REVIEW OF TECHNOLOGICAL, ECONOMIC, AND WELFARE ASPECTS IN EGG PRODUCTION SYSTEMS

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Abstract

Egg production systems represent a complicated interaction between welfare concerns, financial limitations, and technical advancements. This review evaluates the effects of technical developments in housing, feeding, and monitoring systems on production and egg quality by synthesizing existing research in these areas. Economic factors are thoroughly assessed, including cost effectiveness, market trends, and consumer-driven premiums for organic and cage-free eggs. The review also looks at welfare criteria and how they affect system design, with a particular emphasis on the behavioral and physiological effects on laying hens. According to comparative study, alternative models provide better welfare results but come with hefty investment costs, while conventional systems continue to maintain higher economic efficiency. For the future of egg production, the study emphasizes the necessity of integrated approaches that incorporate ethical considerations, sustainable economic strategies, and technical advancements.

Key words: *Egg production systems, technological innovation, economic efficiency, animal welfare, sustainability*

INTRODUCTION

Egg production represents one of the most efficient livestock sectors in terms of protein conversion and market accessibility, contributing significantly to food security in both developed and emerging economies [1,2]. In recent years, the poultry industry has been pressured to align productivity goals with rising expectations for animal welfare, sustainability, and transparent production systems [3,4]. Conventional caged systems remain economically dominant due to their high stocking density and favorable feed conversion ratios [5], yet they face criticism for restricting natural behavioural needs such as perching, wing-flapping and dust-bathing [6].

Alternative housing models, including enriched cages, free-range, and organic systems, have been reported to improve welfare outcomes, with some studies documenting up to 30% lower stress biomarker levels compared to traditional cages [7,8]. However, these systems come with 20–30% increased production costs and require more advanced management practices to maintain profitability and animal health [9,10].

Beyond housing design, environmental and metabolic stress has become a central welfare concern. Laying hens exposed to constant heat stress of 37–38.5°C develop significant metabolic alterations in glycogenolysis pathways [11], indicating a shift in energy allocation towards homeostatic survival rather than production. Remarkably, the same study found that targeted probiotic-based technological nutritional interventions partially restored metabolic balance, suggesting that innovative feeding and sensor-supported monitoring strategies may function as welfare-enhancing technologies, particularly in climate-stressed production systems.

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In Europe, including Romania, the transition toward cage-free systems is accelerating under consumer and regulatory pressure [12,13], but adoption remains uneven due to financial constraints and lack of integrated technological support at farm level. These dynamics indicate the need for a systemic approach that evaluates housing technology, welfare physiology, and economic feasibility simultaneously, rather than as isolated categories.

Therefore, this review aims to: synthesize current evidence (mostly 2018–2025) on the technological, welfare, and economic performance of different egg production systems; identify key trade-offs between productivity, welfare improvement, and investment cost; and evaluate the potential of emerging technologies, including digital monitoring, precision nutrition, and climate adaptation strategies, to support a sustainable and welfare-centered evolution of the egg production sector in Romania and the European context.

MATERIAL AND METHOD

This review was conducted following a structured literature-based methodology adapted for agricultural system synthesis. Scientific databases including Scopus, Web of Science, Google Scholar, ScienceDirect, and CAB Abstracts were searched for peer-reviewed articles published between 2018 and 2025, using combinations of keywords such as “egg production systems”, “animal welfare”, “economic efficiency”, “precision poultry”, “cage-free”, “heat stress laying hens”, “technological innovation poultry”.

Official market and policy reports such as EggTrack (2022) and regional EU poultry economic assessments were also considered to complement scientific data.

Data were categorized under three analytic axes: technological innovations, economic performance indicators, and physiological/welfare outcomes. Comparative observations from Romanian and Eastern European context were extracted and treated as a subcategory to emphasize regional relevance.

RESULTS AND DISCUSSION

1.1. Enriched cage systems

Enriched cages are designed to provide laying hens with more space than conventional cages, along with environmental enrichments such as perches, nesting boxes, and dust-bathing areas. However, despite these improvements, enriched cages still impose significant limitations on the expression of natural behaviors. Studies have shown that hens in enriched cages exhibit higher levels of feather pecking and keel bone fractures compared to those in non-cage systems [14]. These issues arise due to the restricted space, which limits hens’ ability to engage in behaviors such as foraging and dust-bathing. Behavioral, physical, and physiological measures are essential for a comprehensive welfare evaluation, as enriched cages still restrict many behavioral expressions, leading to frustration and stress [15].

Similarly, the examined animal-based measures (ABMs), highlighted that enriched cages offer some improvements over conventional cages but still present challenges related to behavioral restriction and social stress [16]. In this study, hens housed in enriched cages were observed to express less natural behavior than those in free-range or organic systems, particularly when access to outdoor space is restricted. The study underscores the importance of continuous monitoring of welfare indicators such as keel bone condition, feather cover, and hock burns, all of which were found to be more prevalent in enriched cages compared to alternative housing systems.

While enriched cages show improvements in some welfare aspects, they still fail to meet the full welfare potential found in non-cage systems like free-range or organic systems, which allow for greater expression of natural behaviors [17].

Enriched cages remain one of the more cost-effective housing systems compared to alternative systems like free-range or organic systems. Banning enriched cage systems would lead to significant economic challenges in the Hungarian table egg sector, which could experience increased production costs due to the transition to aviary or barn systems [18]. The study assessed the economic impact of banning enriched cages and found that aviary systems and barn systems lead to much higher production costs, driven by larger space requirements, higher feed costs, and additional management.

While free-range and organic systems offer higher welfare standards, they come with substantial economic trade-offs [19]. Enriched cages, on the other hand, maintain a balance between welfare and economic feasibility. The EU laying hen sector faces a transition from conventional to alternative housing systems, where investment costs in enriched cages remain lower compared to aviary or free-range systems. This balance is crucial for producers who aim to meet consumer demand for higher welfare standards without significantly increasing production costs.

Although enriched cages offer higher economic efficiency, their long-term economic sustainability may be at risk due to regulatory pressures and market demand shifting towards cage-free and organic products [20]. Therefore, while enriched cages are a cost-efficient option in the short term, long-term profitability could depend on consumer preferences and regulatory developments favoring more ethical systems.

Technological advancements in enriched cage systems have been focused on monitoring hen behavior, health, and productivity. Poultry Farm Intelligence, an AI-based platform integrates multiple sensors to enhance welfare and productivity in poultry farming [21]. In enriched cage systems, the use of computer vision, RFID, and infrared thermography is enabling the early detection of health and welfare issues, such as hock burns, feather pecking, and lameness. These technologies allow for real-time monitoring of animal welfare and help farmers implement proactive management strategies.

The use of multimodal AI systems in enriched cages was explored and AI-driven systems provide valuable insights into hen health and behavior [22]. Their study highlights how AI technologies are being increasingly utilized in poultry farming to optimize feed conversion ratios (FCR) and welfare outcomes, ensuring more efficient production systems while minimizing animal stress. They argue that these systems can be adapted to monitor stress-related behaviors and adjust environmental parameters in real-time, significantly improving both welfare and economic productivity.

The integration of these technologies in enriched cage systems is crucial to bridge the gap between welfare improvement and production efficiency. By enabling real-time monitoring of behavioral and physiological indicators, these technologies help detect potential welfare issues early, reducing the need for invasive interventions and allowing for more targeted welfare management [23].

1.2. Free-Range Systems

Free-range systems allow laying hens to access outdoor areas, providing more space and a broader range of natural behaviors compared to enriched cages. Free-range systems enable hens to express a wider range of natural behaviors such as foraging, dust-bathing, and perching [24]. These behaviors are essential for the overall well-being of hens, and free-range systems are often considered to offer superior welfare outcomes compared to caged systems. The welfare benefits of free-range systems are heavily dependent on management practices and environmental conditions, such as range design, shelter, and weather management [25]. Poor management of these factors can lead to health issues, such as keel bone fractures, footpad dermatitis, and increased parasite exposure.

It was examined the potential of understory production systems to further enhance welfare in free-range laying hens [26]. They found that the addition of environmental enrichments such as vegetation and shelters can help reduce stress and improve comfort for hens in free-range systems, especially during adverse weather conditions. The study emphasized that proper management and environmental enrichment are key to maximizing the welfare potential of free-range systems, ensuring hens remain comfortable and healthy while engaging in natural behaviors.

A relevant Romanian study [27] focuses on welfare indicators in free-range systems in Romania. The study examined keel bone fractures and parasite load in several Romanian farms, concluding that free-range systems, while improving natural behavior, must be carefully managed to avoid health issues like injuries and infections. The study suggests that range design and regular veterinary care are crucial for ensuring hen welfare in these systems, particularly in more extensive farming models used in Romania.

The economic viability of free-range systems is often debated due to the higher production costs associated with these systems. It was explored the economic sustainability of aviary systems and was noted that free-range systems, similar to aviary systems, face higher production costs due to the larger space requirements, increased labor, and feed costs [28]. While free-range systems provide significant welfare advantages, they come with substantial operational costs that make them less competitive compared to caged systems. In particular, feed costs, which account for 70-75% of total costs, are notably higher in free-range systems because hens are less efficient in feed conversion due to outdoor activity and less intensive farming methods.

There were examined the perspectives of egg producers in Asia, highlighting the economic challenges and financial considerations of adopting cage-free systems, including free-range [29]. They noted that while there is consumer demand for cage-free eggs, the cost premium associated with free-range eggs can limit profit margins. The research emphasizes that the economic feasibility of free-range systems largely depends on market dynamics and consumer willingness to pay higher prices for ethically produced eggs.

Technological innovations are increasingly being adopted in free-range systems to enhance welfare and productivity. Two studies [22, 30] highlight the growing role of technology in optimizing the performance of free-range systems. The use of multimodal AI systems to improve welfare and productivity in laying hens was approached, as well [22]. The study highlights the application of AI-driven technologies to track and analyze hen behavior, health, and environmental conditions. These technologies help detect stress-related behaviors and health issues early, allowing farmers to make data-driven decisions to optimize welfare and reduce health-related costs.

A similar concept with the Poultry Farm Intelligence platform, which integrates multi-sensor AI technology for real-time monitoring of hen welfare was presented [30]. The system tracks various factors such as activity levels, range use, and health status, providing valuable insights for farm managers.

1.3. Organic Systems

Organic systems provide the highest welfare standards among the various housing types. Organic standards mandate outdoor access and lower stocking densities, offering substantial welfare potential, particularly in terms of behavioral expression and space [31]. These features allow laying hens to engage in natural behaviors such as foraging, dust-bathing, and perching, which are essential for their overall well-being. In fact, organic systems can support optimal welfare if managed correctly, with a significant improvement in physical and mental health compared to conventional caged systems.

Other authors [32] highlights some persistent risks associated with organic systems, including bone lesions, parasites, and predation. These risks arise from the outdoor access provided to hens, which exposes them to various environmental challenges, such as adverse weather conditions and predator attacks. It was also noted that, while organic systems offer high welfare potential, these benefits can only be fully realized with enhanced preventive management, which includes effective parasite control, range design, and shelter provisions to protect hens from the harsh environmental conditions that may arise.

These welfare issues were also discussed [33], noting that organic systems tend to reduce pesticide use, which is a major benefit for animal health. However, they also caution about the barriers to adoption, especially in areas where range design and farm management practices are not sufficiently advanced to handle the inherent challenges posed by outdoor production systems. The study highlights that, despite the health benefits associated with organic feed and practices, management complexity remains a significant hurdle for small and medium-scale producers.

In Romania, a study conducted on organic poultry farming in Transylvania found that organic farms with proper range management experienced better health outcomes for their hens, including lower levels of footpad dermatitis and injuries [27]. The study emphasized that natural behaviors could be more fully expressed when farms adopted suitable management systems for outdoor access. However, the study also indicated that pest control and weather-resistant housing were critical factors in minimizing health risks.

The economic challenges of organic systems are well-documented. There were assesses the economic implications of banning enriched cages in Hungary and discuss the significant investment costs associated with organic production systems [19]. The study shows that organic systems, while beneficial in terms of animal welfare, come with higher initial capital investments due to the need for larger land areas, specialized equipment, and certification costs. These factors contribute to the high unit costs of organic eggs, making them the costliest of all the production systems.

Other authors [19] further support this by showing that organic systems are the most expensive option in terms of both investment costs and operating costs. The authors note that while organic eggs command premium prices, the profitability of organic systems depends critically on securing consistent consumer demand and access to premium retail channels. The study also highlights that feed costs, which are typically higher in organic systems, significantly contribute to overall cost increases.

In Romania, it was found that local organic egg producers struggle with profitability due to limited access to high-demand markets and high production costs [34]. The study suggested that, in order to increase profitability, Romanian organic farms need to improve supply-chain efficiency and build stronger relationships with supermarkets and retailers that support organic products.

Organic farms have increasingly adopted advanced technologies to enhance welfare and productivity, while maintaining the standards of organic certification. It was discussed the use of multimodal AI systems to monitor and optimize welfare in organic systems [35]. These systems use multiple sensors to track behavioral and health data in real-time, allowing farm managers to detect stress-related behaviors, health issues, and environmental conditions. The study suggests that AI technologies can be a valuable tool in balancing the welfare of organic hens with the economic demands of efficiency.

Poultry Farm Intelligence, an AI-powered platform was also presented on organic systems [30] and it uses multi-sensor technology to monitor range use, feed conversion, and health status. This platform can be adapted for organic systems to help producers ensure optimal welfare conditions while managing biosecurity and heat mitigation in extensive outdoor systems. The integration of such technologies helps farms adapt to climatic challenges while maintaining the welfare standards required for organic certification.

In Romania, organic poultry farms are beginning to integrate similar technologies, such as temperature sensors and range-quality monitoring systems, to better manage their outdoor areas. These systems help ensure that organic farms can balance welfare with biosecurity and improve sustainability in line with organic farming principles. Romanian organic producers are starting to adopt automated systems that monitor microclimate conditions to reduce heat stress and improve overall productivity [36].

CONCLUSIONS

The analysis of Enriched Cages, Free-Range, and Organic Systems reveals the unique strengths and challenges of each system, particularly in relation to animal welfare, economic viability, and technological advancement.

Enriched cages offer a balanced solution, providing improved welfare over conventional cages while maintaining relatively low production costs. However, they still limit natural behaviors and face increasing pressure from consumer demand for more ethical systems. As regulations evolve, enriched cages may struggle to maintain their economic viability in the long term.

Free-range systems provide the highest welfare outcomes by allowing hens to engage in natural behaviors, but they come with higher costs due to the need for larger space, increased labor, and more intensive management. Although these systems offer welfare benefits, their economic sustainability depends on securing premium pricing and managing production costs effectively.

Organic systems represent the highest welfare standard due to outdoor access, lower stocking densities, and organic feed. However, the high costs associated with organic feed, certification, and infrastructure make them the most expensive option. Despite the challenges, organic systems offer the potential for premium pricing and have strong consumer demand for ethically produced eggs.

Technological advancements, such as AI systems, sensor technologies, and automated monitoring, are playing a crucial role in improving the efficiency and welfare outcomes of all production systems. These innovations allow for real-time monitoring and early intervention, enhancing productivity while ensuring that welfare standards are maintained.

In conclusion, while each system has its own advantages, the future of egg production will depend on balancing welfare improvement with economic feasibility. As consumer demand for higher-welfare products grows, producers will need to invest in technology and management practices to maintain competitive and sustainable operations.

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