematics integration and cognitive skill development in engineering students.

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