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Integrating environmental, economic, and welfare dimensions in sustainable dairy farming: Literature review

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Abstract. Sustainable cow milk production is critical for global food security, rural livelihoods, and human nutrition, yet it poses environmental, economic, and ethical challenges. Dairy systems contribute significantly to greenhouse gas emissions, water and land use, nutrient losses, and biodiversity impacts, while also shaping animal welfare and farm profitability. This review aimed to examine how environmental protection, economic viability, resource efficiency, and animal welfare were integrated in sustainable dairy production systems. A structured narrative review of recent scientific literature was conducted, and evidence on greenhouse gas emissions, land and water use, nutrient management, animal health, housing, farm profitability, precision livestock farming, genetic improvement, nutrition, circular economy strategies, and policy support was synthesised. The review established that sustainable dairy production required balanced action across environmental, economic, and social dimensions, since improvements in one area often produced trade-offs in another. Environmental impacts were investigated through strategies such as improved feed efficiency, methane-reducing diets, manure management, pasture-based systems, water stewardship, nutrient recycling, renewable energy use, and integrated crop and livestock farming. Animal welfare was analysed as a central component of sustainability, and appropriate housing, pasture access, preventive health care, reduced lameness and mastitis, longer productive lifespan, and welfare certification were identified as factors that supported both ethical responsibility and farm performance. Economic sustainability was summarised as a prerequisite for adoption of sustainable practices, because production efficiency, cost control, market incentives, policy support, and risk management determined whether farmers could maintain profitability while improving environmental and welfare outcomes. The results could be used by dairy farmers, advisers, researchers, policymakers, certification bodies, and industry stakeholders to design, evaluate, and promote more resilient, efficient, and ethically responsible dairy production systems

Keywords: agroecology; circular economy; feed efficiency; precision livestock farming; resource efficiency

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INTRODUCTION

Dairy production plays a central role in global agricultural systems, contributing significantly to human nutrition, rural livelihoods, and food security; however, its role is increasingly contested due to environmental and ethical concerns. Cow milk is widely valued as a nutrient-rich food, while dairy farming supports employment, income generation, and the social structure of many rural areas. At the same time, milk production raises important sustainability concerns because it depends on natural resources, generates environmental pressures, and involves ethical responsibilities related to animal welfare. For these reasons, improving the sustainability of cow milk production is an important priority for researchers, farmers, policymakers, and the dairy industry.

Accordingly, to B.O. Manono (2026), sustainability in livestock production is a key priority, addressing climate change, resource pressure and environmental harm, with dairy farming contributing significant methane and manure emissions. Nevertheless, the magnitude of these impacts varies substantially between production systems, limiting the generalisability of mitigation strategies. M. Cheng *et al.* (2022) added that livestock supply chains also contribute substantially to global greenhouse gas (GHG) emissions through methane (CH₄), nitrous oxide, (N₂O) and carbon dioxide (CO₂) released during animal digestion, manure handling, feed production, and land use change.

M. Herrero *et al.* (2023) argued that sustainable cow's milk production must address economic and social factors, as livestock supports livelihoods, employment and food security, especially within rural economies worldwide. Ensuring farm profitability and resilience is therefore a fundamental component of sustainability in dairy systems, as economically viable farms are better able to maintain production while adapting to environmental and market pressures. The integration of environmental performance, economic viability, and social considerations, including animal welfare, reflects the broader concept of sustainability, which is commonly described through the three interconnected pillars of environmental, economic, and social responsibility in agricultural systems. In practice, however, these pillars often conflict, requiring trade-offs rather than simultaneous optimisation.

A.N. Hristov *et al.* (2022) indicated that researchers and practitioners are exploring strategies to enhance dairy sustainability, including improving feed efficiency and optimising diets to reduce CH₄ emissions while maintaining milk productivity. In addition, E. Mixtajo-va *et al.* (2026) indicated that further mitigation approaches focus on improved manure management, genetic selection, and integrated herd management strategies to reduce GHG emissions and enhance production efficiency. Adoption of precision livestock farming (PLF) technologies, including sensors and automation, can optimise management practices, improving

efficiency while reducing environmental impacts within dairy systems. H.H.E. Van Zanten *et al.* (2023) concluded that circular agriculture and resource-efficient livestock systems promote feeding by-products and non-edible biomass, improving efficiency, reducing environmental impacts, and supporting resilient, productive food systems. While these approaches can reduce emissions intensity, their effectiveness depends strongly on local conditions and baseline system efficiency. Recent systematic reviews such as C. Pavanello *et al.* (2024) highlighted that research draws on a wide array of indicators and assessment frameworks to capture environmental, economic and social performance, with no single set of metrics universally adopted, such as multiple environmental, economic and social indicators identified in EU dairy systems literature. The purpose of this review was therefore to provide an integrated synthesis of the main factors shaping sustainable cow milk production and to identify management and research priorities that may support more resilient, efficient, and welfare-oriented dairy systems.

This article was developed as a narrative literature review. Scientific sources published between 2020 and 2026 were selected according to their relevance to sustainable cow milk production, with priority given to recent peer-reviewed studies addressing environmental impacts, resource efficiency, animal welfare, economic viability, technological innovation, and policy or market instruments. The literature was identified through targeted searches using combinations of terms related to dairy sustainability, greenhouse gas emissions, feed efficiency, manure management, water use, animal welfare, farm profitability, PLF, genetic improvement, circular economy, and agroecological dairy systems. The selected sources were analysed qualitatively and systematised according to the main sustainability dimensions addressed in the review: environmental performance, animal welfare, economic viability, and innovation strategies. Evidence was compared across production systems and management approaches in order to identify common challenges, practical mitigation options, synergies, and trade-offs.

Concept of sustainability in dairy production

Sustainability in dairy production means providing nutritious food and economic benefits while minimising environmental impacts and supporting animal and community welfare, guided by the three pillars of environmental, economic, and social performance. For example, systematic reviews identify sets of sustainability indicators expressed under the environmental, economic and social pillars, highlighting how these dimensions overlap and interact within dairy farming assessments and how farm-level sustainability encompasses animal welfare, work-life balance, income and ecosystem services in addition to resource use and

emissions. In milk production, environmental, economic, and social pillars are interconnected; efficiency gains may reduce impacts but also affect profitability and social outcomes, requiring sustainability strategies to balance multiple objectives simultaneously. This inter-

dependence complicates sustainability assessments, as improvements in one dimension may lead to unintended consequences in another. Table 1 summarises this concept, showing the 3 key dimensions, their indicators, challenges, and strategies.

Table 1. Conceptual framework of dairy production sustainability

Pillar	Impacts	Sustainability strategies
Environmental	Environmental impacts include greenhouse gas emissions such as methane and nitrous oxide, water and land use, nutrient losses, biodiversity decline, nutrient pollution, water scarcity, and land-use pressure.	Improved feed efficiency, dietary interventions, manure management, PLF, efficient irrigation.
Economic	Economic impacts include profitability, production efficiency, input costs and farm resilience, with key challenges arising from price volatility, rising feed and energy costs, and financial barriers to innovation.	Cost optimisation, efficiency improvements, diversification, policy support, market incentives.
Social / animal welfare	Animal welfare and health impacts include animal health, behaviour, longevity, housing conditions and societal acceptance, with key challenges including lameness, mastitis, inadequate housing and ethical concerns.	Improved housing, pasture access, preventive health care, welfare certification schemes.

Source: compiled by the author

Research on sustainable dairy systems has expanded, driven by climate change, resource pressures, and environmental impacts, with publications increasingly addressing GHG emissions and broader sustainability challenges. P.F.P. Ferraz *et al.* (2024) found that in dairy production, greenhouse gas emissions, primarily CH₄ from enteric fermentation and manure, as well as N₂O from manure and fertilisers, constitute a substantial share of total emissions and are therefore key indicators in life-cycle and whole-farm sustainability assessments. Dairy systems provide important ecosystem services as well as food and economic benefits, such as converting fibrous feed into highquality protein, supporting rural livelihoods and contributing to food security, which are increasingly recognised in sustainability frameworks that seek to balance environmental burdens with socioeconomic gains. For this reason, contemporary sustainability frameworks increasingly aim to balance the environmental burdens of dairy production with its socio-economic gains. Consequently, contemporary sustainability assessments of dairy production use integrated frameworks that combine environmental indicators (e.g. GHG emissions, nutrient flows), economic performance (e.g. resource efficiency, profitability) and social and animal welfare outcomes to reflect the multifaceted nature of sustainability in milk production systems (Fiorillo & Amico, 2024).

Life cycle assessment (LCA) is widely used to evaluate dairy environmental impacts, systematically quantifying emissions and resource use across the entire milk production chain, from feed cultivation to on-farm operations and processing stages. A systematic review L.S. Carvalho *et al.* (2022) showed LCA is a key tool in milk production sustainability research, assessing inputs, outputs, and impacts like global warming, eutrophication, acidification, and resource use to guide environmental interventions. Study consistently showed feed production, enteric CH₄, and manure management as major contributors to milk's environmental footprint;

cradle-to-farm-gate assessments highlight CH₄ and N₂O from these sources per kilogram of milk. These findings reveal the importance of improving feed efficiency, optimising manure management practices and enhancing overall farm management as ways to reduce environmental burdens in dairy systems and improve sustainability outcomes.

Technological and management innovations, particularly PLF, are explored to enhance dairy sustainability. Sensor-based and digital tools monitor health, behaviour, feed intake, and milk production, improving efficiency, welfare, and productivity. S. Das *et al.* (2023) showed advanced technologies, computer vision, machine learning, and sensors, monitor behaviour, detect disease, and optimise feeding, supporting more sustainable, efficient, and welfare-friendly dairy production systems. Additionally, research showed that ICT-based monitoring systems can improve reproductive health management and labour efficiency, further supporting sustainable farm performance.

Genetic improvement programmes enhance dairy sustainability by selecting for feed efficiency, disease resistance, longevity, and reduced CH₄ emissions, enabling cumulative genetic progress that lowers environmental impacts while maintaining productivity and profitability in commercial herds. C. Richardson *et al.* (2025) showed that CH₄ emission traits in dairy cattle are heritable and can therefore be targeted through genetic selection. Their findings indicate that incorporating CH₄-related and feed-efficiency traits into breeding goals can contribute to a gradual reduction in greenhouse gas emissions across generations. L.M. Alderkamp *et al.* (2025) emphasised that integrated and agroecological farming approaches can enhance dairy sustainability by combining crop and livestock production, recycling nutrients, reducing dependence on external inputs, and improving resource efficiency, soil fertility, and system resilience. Compared with specialised systems, such approaches may also contribute to lower greenhouse gas emissions. By embedding

eco-logical principles alongside modern management practices, these systems support long-term sustainability in dairy farming, balancing productivity with environmental and socio-economic benefits.

Sustainability in dairy production is conceptualised through three interconnected pillars – environmental, economic, and social/animal welfare – whose interactions mean that improvements in one dimension can create trade-offs or unintended consequences in another. Assessing this multidimensional concept relies on integrated analytical tools, particularly life cycle assessment, alongside emerging technological and genetic innovations such as precision livestock farming and methane-focused breeding programmes. Ultimately, sustainable dairy systems must balance resource efficiency and productivity with broader socio-economic and ecological goals, including rural livelihoods, food security, and long-term farm resilience.

Environmental sustainability of cow milk production

Environmental sustainability is a key component of sustainable dairy farming, as milk production systems can exert considerable pressure on natural resources and ecosystems. Dairy production is associated with GHG emissions, land and water use, nutrient losses, and potential impacts on biodiversity. As global demand for dairy products increases, improving the environmental performance of cow milk production systems has become an important priority for researchers, policymakers, and farmers. Addressing these challenges requires the adoption of management practices and technological innovations that reduce environmental impacts while maintaining productive and economically viable farming systems.

Greenhouse gas emissions represent one of the most widely discussed environmental impacts of dairy farming because dairy cattle produce CH₄ through enteric fermentation, a natural digestive process in the rumen. Methane is a potent GHG with a much higher global warming potential than CO₂ over shorter time periods, roughly 27–30 times greater than CO₂ over a 100-year horizon as used in climate assessments, making its reduction important for climate mitigation efforts (Lei *et al.*, 2024). Enteric CH₄ emissions account for a substantial proportion of the total climate impact associated with dairy production, with enteric fermentation being the largest direct source of CH₄ emissions from dairy systems and often representing over half of the direct GHG emissions from dairy cattle when assessed on a CO₂-equivalent basis.

In addition to enteric fermentation, GHGs are also produced through manure management and the use of nitrogen fertilisers in feed crop production. Manure stored and handled on farms emits both CH₄ and N₂O during storage and decomposition, with emissions varying by storage practice and duration (Al Zahra *et al.*, 2024). At the same time, fertiliser use in feed crop cultivation

contributes to N₂O release from soils through microbial nitrification and denitrification processes, making fertiliser-related N₂O an important part of dairy feed crop emissions and the overall carbon footprint of milk production. These on-farm and off-farm sources of CH₄ and N₂O collectively contribute substantially to the GHG profile associated with dairy farming, alongside enteric emissions (Al Zahra *et al.*, 2020). Technologies such as anaerobic digestion, improved manure storage and nutrient recycling have been proposed to mitigate these emissions, although adoption remains constrained by economic and technical barriers, particularly on smaller-scale farms (Vergote *et al.*, 2020).

Several strategies have been explored to mitigate GHG emissions in dairy systems. S. Roques *et al.* (2024) reported that improving feed quality and digestibility, particularly by increasing forage digestibility, can enhance rumen fermentation efficiency and reduce CH₄ emissions per unit of milk produced by influencing volatile fatty acid profiles and rumen passage rates. The same authors also noted that dietary interventions with feed additives, such as 3-nitrooxypropanol (3-NOP), have consistently demonstrated CH₄-reducing effects in dairy cattle. In the longer term, S. Roques *et al.* identified genetic selection for improved feed efficiency and lower CH₄ intensity traits as a promising mitigation approach, since genetic variation exists in CH₄ emission-related phenotypes and selection can progressively reduce emissions across generations. A.N. Hristov *et al.* (2022) further showed that dietary supplementation with lipids and tannin-containing feeds can alter rumen fermentation and suppress methanogenesis.

Land use is another important factor influencing the environmental sustainability of dairy production because dairy farming requires substantial land both for grazing and for the cultivation of feed crops such as maize, grass silage and other forage plants. The expansion of feed crop production and pasture often leads to conversion of natural ecosystems to agricultural land, resulting in habitat loss, forest degradation and reductions in biodiversity, particularly where agricultural land expansion occurs in highly biodiverse regions (Salari *et al.*, 2025). Agricultural land use, including pasture and cropland for livestock feed, is a dominant driver of terrestrial biodiversity loss globally, as the conversion of forests and other natural habitats to agriculture significantly disrupts species' habitats and contributes to declines in species richness and ecosystem integrity. At the same time, pasture systems typically require more land per unit of milk than intensive systems, creating a trade-off between productivity and land occupation.

Intensive dairy systems often rely on imported feed such as soybean meal, a common high-protein ingredient in cattle rations that is predominantly sourced from major exporters like Brazil and Argentina. This reliance on imported soy shifts a substantial portion of the environmental impact of dairy production to regions where

soy cultivation has been linked with land-use change and deforestation, raising concerns about biodiversity loss and carbon emissions associated with agricultural expansion. Soybean production for livestock feed drives agricultural land expansion in South America, contributing to habitat conversion and ecosystem pressures far from the consuming region, illustrating the global environmental consequences of intensive livestock systems that depend on international feed supply chains.

Pasture-based dairy systems, when managed sustainably, may offer certain environmental benefits because well-maintained grasslands can support soil carbon storage, enhance biodiversity and contribute to ecosystem services such as nutrient cycling and habitat provision. Meta-analysis of grazing effects by J. Su *et al.* (2023) showed that moderate grazing can increase plant diversity and soil organic carbon content relative to ungrazed or poorly managed systems, indicating potential benefits for biodiversity and carbon sequestration. However, grazing impacts are context-dependent; higher grazing intensity and poor pasture management tend to degrade natural capital, reducing soil health, plant diversity and other supporting ecosystem services, underscoring the importance of appropriate pasture management to balance productivity with ecological protection (O'Grady *et al.*, 2024).

Water use is a key environmental concern in dairy production. While cattle need water for drinking and farm operations, most consumption is indirect, coming from irrigation of feed crops. C.D. Higham *et al.* (2024) showed that green and blue water used for forage and pasture growth represent the largest share of milk's water footprint, varying by region and climate, and dominating total freshwater use per unit of milk. Direct water use on the farm (for animal water consumption, cleaning and other service demands) represents a small fraction of the overall footprint compared with the water required for growing feed crops, making indirect water use via irrigation a major driver of dairy water demand and a central focus in efforts to improve sustainability.

In regions experiencing water scarcity, excessive agricultural water use can exert significant pressure on local freshwater resources, making improved water-use efficiency in dairy farming a key sustainability objective. Dairy water footprints are dominated by indirect consumption for irrigation of pastures and feed crops, and higher water demand in arid regions is linked to increased blue water use and associated scarcity impacts (Higham *et al.*, 2024). Practices such as efficient irrigation systems, water recycling on farms and improved water management technologies have been identified as effective ways to reduce the water footprint and enhance water-use efficiency in dairy production systems (Monteiro *et al.*, 2023).

Nutrient management is closely related to both water quality and soil health because dairy manure contains valuable nutrients such as nitrogen (N) and

phosphorus (P) that can support crop growth when applied appropriately. E. Young *et al.* (2022) reported that excess or poorly managed manure application can substantially increase nitrogen and phosphorus loading in runoff, thereby contributing to water quality deterioration and the eutrophication of aquatic ecosystems. T.J. Van der Weerden *et al.* (2023) further noted that manure storage and land application are significant sources of ammonia (NH₃) and N₂O emissions. In particular, NH₃ volatilisation from manure contributes to air pollution and nitrogen deposition, whereas N₂O emissions from manure-amended soils represent an important source of greenhouse gas emissions. Effective nutrient management in dairy systems includes balanced fertilisation, improved feed formulation to reduce nutrient excretion, and integration of crop and livestock production to enhance recycling of manure nutrients. In addition, anaerobic digestion of dairy manure can capture CH₄ for energy production while producing a nutrient-rich digestate that can be used as a biofertiliser, potentially substituting synthetic fertilisers and supporting soil health and nutrient cycling when applied appropriately (Martín-Sanz-Garrido *et al.*, 2025).

Improving environmental sustainability in dairy milk production requires integrated approaches addressing GHG emissions, land use, water consumption, and nutrient management. Strategies such as enhanced feed efficiency, manure management, pasture-based systems, efficient irrigation, and anaerobic digestion can reduce environmental impacts while maintaining productivity. By combining improved farm management with technological innovation and sustainable resource use, dairy systems can lower their environmental footprint while continuing to supply safe and nutritious milk globally.

Animal welfare in sustainable dairy production

Animal welfare is increasingly recognised as a fundamental component of sustainable dairy production systems. Modern sustainability frameworks extend beyond environmental and economic performance to include ethical responsibilities, particularly the treatment of animals (Arvidsson Segerkvist *et al.*, 2020). Ensuring that dairy cattle are raised under conditions that support health, comfort, and the expression of natural behaviours is now considered essential for both productivity and system sustainability (AHAW *et al.*, 2023). Growing public awareness of animal welfare has significantly influenced consumer expectations, market demands, and policy development. Consumers increasingly prefer products derived from systems perceived as humane, prompting the adoption of welfare standards and transparent assessment methods (Linstädter *et al.*, 2024). Consequently, animal welfare is now widely embedded in sustainability indicators and agricultural policies, reinforcing its role as a key pillar of responsible and sustainable dairy farming (Pavanello *et al.*, 2024). Systematic review by M. Verdon *et al.* (2025)

of dairy cow welfare research show a growing number of studies addressing welfare domains such as health, environment and behaviour, reflecting increasing scientific and public interest.

In dairy production systems, animal welfare is influenced by multiple interrelated factors, including housing conditions, nutrition, health management, and the opportunity for animals to express natural behaviours. Adequate housing design, appropriate feeding strategies, and effective disease prevention are essential to maintaining both welfare and productivity in dairy cattle (AHAW *et al.*, 2023; Linstädt *et al.*, 2024). Sustainable dairy systems, therefore, aim to provide environments that minimise stress, reduce the incidence of disease, and support normal behavioural expression. Poor welfare conditions can result in significant ethical and economic consequences. Compromised welfare is associated with decreased milk yield, higher veterinary costs, and reduced longevity of animals within the herd, ultimately undermining farm sustainability. Consequently, improving animal welfare is not only a moral obligation but also a practical strategy to enhance efficiency, resilience, and long-term sustainability in dairy production systems.

Housing design plays a crucial role in determining the welfare of dairy cattle. Well-designed systems provide adequate space, comfortable resting areas, proper ventilation, and reliable access to clean water and feed, all of which are essential for maintaining health and productivity (AHAW *et al.*, 2023). Particular emphasis is placed on lying comfort, as dairy cows spend a substantial proportion of their time resting. The provision of well-bedded lying areas, using materials such as straw or sand, has been shown to improve cow comfort, reduce the risk of injuries and lameness, and support natural resting behaviour (Linstädt *et al.*, 2024). Adequate rest is closely linked to improved physiological functioning, including enhanced milk yield and better overall welfare outcomes. Conversely, poorly designed housing can restrict movement, increase stress, and predispose animals to disease, thereby negatively affecting both welfare and farm performance (Arvidsson Segerkvist *et al.*, 2020). Ensuring appropriate housing conditions is therefore a key component of sustainable dairy production systems.

Modern dairy housing systems often incorporate free-stall barns, which allow cows to move freely within designated areas and express more natural behaviours compared with more restrictive systems. These housing designs are intended to reduce stress, improve comfort, and support overall welfare (AHAW *et al.*, 2023). By enabling voluntary movement between feeding, resting, and social areas, free-stall systems contribute to better behavioural and physiological outcomes in dairy cattle. Proper flooring, adequate space, and effective ventilation are essential in dairy systems. They reduce lameness, competition, and stress, while maintaining

temperature, humidity, and air quality to prevent heat stress. Together, these factors help to ensure hygiene, reduce disease risk, and enhance both animal welfare and productivity within sustainable dairy systems.

Access to pasture is widely associated with improved animal welfare in dairy systems. Grazing enables cows to express natural behaviours such as foraging, walking, and social interaction, which are important indicators of positive welfare. In addition, outdoor access has been linked to a lower incidence of certain health issues, particularly lameness, which is often associated with prolonged exposure to hard indoor flooring. Pasture-based systems need careful management to ensure welfare, providing adequate nutrition, protection from extreme weather, and proper grazing practices, including controlled stocking density and rotation, to prevent overgrazing and maintain pasture quality.

Maintaining good health is fundamental to ensuring high levels of animal welfare in dairy production systems. Dairy cattle are susceptible to several prevalent health disorders, including mastitis, lameness, metabolic issues and reproductive problems, each of which can cause pain and discomfort and impair well-being if not effectively managed (AHAW *et al.*, 2023). Mastitis is one of the most frequent and costly diseases in dairy herds, reducing milk yield and quality while increasing veterinary and replacement costs, and remains a leading cause of culling when recurrent or severe. Lameness, often stemming from hoof lesions or suboptimal flooring and housing conditions, is a major welfare concern due to its association with pain, reduced mobility and impaired natural behaviours (Thomsen *et al.*, 2023). Together, these health challenges not only compromise animal welfare but also lead to significant economic losses for farmers, underscoring the importance of proactive health management and welfare-focused practices in sustainable dairy systems. P.T. Thomsen *et al.* (2023) estimated mean lameness prevalence at around 23% in dairy herds.

Preventive health management is a critical component of sustainable dairy farming. Regular veterinary monitoring, vaccination programmes, and early detection of disease symptoms help maintain herd health and reduce reliance on therapeutic interventions (AHAW *et al.*, 2023). Maintaining good hygiene during milking, managing bedding effectively, and providing balanced nutrition are also essential measures to prevent common health problems such as mastitis, metabolic disorders, and lameness (Thomsen *et al.*, 2023). By prioritising preventive strategies, farmers can improve animal welfare, reduce economic losses from disease, and enhance productivity. Integrating these practices into routine farm management supports both ethical responsibilities and the long-term sustainability of dairy production systems.

Lameness is one of the most prevalent welfare issues in dairy cattle and is often linked to poor flooring

conditions, inadequate hoof care, or prolonged standing times (Garvey, 2022). Clinical lameness not only causes pain and reduced mobility but also negatively affects feeding behaviour and milk production, making its prevention essential for both welfare and productivity. M.B. Sadiq *et al.* (2021) showed that implementing regular hoof trimming as part of a comprehensive hoof health programme can significantly reduce the incidence of lameness and the prevalence of hoof lesions in dairy herds. Improvements to flooring surfaces and the provision of comfortable resting areas further reduce mechanical stress on the hooves and joints, thereby helping to minimise lameness risks. P.T. Thomsen *et al.* (2023) also emphasised that peri-partum metabolic disorders, such as ketosis and displaced abomasum, can alter cow behaviour and activity, which underscores the importance of systematic health monitoring and proper nutrition.

R. Han *et al.* (2022) identified longevity as an increasingly important indicator of both animal welfare and sustainability in dairy systems. They noted that dairy cows with longer productive lifespans contribute to improved system efficiency because fewer replacement animals are required, reducing the resources and environmental impacts associated with raising heifers. Prolonged productive life may also reflect better health and management practices that support animal welfare. G.M. Dallago *et al.* (2021) further reported that short cow longevity is often associated with increased involuntary culling due to health and reproductive problems, which can compromise welfare and increase production costs. Reducing herd turnover lowers the need for rearing replacement heifers, thereby decreasing feed, water and energy requirements and the associated greenhouse gas emissions per unit of milk produced. Longer productive lifespans can therefore enhance environmental performance as well as economic outcomes.

Several factors influence the longevity of dairy cows, including genetics, nutrition, health management, and housing conditions. Genetic selection that balances production with functional traits such as disease resilience, fertility and structural soundness can contribute to longer productive lifespans, although the genetic basis of longevity is complex and involves multiple correlated traits. Genetic analyses indicate that health traits such as resistance to locomotory and metabolic diseases are genetically associated with longevity, providing targets for breeding programmes aimed at enhancing durability and resilience (Hu *et al.*, 2024). In addition, good herd management practices that prioritise animal health and welfare, such as preventive health care, balanced nutrition and comfortable housing, can extend productive life and reduce involuntary culling due to disease or injury (Dallago *et al.*, 2021; Han *et al.*, 2022). By improving both genetic potential and management conditions, dairy systems can support longer cow longevity, enhancing sustainability and reducing resource use.

Ethical considerations surrounding livestock production have become increasingly prominent in discussions of sustainable agriculture. Many consumers express concern about how animals are raised and are willing to pay premiums for products from higher-welfare systems, reflecting a growing ethical dimension in food choice behaviour (Mata *et al.*, 2026). Public expectations around animal welfare have also driven interest in welfare certification schemes, which aim to provide transparent information about on-farm practices and allow consumers to identify products from farms meeting defined welfare standards (Chang & Chen, 2022).

Welfare labelling and voluntary certification schemes, such as Certified Humane and assured by an animal welfare charity such as The Royal Society for the Prevention of Cruelty to Animals, the RSCPA Assured scheme in the UK, provide market incentives for improved animal care (Tuytens *et al.*, 2025). Effective welfare schemes rely on clear standards, strict audits, and informed consumers, driving on-farm improvements and encouraging adoption of welfare-focused practices through market influence and policy support. High welfare standards in dairy farming offer ethical and economic benefits, granting access to premium markets, boosting consumer trust, and promoting healthier, more productive animals, thereby improving efficiency and sustainability (Tuytens *et al.*, 2025).

Animal welfare is a fundamental aspect of sustainable dairy production. High welfare standards also have economic and market benefits. Farms demonstrating strong welfare practices can access premium markets, build consumer trust, and reduce costs associated with disease and high herd turnover. Certification schemes and welfare labelling provide incentives for producers to adopt these practices, encouraging transparency and aligning production with societal expectations. Integrating animal welfare into dairy systems is therefore essential for both ethical responsibility and the long-term sustainability of milk production.

Economic sustainability and farm viability

Economic sustainability is fundamental to dairy production, as profitability ensures long-term farm viability while supporting environmental stewardship and animal welfare. Efficient resource management, cost control, and productivity optimisation are essential to maintain competitiveness. Dairy farms must also respond to challenges such as market volatility, fluctuating milk prices, and rising input costs, which threaten financial stability (Savickienė & Galnaitytė, 2024). V. Fiorillo & B.M. Amico (2024) showed that economically resilient farms are more capable of adopting and sustaining environmentally beneficial practices, aligning financial and ecological goals.

Dairy farming operates within highly dynamic and competitive markets, where milk prices fluctuate in response to global and regional supply-demand

dynamics. According to OECD/FAO (2022) and OECD/FAO (2024) agricultural market projections, global dairy commodity prices are expected to remain volatile over the medium term, with demand growth increasingly concentrated in emerging economies while production costs continue to rise in established dairy-exporting regions; the 2024-2033 outlook also points to slower expected growth in global milk production compared with the 2022-2031 projections, reflecting tightening margins and resource constraints. Farmers also face variable costs for feed, energy, labour, and veterinary services, all of which influence profitability and long-term viability (Savickienė & Galnaitytė, 2024). Such volatility increases financial risk and uncertainty. Consequently, improving technical efficiency, optimising input use, and adopting cost-reduction strategies are essential for maintaining economic sustainability and resilience in dairy systems. Production costs and profitability vary widely between farms, which significantly influences farm-level economic.

One of the main drivers of economic sustainability is production efficiency, often measured by milk yield per cow or per unit of feed. Higher productivity enables fixed costs, such as housing and machinery, to be distributed across greater outputs, thereby improving profitability (Pavanello *et al.*, 2024). However, this must be balanced with broader sustainability objectives, as excessive intensification can increase environmental pressures, compromise animal welfare, and heighten long-term risks. R. Savickienė & A. Galnaitytė (2024) highlighted that optimising, rather than maximising, production is essential for sustaining both economic performance and overall system resilience. G. Salcedo *et al.* (2025) provided empirical support for this view in temperate Atlantic dairy systems, showing that farms pursuing sustainable intensification, through moderate increases in stocking density combined with improved nutritional management, achieved higher milk output without proportional increases in environmental burden. However, their findings also indicated that further intensification beyond this point resulted in diminishing economic and environmental returns.

Cost management plays a vital role in maintaining dairy farm viability, with feed representing a substantial proportion of total production expenses. Improving feed efficiency and optimising nutrition are therefore critical for controlling costs and sustaining profitability (Pavanello *et al.*, 2024). Approaches such as precision feeding, the use of agricultural by-products, and improved ration formulation can reduce feed costs while maintaining milk yield. In addition, enhancing energy and water use efficiency further lowers operational expenses, contributing to overall economic sustainability and reinforcing the resilience of dairy farming systems (Savickienė & Galnaitytė, 2024). Beyond cost control, milk quality parameters such as protein and fat content and somatic cell counts directly affect farm-gate prices

under most milk-pricing systems, making quality management an integral component of dairy farm profitability alongside efficiency gains.

Market structures, incentives, and policy frameworks strongly influence economic sustainability. Certification schemes and eco-labelling for sustainable or high-welfare dairy products can allow farmers to access premium markets and secure higher returns, as consumers frequently show willingness to pay higher prices for sustainability-labelled attributes (e.g., organic, welfare, origin) in dairy and plant-based milk alternatives (Madududu *et al.*, 2024). Y. Zhan *et al.* (2025) also found that recognition of eco-labels, such as carbon or environmental labels, increases consumer willingness to pay premiums, reinforcing market incentives for sustainable dairy practices. Sustainability certification standards, covering environmental, welfare and social criteria, are increasingly used to differentiate dairy products, although their scope and uptake vary widely.

Government policies and subsidies play a key role in supporting sustainable dairy production by lowering financial barriers and encouraging the adoption of environmentally friendly practices. Subsidies, regulatory programmes, and financial and technical assistance are among the main mechanisms used by governments to incentivise sustainable agricultural initiatives, including manure management, renewable energy uptake, and pasture-based systems. Public extension services and training enhance farmer capacity to implement improved practices, while targeted financial assistance and low-interest loans can bolster long-term economic resilience and farm viability.

Economic sustainability in dairy farming requires resilience to external risks such as market volatility, climate variability, and disease outbreaks. Diversifying income through integrated crop-livestock systems, production of value-added dairy products, or participation in cooperatives can buffer farms against fluctuating milk prices. Additionally, insurance schemes and risk management tools protect against catastrophic events, enhancing the financial stability and long-term viability of dairy operations. Investments in herd health, housing infrastructure, and technology enhance productivity and animal welfare while reducing economic vulnerability. Maintaining healthy cows with longer productive lifespans lowers replacement costs, and improved housing or automated systems reduce labour requirements and operational risks. Such strategic investments strengthen farm efficiency and resilience, supporting long-term economic sustainability in dairy production.

Achieving economic sustainability in dairy farming goes beyond simply maximising profits. Sustainable systems require balancing economic, environmental, and social objectives. Practices such as improved manure management or pasture-based systems may incur higher upfront costs but can reduce long-term risks, enhance farm resilience, and enable access to

value-added markets. Likewise, investments in animal welfare support healthier, more productive cows, improving economic performance while meeting societal expectations for ethical farming (Fiorillo & Amico, 2024). C. Pavanello *et al.* (2024) highlights that economically resilient farms are better able to implement sustainable technologies, respond to market and climatic shocks, and align production with consumer and societal expectations.

Economic sustainability ensures that dairy farms remain viable over the long term, supporting rural livelihoods and the continued supply of milk as a critical food resource. Beyond the individual farm, a financially resilient dairy sector sustains rural employment, inter-generational farm succession, and the broader agri-food economy of dairy-producing regions. By integrating cost-effective management, production efficiency, risk mitigation, and market-oriented strategies, farms can maintain profitability while adopting environmentally and socially responsible practices. As global demand for dairy products continues to grow, the ability of farms to remain economically viable will become increasingly important for ensuring a stable and sustainable milk supply. Economically resilient farms are better able to implement sustainable technologies, respond to market and climatic shocks, and align production with consumer and societal expectations. Ultimately, economic viability cannot be treated in isolation: it is the foundation that enables farms to sustain the environmental and welfare-related improvements discussed throughout this review.

Innovations and strategies for sustainable dairy systems

Advancing the sustainability of cow milk production requires adopting innovative management practices, technologies, and system-level strategies that concurrently address environmental, economic, and animal welfare objectives. Digital and PLF technologies, such as sensors, automated milking, and data systems, enhance monitoring, productivity, and decision-making, promoting efficiency and sustainability on dairy farms (de Oliveira *et al.*, 2024). In addition, selective breeding and genomic tools can improve genetic potential for balanced production, fertility, and longevity, supporting resource efficiency and lowering emissions per unit of milk (Bell, 2024). PLF involves using technology to monitor, analyse, and manage individual animals or groups in real time. Tools such as sensors, automated milking systems, wearable devices, and data analytics allow farmers to track milk yield, feed intake, body condition, activity, and health status. By providing detailed, cow-level information, PLF supports early detection of health issues, optimisation of feeding strategies, and more efficient herd management, ultimately improving productivity, animal welfare, and economic sustainability in dairy systems.

Implementing PLF technologies can reduce feed waste, improve milk production efficiency, and enhance

animal welfare by detecting discomfort or disease early. Additionally, PLF supports environmental sustainability by enabling precise nutrient management, which lowers N and P excretion and decreases GHG emissions associated with overfeeding. N. Liu *et al.* (2023) demonstrated that integrating PLF into dairy operations improves productivity while simultaneously promoting economic, environmental, and animal welfare objectives. Genetic selection is a long-term strategy to improve sustainability in dairy systems by incorporating traits beyond milk yield, such as feed efficiency, disease resistance, fertility, and longevity, into breeding goals. Breeding programmes that target lower enteric CH₄, along with efficiency, can cumulatively reduce emissions and resource use, enhancing both environmental and economic sustainability of dairy production (Richardson *et al.*, 2025).

Innovations in dairy nutrition play a central role in sustainable milk production by optimising rumen efficiency and mitigating enteric methane emissions. Diet manipulation and specific feed additives, such as fats, tannins, and methane-inhibiting compounds like 3-NOP, have been shown to reduce methane output while maintaining productivity (Hristov, 2024). Increasing forage digestibility and incorporating high-quality forages or by-products from other agricultural sectors can also lower CH₄ intensity per unit of milk and support circular resource use.

Precision feeding strategies, which customise nutrient supply for individual cows or specific production stages, enhance feed efficiency and reduce nutrient excretion into the environment. Optimising diet composition through precision feeding improves rumen function, animal health, welfare, and milk quality, thereby supporting both economic performance and ethical standards in dairy farming. A.N. Hristov (2024) demonstrated that these targeted nutritional approaches contribute significantly to the sustainability of dairy systems by aligning productivity, environmental stewardship, and animal welfare goals. System-level innovations, such as integrated crop-livestock systems and agroecological approaches, enhance sustainability by combining ecological principles with productive farming. Integrating crop and livestock production enables the recycling of nutrients and organic matter, reduces dependence on external inputs, and promotes soil health. Dairy manure can be used as a fertiliser for feed crops, creating a closed nutrient loop that benefits both crop and livestock production and contributes to agricultural sustainability.

Agroecological strategies emphasise biodiversity, diversified forage species, and pasture-based systems that provide ecosystem services such as carbon sequestration, soil conservation, and habitat support. For example, silvopastoral systems that combine trees, pastures and livestock enhance nutrient cycling, soil fertility, biodiversity and carbon storage compared with

simpler systems, thereby reducing reliance on intensive, input-heavy practices while supporting ecosystem functions and sustainability (de Macêdo Carvalho *et al.*, 2024). Renewable energy technologies such as anaerobic digestion, solar panels, and biogas production contribute to sustainable dairy systems by reducing dependence on fossil fuels and lowering GHG emissions. Anaerobic digestion of dairy manure produces biogas that can be used for heat and electricity, cutting CH₄ emissions from manure management and supplying renewable energy on-farm, thereby offering both environmental and economic advantages.

Circular economy principles in dairy systems encourage use of agricultural by-products as feed, efficient water recycling, and reduced waste generation. Creating closed-loop systems that maximise resource efficiency, from recovering nutrients in effluent to valorising dairy co-products like whey, can reduce environmental impact while maintaining productivity and animal welfare. Such circular approaches are increasingly recognised as essential for sustainable dairy supply chains (Terpou *et al.*, 2025).

Despite the demonstrated benefits, the widespread adoption of innovative strategies faces several challenges, including high initial investment costs, technical complexity, and the need for farmer training. Evidence shows that increased costs and lack of

supportive networks or advisory services are significant barriers limiting the uptake of sustainable practices on farms. Policy support, extension services, and market incentives are therefore critical to facilitate adoption and improve sustainable agricultural outcomes. Innovations and strategic approaches in dairy farming provide multiple pathways to enhance sustainability. PLF technologies, genetic improvement, nutritional optimisation, integrated farming systems, and renewable energy applications collectively contribute to creating resilient, resource-efficient, and ethically responsible dairy systems.

Strategies, trade-offs, and future perspectives

Sustainable cow milk production is often presented as a matter of improving efficiency or adopting new technologies, yet the evidence suggests a more complex reality. In practice, dairy systems operate under competing pressures: increasing production to meet demand, reducing environmental impacts, and responding to societal expectations around animal welfare. These goals do not fully align, and much of the challenge lies in managing the tensions between them rather than resolving them. Table 2 summarises the effects of main strategies in dairy production across the key environmental, economic, and animal welfare sustainability dimensions, highlighting potential synergies and trade-offs.

Table 2. Effects of main strategies in dairy production across the three key sustainability dimensions, highlighting potential synergies and trade-offs

Strategy	Environmental Impact	Economic Impact	Animal Welfare Impact
Improved feed efficiency	Reduces CH ₄ emissions and resource use per unit of milk	Lowers feed costs, improves productivity	Generally neutral to positive
PLF	Reduces nutrient losses and optimises resource use	Improves efficiency and labour productivity	Enhances health monitoring and early disease detection
Genetic selection (efficiency, longevity)	Long-term reduction in emissions intensity	Increases productivity and lifetime performance	Improves longevity and resilience
Manure management	Reduces CH ₄ and N ₂ O emissions, enables nutrient recycling	Provides renewable energy and additional income streams	Neutral
Pasture-based systems	Can enhance biodiversity and ecosystem services, but may increase land use	Variable profitability depending on system	Improves behavioural welfare and natural expression
Use of agricultural by-products	Reduces demand for feed crops and resource use	Lowers feed costs and improves efficiency	Neutral

Source: compiled by the author

Improving efficiency is frequently highlighted as a key pathway to sustainability. Strategies such as optimising feed use, improving genetics, and increasing milk yield per cow can reduce emissions per unit of output. While this is an important contribution, it does not necessarily translate into lower overall environmental impact. In systems where production continues to expand, efficiency gains may be offset by higher total output. This suggests that efficiency should be viewed as a necessary but insufficient condition for sustainability, rather than a complete solution. The contrast between intensive and pasture-based systems illustrates the difficulty of defining a single “optimal”

model. Intensive systems tend to achieve higher productivity and lower emissions per unit of milk, but they often depend on external inputs and may raise concerns regarding animal welfare and indirect environmental effects. Pasture-based systems, in contrast, are commonly associated with improved welfare and ecosystem services, yet they generally require more land and may show lower production efficiency. These differences highlight that sustainability outcomes are highly context-dependent and that system performance cannot be assessed using a single metric.

Animal welfare further complicates this picture. It is increasingly recognised as a core component of

sustainability, but it does not always improve in parallel with environmental or economic performance. In some cases, management practices that enhance productivity can place additional pressure on animals, while higher-welfare systems may involve trade-offs in efficiency or cost. This indicates that welfare should be treated as an independent objective within sustainability frameworks, requiring specific attention rather than being assumed as a secondary benefit of other improvements. Economic viability remains a decisive factor in determining whether sustainable practices are adopted. Many of the strategies identified in the literature, including precision technologies, improved housing, and renewable energy systems, require substantial investment (AHAW *et al.*, 2023; Kaur *et al.*, 2023; Greene *et al.*, 2024). For farmers operating under variable milk prices and rising input costs, the adoption of such measures is not always feasible. This gap between technical potential and practical implementation is a recurring issue, suggesting that economic conditions and policy support are central to any meaningful transition toward sustainability.

Technological innovation is often presented as a major driver of progress in dairy systems. PLF, genetic improvement, and advanced feeding strategies offer clear advantages in monitoring, efficiency, and management. However, their impact should not be overstated. Technology can improve the performance of existing systems, but it does not eliminate the underlying trade-offs between productivity, environmental impact, and welfare. In some cases, it may even reinforce existing production models rather than encouraging more fundamental changes. Rather than focusing on identifying a single best approach, a more realistic objective is to improve the balance between environmental, economic, and welfare outcomes within existing systems. This involves recognising trade-offs, prioritising context-appropriate strategies, and integrating multiple approaches in a coordinated way. Progress is therefore likely to depend less on individual innovations and more on how effectively they are combined and adapted in practice.

Sustainable cow milk production is a complex and multi-dimensional horizon, requiring the integration of environmental, economic, and social considerations. Despite advances in management practices, technology, and policy frameworks, several challenges continue to affect the adoption and effectiveness of sustainable dairy systems. Additionally, recognising research limitations is critical for guiding future studies and evidence-based decision-making. A central challenge in dairy systems is balancing high productivity with environmental and social sustainability. Intensive production can increase milk yield per cow and reduce per-unit costs, but often results in higher greenhouse gas emissions, nutrient surpluses, and potential welfare concerns. Conversely, low-input or pasture-based systems may enhance biodiversity, animal welfare,

and ecosystem services but can reduce productivity per hectare and require more land. Effective strategies must consider local conditions, resource availability, and farm-scale contexts to manage these trade-offs.

Climate variability and extreme weather events pose both direct and indirect threats to sustainable dairy production. Heat stress, drought, and altered rainfall patterns can affect forage availability, water resources, and animal health, reducing milk yield and herd resilience. Additionally, dairy farming contributes to climate change through CH₄ and NO₂ emissions, creating a feedback loop that necessitates both mitigation and adaptation strategies. Economic viability remains a major barrier to implementing sustainable practices. High initial costs for precision technologies, renewable energy, or improved housing can limit adoption, particularly for small-scale farms. Market volatility, fluctuating milk prices, and limited access to premium markets for sustainably produced milk reduce incentives for change. Financial support mechanisms, subsidies, and access to markets are essential to encourage investment in sustainable solutions. Fragmented or inconsistent policy frameworks can hinder the adoption of sustainable practices. Integrated policies that simultaneously address environmental impact, animal welfare, and economic viability are rare, making it difficult for farmers to align their management with sustainability goals. Clear, consistent, and incentivised regulatory frameworks are essential to accelerate the transition to sustainable dairy systems.

CONCLUSIONS

This study showed that sustainable cow milk production is a multidimensional issue that depends on the balanced integration of environmental, economic, and animal welfare objectives. It was found that dairy systems contribute important benefits to food security, rural livelihoods, and the supply of high-quality animal protein, but the analysis also showed that these benefits are accompanied by relevant sustainability pressures. In particular, cow milk production was associated with environmental impacts such as greenhouse gas emissions, especially methane and nitrous oxide, as well as water use, land use, nutrient losses, biodiversity decline, nutrient pollution, water scarcity, and land-use pressure. These findings confirm that environmental sustainability remains one of the central challenges for the dairy sector.

The analysis also showed that economic sustainability is essential for the adoption of improved production practices. Profitability, production efficiency, input costs, and farm resilience were identified as key dimensions influencing the capacity of dairy farms to implement more sustainable strategies. It was found that price volatility, rising feed and energy costs, and financial barriers to innovation can limit the transition towards more efficient and environmentally responsible

systems. Therefore, economic viability should not be treated as separate from sustainability, but as a necessary condition for farmers to invest in new technologies, improved management, and long-term adaptation.

Animal welfare was also identified as a central component of sustainable dairy farming. The study showed that animal health, behaviour, longevity, housing conditions, and societal acceptance are closely linked to both productivity and ethical responsibility. It was found that problems such as lameness, mastitis, inadequate housing, and broader ethical concerns remain major barriers to achieving sustainable milk production. These results indicate that improving animal welfare can support better health, longer productive life, improved efficiency, and stronger consumer trust.

Altogether, the findings show that no single solution is sufficient to ensure sustainable cow milk production. Instead, sustainability depends on combining technological, nutritional, genetic, managerial, economic, and welfare-based strategies within context-specific production systems. Precision livestock farming, automated monitoring, data analytics, selective breeding and genetic improvement, optimised nutrition, methane-reducing diets, circular feeding systems, renewable energy, nutrient recycling, agroecological approaches, and crop-livestock integration were all identified as

relevant tools. However, the study showed that their effectiveness depends on practical implementation, farm resources, market conditions, policy support, and consumer expectations.

Future research should focus on integrating these tools into coherent, multi-dimensional frameworks that address environmental, economic, and social objectives simultaneously, rather than treating them as isolated interventions. Further studies should also examine how market and consumer influence, including demand for sustainable and high-welfare dairy products, labelling, certification schemes, and premium pricing, can support adoption at farm level. Collaborative research involving farmers, researchers, policymakers, and industry stakeholders will be essential to develop context-specific solutions that balance productivity, environmental stewardship, animal welfare, and social responsibility.

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Інтеграція екологічних, економічних та соціальних аспектів у сталий розвиток молочного тваринництва: огляд літератури

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Анотація. Стале виробництво коров'ячого молока має вирішальне значення для глобальної продовольчої безпеки, засобів до існування сільського населення та харчування людей, проте воно пов'язане з екологічними, економічними та етичними викликами. Системи молочного тваринництва суттєво впливають на викиди парникових газів, використання води та землі, втрати поживних речовин та біорізноманіття, а також визначають добробут тварин і прибутковість господарств. Мета цього огляду полягала в тому, щоб дослідити, як захист навколишнього середовища, економічна доцільність, ефективне використання ресурсів та добробут тварин інтегровані в сталі системи молочного тваринництва. Було проведено структурований описовий огляд новітньої наукової літератури та узагальнено дані щодо викидів парникових газів, використання землі та води, управління поживними речовинами, здоров'я тварин, умов утримання, прибутковості господарств, точного тваринництва, генетичного вдосконалення, харчування, стратегій циркулярної економіки та політичної підтримки. Огляд показав, що стале молочне виробництво вимагає збалансованих дій у екологічному, економічному та соціальному вимірах, оскільки покращення в одній сфері часто призводить до компромісів в іншій. Вплив на навколишнє середовище досліджувався через такі стратегії, як підвищення ефективності годівлі, раціони, що зменшують викиди метану, управління гноєм, пасовищні системи, раціональне використання води, рециркуляція поживних речовин, використання відновлюваних джерел енергії та інтегроване рослинництво й тваринництво. Питання добробуту тварин було проаналізовано як центральний компонент сталого розвитку, а належні умови утримання, доступ до пасовищ, профілактична ветеринарна допомога, зменшення випадків кульгавості та маститу, подовження продуктивного віку тварин та сертифікація добробуту були визначені як фактори, що сприяють як етичній відповідальності, так і підвищенню ефективності господарств. Економічну стійкість було визначено як необхідну передумову для впровадження стійких практик, оскільки ефективність виробництва, контроль витрат, ринкові стимули, політична підтримка та управління ризиками визначають, чи зможуть фермери зберегти прибутковість, одночасно покращуючи екологічні показники та показники добробуту тварин. Ці результати можуть бути використані молочними фермерами, консультантами, дослідниками, політиками, органами сертифікації та зацікавленими сторонами галузі для розробки, оцінки та просування більш стійких, ефективних та етично відповідальних систем виробництва молочної продукції

Ключові слова: агроєкологія; циркулярна економіка; ефективність використання кормів; точне тваринництво; ефективне використання ресурсів
