CIRCULAR ECONOMY IMPLEMENTATION IN THE AGRICULTURAL SECTOR, EGGSHELLS APPLICATION

***Vjaceslavs Kocetkovs[1], *Andra Zvirbule[1], Vitalijs Radenkovs[1,2]**
[1]Latvia University of Life Sciences and Technologies, Latvia
[2]Institute of Horticulture, Latvia
*Corresponding author's email: info@kocetkovs.com, andra.zvirbule@lbtu.lv

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).

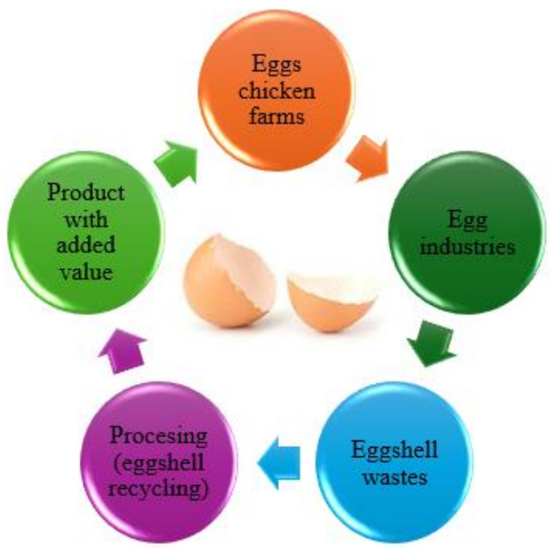
Germany: Investments in biogas facilities where poultry waste is converted into renewable energy. Germany has developed advanced systems for managing poultry by-products. Germany implements sustainable housing systems aligned with animal welfare standards, which support higher resource efficiency and 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 ʽpolluter 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).

Eggshells 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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