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World dairy system sustainability: a milk quality perspective

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The dairy industry is a crucial component of global food systems, providing essential nutrition and economic benefits to billions of livelihoods worldwide. Amidst growing challenges, the potential of milk quality to transform sustainability efforts in the dairy processing industry and milk production systems is increasingly evident. This review discusses and investigates milk quality as a key driver for achieving environmental efficiency, reducing waste, and enhancing processing outcomes, all while safeguarding consumer health and delivering superior nutritional value. The use of improved technologies such as precision farming, automatic milking systems, and genetic selection are explored as transformative tools to enhance milk quality and optimize resource use to uplift sustainability within the industry. The dairy industry must reduce emissions associated with milk processing, while the dairy farming sector must address emissions at the raw milk production stage. Case studies included in this article illustrate successful models integrating milk quality into sustainability frameworks, emphasizing regional adaptations. Future research must prioritize to maintain or uplift the milk quality through development of climate-resilient dairy systems, innovations in circular economy practices, and scalable solutions for low- and middle-income regions. Integrating milk quality into sustainability initiatives ensures balanced economic, environmental, and social benefits, fostering resilience in the global dairy sector.

KEYWORDS

milk hygiene standards, sustainable livestock farming, premium-quality raw milk, circular dairy economy, climate-resilient dairy

1 Introduction

Dairy products provide vital nutrients, including protein, calcium, and vitamins, integral to human health, particularly for vulnerable populations such as children and the elderly (Rozenberg et al., 2016). Furthermore, the dairy sector supports millions of livelihoods, from smallholder farmers in developing nations to large-scale operations in industrialized countries (FAO, 2021). As demand for dairy products increases due to factors like population growth, urbanization, changing food preferences, and rising incomes, the dairy sector faces significant sustainability challenges, as highlighted in the IFCN Dairy Report (2024). The report notes a recovery in demand but also growing pressures from high input costs, trade imbalances, and environmental concerns. These challenges also include environmental impact, animal welfare, resource efficiency, economic viability, and milk quality assurance.

High-quality milk or premium-quality raw milk, as defined by international standards such as Codex Alimentarius and European Commission (2004), refers to raw milk with low total bacterial count (typically <100,000 cfu/mL), low somatic cell count (<400,000 cells/mL), absence of antibiotic and chemical residues, optimal composition (fat and protein content), and proper hygiene. Such quality benchmarks enhance operational efficiency, reduce environmental impacts, and support sustainable dairy system

(Fiorillo and Amico, 2024; FAO, 2021). However, achieving sustainability requires a holistic evaluation that integrates quality-focused performance indicators with economic dimensions such as operational efficiency, strategic investments, and financial strength. By adopting a comprehensive and collaborative approach across the supply chain, the dairy industry can innovate, adapt to challenges, and ensure long-term sustainability.

Milk meeting hygiene and compositional standards enhances yield, reduces waste, enhances processing efficiency, and supports consumer health, all of which are critical for the long-term viability of the dairy industry. Conversely, poor-quality milk that is characterized by high somatic cell counts (SCC), microbial and other contamination, residuals or adulteration on the other hand, can lead to increased safety risks for consumers, higher resource use, increased food waste, and greater environmental footprints, undermining efforts to create a sustainable dairy system. By prioritizing milk quality, stakeholders in the dairy industry can navigate these challenges and build a system that balances productivity, sustainability, and equity. Hence this article, explores the interplay of milk quality and sustainability across traditional, plant-based, and artificial milk systems, focusing on environmental, nutritional, and socioeconomic impacts. The discussions further emphasizes innovations in dairy practices, comparative Life Cycle Assessment (LCA), and regional case studies, aligning milk production with Sustainable Development Goals (SDGs) to foster a resilient, equitable, and sustainable dairy industry.

2 The role of milk quality in sustainability

From a sustainability perspective, improving milk quality contributes to three major areas as illustrated in Figure 1 and discussed within this section.

2.1 Reducing resource use

Milk that meets strict hygiene and compositional criteria is critical in enhancing the efficiency and sustainability of both milk production and downstream processing systems. The intrinsic quality of milk that is characterized by low bacterial counts, optimal SCC, appropriate freezing point and composition (e.g., fat and protein levels), and the absence of residuals and contaminants have far-reaching implications for reducing environmental impacts, energy consumption, and resource use. Thus, ensuring delivery of milk meeting hygiene and compositional standards, at the production stage is crucial for achieving sustainable and resource-efficient dairy systems. A study by Lovarelli et al. (2024) reported that precision livestock farming technologies, such as mechanical ventilation and automatic milking systems (AMS), further enhance resource use efficiency and thereby environmental sustainability. Using a case study on an Italian dairy farm and fat and protein corrected milk as functional unit, authors demonstrated that mechanical ventilation reduced the impact of climate change by 16%, while AMS contributed an additional 3% reduction by improving productivity. Additionally, Tse et al. (2018) have reported that AMS can reduce labor and improve milking consistency, their impact on milk quality depends on management practices such as hygiene protocols and cow traffic management.

Resource-efficient dairy systems may have the potential to reduce the environmental footprint by minimizing the need for corrective measures, optimizing energy use, and conserving water and chemical resources. Farm-level best practices, quality monitoring, and advancements in milk processing are vital for achieving resource-efficient and sustainable dairy systems. Furthermore, it supports a circular economy approach and aligns with broader sustainability goals in agriculture and food systems. However, future research should integrate environmental and economic evaluations to ensure the sustainable adoption of mitigation actions related to the environmental impact of milk production (Rencricca et al., 2023). Thus, continued emphasis on farm-level best practices, quality monitoring, and innovations in milk processing will be essential for maximizing these benefits as detailed below.

2.1.1 Impact on processing efficiency and resource conservation

Milk with low bacterial counts minimizes the need for frequent cleaning and sterilization in processing plants, significantly reducing water consumption and the use of cleaning agents, such as detergents and sanitisers. Studies have shown that microbial contamination in milk can lead to biofilm formation in pipelines and processing equipment, necessitating rigorous cleaning protocols. These hygiene practices apply also primarily at the farm level, such as teat cleaning and equipment sanitation, but extend to processing facilities as well. For example, according to Goetz et al. (2024), biofilm build-up in milk processing plants not only compromises product quality but also increased the frequency of cleaning cycles, leading to higher water and energy demands. By supplying premium-quality raw milk, the dairy industry can cut down on cleaning cycles, saving substantial quantities of water and cleaning chemicals.

2.1.2 Reduction in corrective actions

Corrective treatments, such as chemical adjustments to stabilize pH or re-pasteurization to eliminate microbial contaminants, are resource-intensive processes. Premium-quality raw milk that meets required standards upon initial collection reduces the likelihood of such interventions. Re-pasteurization, for example, can increase energy consumption significantly; with one study estimating that correcting suboptimal milk quality can double the energy requirement for processing (Hemme et al., 2014). Moreover, avoiding corrective treatments reduces the risk of off-flavors or nutritional losses in the final product, improving overall product quality and consumer acceptance. According to Calahorrano-Moreno et al. (2022), alternative methods for cow's milk treatment, including high-pressure processing, and membrane filtration, offer safer, more energy-efficient options. These methods aim to eliminate microbial contaminants and improve milk safety while preserving its quality. Research into these alternatives showed potential for reducing energy use, offering a more sustainable approach to milk treatment while maintaining consumer acceptance and nutritional integrity.

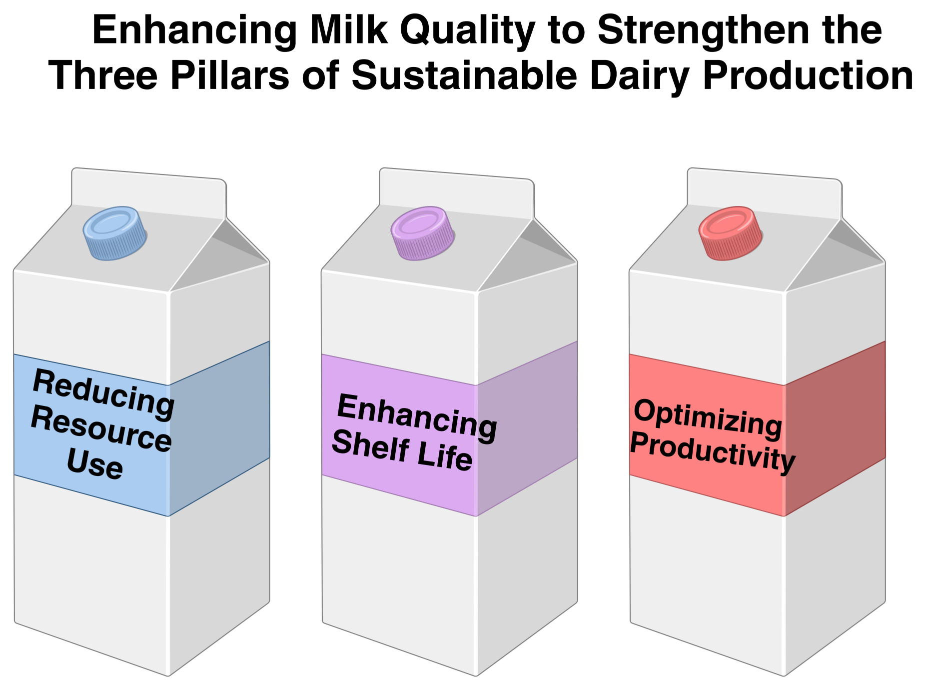

FIGURE 1
Enhancing milk quality to strengthen the three pillars of sustainable dairy production. Created in BioRender. Priyashantha, H. (2025) https://BioRender.com/i30r886.

2.1.3 Energy efficiency and carbon footprint

Energy efficiency and carbon footprint are critical factors in enhancing milk quality and sustainability, particularly for small dairy systems. Malliaroudaki et al. (2022) discussed, in deciding on the most energy-conserving methods, one is to establish a set of small-scale dairy production sites dispersed across an area, which can reduce energy consumption in transport and contribute to local agricultural development. Alternatively, upgrading and enlargement of existing dairy production sites can achieve maximum energy efficiency, since larger sites generally have lower per-unit output energy requirements, though with higher distribution energy demands. A study by Egas et al. (2021) highlighted that small dairies consume significant energy during both farming and processing stages, with diesel and electricity as major contributors to energy use and CO_2 emissions. Key improvements, such as implementing LED lamps and energy management systems, can reduce electricity consumption by 5%, lowering emissions and costs while supporting environmental performance. Optimizing cold chamber operations and mitigating temperature losses can further enhance efficiency. These measures not only reduce the environmental impact but also ensure sustainable production and improved milk quality

At the processing stage, particularly in cheese and yogurt production, milk quality directly influences yield and product quality. Milk with high SCC or bacterial contamination requires additional cooling, heating, or separation steps, all of which consume more energy. For instance, Benbrook et al. (2018) highlighted that low-SCC milk facilitates improved cheese yield and reduces the need for enzymatic or chemical additives, reorganizing the processing chain, and cutting energy inputs. Additionally, by reducing the need for secondary treatments, processors can avoid releasing excess carbon emissions, contributing to more sustainable dairy operations.

2.1.4 Implications for antibiotic use

Producing premium-quality raw milk that meets required standards upon initial collection reduces the begins at the farm level, where good management practices, such as proper milking hygiene and udder health monitoring, play a crucial role in reducing the incidence of mastitis and other infections such as *E. coli*, *Streptococcus uberis*, and *Staphylococcus aureus*. These bacteria are some of the principal aetiological agents of bovine mastitis. *E. coli* commonly produces acute environmental mastitis, *S. uberis* is commonly observed in subclinical and environmental infections, while *S. aureus* is an important contagious pathogen often linked with chronic intramammary infections (Keane, 2019). These practices, along with broader farm-related factors such as feeding strategies, cow breed, milking systems, and environmental conditions, significantly influence the composition, technological properties, and microbiota of raw milk, thereby affecting its suitability for specific end uses, including cheesemaking (Priyashantha and Lundh, 2021). Reduced infection rates translate to decreased reliance on antibiotics, mitigating the risk of antibiotic residues in milk and reducing the environmental footprint associated with antibiotic production and disposal. However, widespread misuse of antibiotics in dairy farming, including practices such as administering without prescriptions or ignoring withdrawal periods, poses significant threats to milk quality, human health, and the environment. Thus, this article advocates the use of "pharmaceuticals" *sensu lato* (in the broad sense) and "antibiotics" *sensu stricto* (in the strict sense).

Training programs for farmers have shown potential to reduce antibiotic residues in milk, highlighting the need for improved animal health monitoring, veterinary oversight, and stricter regulations to promote sustainable and responsible dairy farming practices (Iraguha et al., 2024). Antimicrobial resistance poses a global threat to public health, driven by the misuse and overuse of antibiotics in medicine and food production. In response, the World Health Assembly in 2015 adopted a global action plan focused on raising awareness, advancing research, preventing infections, optimizing antibiotic use, and ensuring sustainable investment in new medical solutions. This aligns with global efforts to promote antibiotic stewardship in agriculture to combat antimicrobial resistance (WHO, 2015).

The misuse of antibiotics in dairy animals leads to residues in raw milk, impacting milk quality and presenting health risks. Commonly detected antibiotics include tetracyclines, sulfonamides, and quinolones, with rapid detection kits and chromatography being the primary monitoring methods. Ensuring the absence of these residues is critical for maintaining milk safety. This necessitates the development of more efficient detection techniques and stricter control measures. These efforts primarily focus on raw milk quality assessment at the farm level, which is crucial for maintaining quality control prior to processing in the dairy industry (Costa et al., 2024). Additionally, the rising antibiotic residues in milk have raised public health concerns, and while chromatography remains a reliable detection method, further research is needed to develop cost-effective alternatives (Sachi et al., 2019).

2.1.5 Circular economy and waste management

Premium-quality raw milk also contributes to a more circular economy within the dairy industry. By minimizing processing waste, such as curd particles or spoilage-related rejections, dairy plants can recover and utilize by-products more efficiently. For example, whey protein, a by-product of cheese production, retains higher nutritional and commercial value when derived from high-quality milk (Smithers, 2008). This reduces waste generation and supports the valorization of dairy co-products, including whey, cream, and permeate, which are better utilized when sourced from milk meeting hygiene and compositional standards, thereby adding both economic and environmental value to the dairy supply chain.

Cheese whey and second cheese whey, traditionally considered waste products, offer significant potential for enhancing milk quality through their incorporation into functional food ingredients. Valorizing these by-products aligns with Circular Economy principles, reducing environmental impact by transforming waste into valuable resources. While cheese whey has been widely utilized in food products, second cheese whey remains underexplored. Future research should focus on developing sustainable technologies to valorise second cheese whey, promoting better milk quality, improving waste management practices, and contributing to economic gains in the dairy industry (Pires et al., 2021).

An integrated framework combining LCA and energy accounting effectively addresses environmental hotspots in dairy production, such as cleaning processes and energy use (Oliveira et al., 2021). Interventions like technological upgrades and renewable energy adoption significantly reduce environmental impacts, enhance resource efficiency, and improve working conditions. This multi-method approach delivers a comprehensive evaluation, promoting sustainability and improving milk quality in dairy systems. The integration of circular economy principles into dairy farming practices offers a transformative approach to improving milk quality while addressing environmental concerns. By employing LCA of manure and sewage management strategies, such as waste-to-energy, composting, and recycling, a study by Zhang et al. (2021) highlighted their potential in reducing environmental impacts like global warming and eutrophication. Technologies like anaerobic mono-digestion stand out for their significant mitigation benefits. However, regional, economic, and farm-scale variations emphasize the need for tailored strategies to maximize sustainability outcomes. Advancing innovations in manure and sewage management strategies can ensure the quality in milk production aligns with circular economy goals, fostering environmental, economic, and social benefits.

2.2 Enhancing shelf life

Premium-quality raw milk, characterized by low SCC, bacterial levels and compositional standards, plays a pivotal role in extending the shelf life of dairy products. High-quality raw milk enhances the production efficiency and quality of processed dairy products by minimizing enzymatic activity and spoilage risks caused by bacterial contamination (Figure 2). A study by Murphy et al. (2016) discussed milk with SCC levels below 200,000 cells/mL yields better cheese quality and reduces defects in fluid milk, yogurt, and milk powder. Furthermore, low bacterial counts provide flexibility in processing and storage, reducing the likelihood of spoilage during extended shelf-life operations.

Low microbial counts (<10,000 cfu/mL) in raw milk reduced the presence of heat-resistant enzymes such as proteases and lipases, which can degrade proteins and fats, leading to off-flavors during storage (Barbano et al., 2006). Similarly, low SCC (<50,000 cells/mL) minimized the levels of plasmin and lipoprotein lipase, enzymes associated with proteolysis and lipolysis that compromise the sensory quality of products over storage. Although regulatory limits for SCC often permit up to 200,000 cells/mL, subclinical mastitis can occur at levels exceeding 100,000 cells/mL (Barbano et al., 2006), thereby impacting cheese yield and shelf life.

Effective farm-level practices, including maintaining cow health, improving sanitation, and rapidly cooling milk, contribute to lowering microbial and SCC levels. Enhanced post-pasteurization technologies, such as microfiltration and precise temperature control, further support the extended shelf life of milk by preventing bacterial growth. Barbano et al. (2006) showed that milk with low SCC and bacterial counts can achieve refrigerated shelf lives of up to 60–90 days, preserving flavor and nutritional quality. Thus, fostering collaborations between farmers and processors to maintain stringent quality standards is essential for producing dairy products with superior shelf life and consumer appeal.

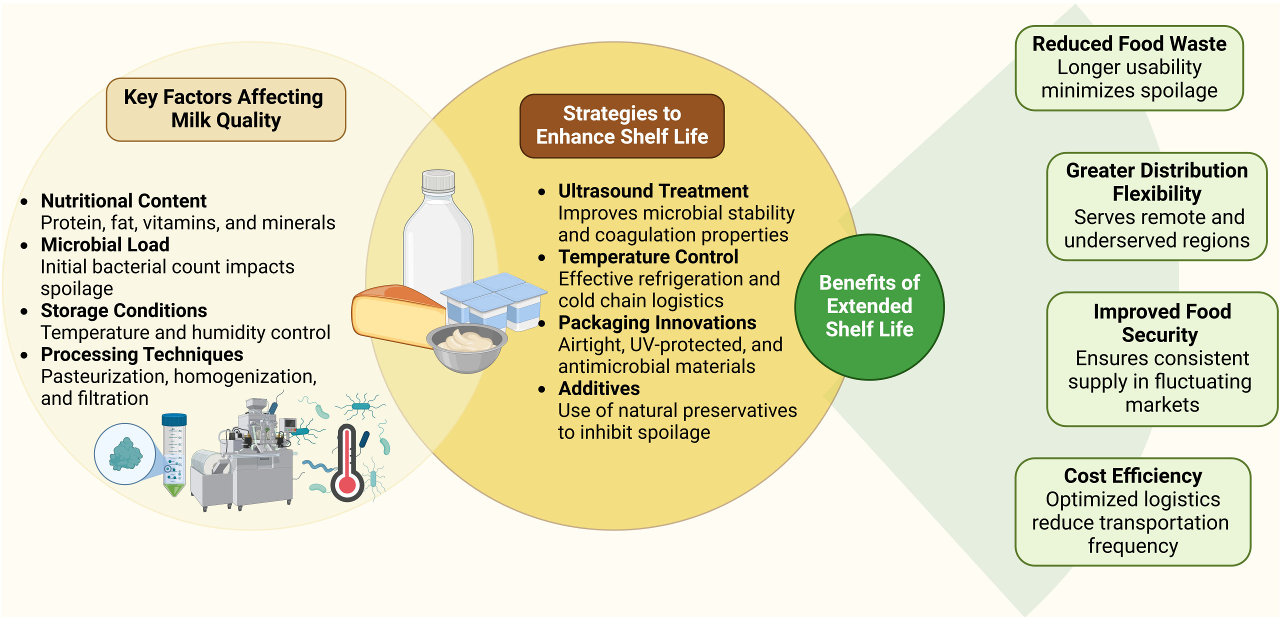

FIGURE 2
Milk quality and shelf life enhancement; Key factors, strategies, and benefits. Created in BioRender. Priyashantha, H. (2025) https://BioRender.com/y36k438.

Longer shelf life is pivotal for improving food distribution, especially in regions with underdeveloped cold chain infrastructure. By allowing more time for storage and transportation, it ensures food quality over extended periods, reducing postharvest losses and food waste (Mustafa et al., 2024). Further, technological advancements like the Internet of Things, radio-frequency identification, and artificial intelligence optimize temperature control and traceability, enabling perishable goods such as dairy to reach remote areas efficiently and safely. These technologies enhance information sharing, collaboration, and transparency in the supply chain, reducing waste and improving customer satisfaction. This flexibility bridges infrastructure gaps, supports equitable access to dairy, and aligns with sustainability goals. Scientific studies have shown that milk with lower SCC and optimal fat-protein ratios produces longer-lasting dairy products, benefiting both consumers and retailers by reducing spoilage rates. Research indicates that digitalization of the supply chain, including the use of blockchain and AI, can significantly improve logistics planning, inventory management, and real-time monitoring, thereby extending the shelf life of dairy products. For example, a study by Kumar and Shankar (2024) demonstrated that implementing IoT and AI in dairy supply chains reduced spoilage and improved delivery times. Future efforts must, therefore, focus on scalable innovations to extend shelf life, fostering resilience in global dairy food supply chains.

2.3 Optimizing productivity

Efficient milk utilization in processing relies on optimizing both yield and composition to improve value-added product outputs like cheese and yogurt. Feed-to-yield concentrate allocation systems as presented by Craig et al. (2022) target nutrient precision by aligning feed intake with cows' requirements, increasing milk yield and production efficiency. However, higher yields are often accompanied by reduced milk fat and protein concentrations due to genetic factors, diet, and dilution effects (Ponnampalam et al., 2024). This decline in milk composition affects the economic value of milk for processing, particularly for products relying on fat and protein content. Strategies to address this include genetic selection for favorable traits, diet optimization to mitigate dilution effects, and incentive structures rewarding both yield and composition. While feed-to-yield concentrate allocation systems enhance nitrogen and energy use efficiency, their economic viability depends on balancing higher yields with maintaining milk quality for value-added products.

Efficient milk use in processing relies on optimizing dairy efficiency through tailored on-farm strategies that balance productivity and sustainability (de Ondarza and Tricarico, 2017). Utilizing multiple efficiency metrics, such as nutrient usage and feed efficiency, milk yield and quality can be improved while reducing environmental impacts. Key interventions such as targeted nutrition, forage management, and consistent feeding practices, which enhance nutrient retention and production of milk rich in fat and protein, which is essential for value-added products like cheese and yogurt. Improving feed efficiency and income over feed cost is essential for sustainable milk production and high-quality dairy processing (Bach et al., 2020). While increased milk yields could reduced the maintenance costs, diminishing nutrient conversion efficiency at higher yields necessitates precision feeding tailored to production levels (Figure 3). Strategic management of feed inputs, genetics, and metabolic efficiency enhances milk composition and supports the production of value-added products like cheese and yogurt.

FIGURE 3
Optimized dairy cow nutrition for enhancing milk quality and sustainability. While the specific feed ingredients of the Total Mixed Ration (TMR) provided in this image are not provided, it is essential to note that balanced and high-quality feed rations are crucial for achieving these goals.

High-protein milk significantly enhances cheese yield, reducing waste during production and improving efficiency. Studies on microbial transglutaminase treatments during cheese-making demonstrate that increased protein retention and reduced curd fine loss are key factors in improving yield and quality (Cadavid et al., 2020). Hence, microbial transglutaminase-treated cheese, derived from protein-rich milk, exhibits enhanced structural integrity and nutritional value due to protein cross-linking, which strengthens the cheese matrix and retains more water and nutrients. High-protein milk enhanced cheese yield and reduces waste, especially when paired with innovative cheesemaking processes that improve control and flexibility while minimizing energy and water use (Chamberland et al., 2019). By enriching liquid pre-cheese with aromatic matrices, these methods optimized milk utilization by maximizing protein retention, minimizing curd loss, and delivering consistent texture and flavor. Such processes offer a sustainable and economically viable approach to cheese production. These outcomes highlight the value of high-protein milk in minimizing waste, improving product consistency, and maximizing economic returns in dairy processing.

Advancements in near-infrared hyperspectral (NIR-HS) imaging, combined with chemometric tools, have enabled dairy facilities to predict cheese ripening end-dates with precision, facilitating the efficient sorting and maturation of cheeses (Priyashantha et al., 2021a). Additionally, hyperspectral imaging technologies provide rapid, non-destructive methods for evaluating milk and cheese composition, particularly during cheese maturation. By enabling spatial and chemical analysis, these technologies predict cheese maturity with 76% accuracy (Priyashantha et al., 2020), supporting more efficient use of ripening facilities and ensuring optimal product quality. This technology exemplifies how advanced analytical methods can optimize resource use and enhance sustainability by ensuring high-quality dairy products are produced while minimizing waste and inefficiencies.

Precision dairy systems such as AMS enabled automated monitoring of milk composition, facilitating the segregation of premium-quality raw milk for value-added products (Hogenboom et al., 2019). Automatic milking systems increased milk production through more frequent milking while maintaining essential milk characteristics crucial for industrial processing. However, managing enzyme activity and bacterial growth due to shorter milk residence times in the udder requires further optimization to ensure consistent quality.

3 Raw milk quality control: a systems approach

Managing raw milk quality while ensuring sustainability demands a comprehensive systems-based approach (Figure 4). Martin et al. (2023) reviewed the importance of a system-based approach to milk quality and microbiological aspects by advocating for integration across the dairy supply chain, proactive management using predictive tools, and data-driven decisions. This aligns with the need to link farm practices, microbial control, and processing parameters to finished product outcomes, ensuring sustainability and minimizing waste while enhancing quality and consumer satisfaction. This framework, extendable to other dairy products and additional sustainability indicators, offers a scalable strategy for designing efficient and sustainable dairy supply chains. Such an approach fosters the production of high-quality raw

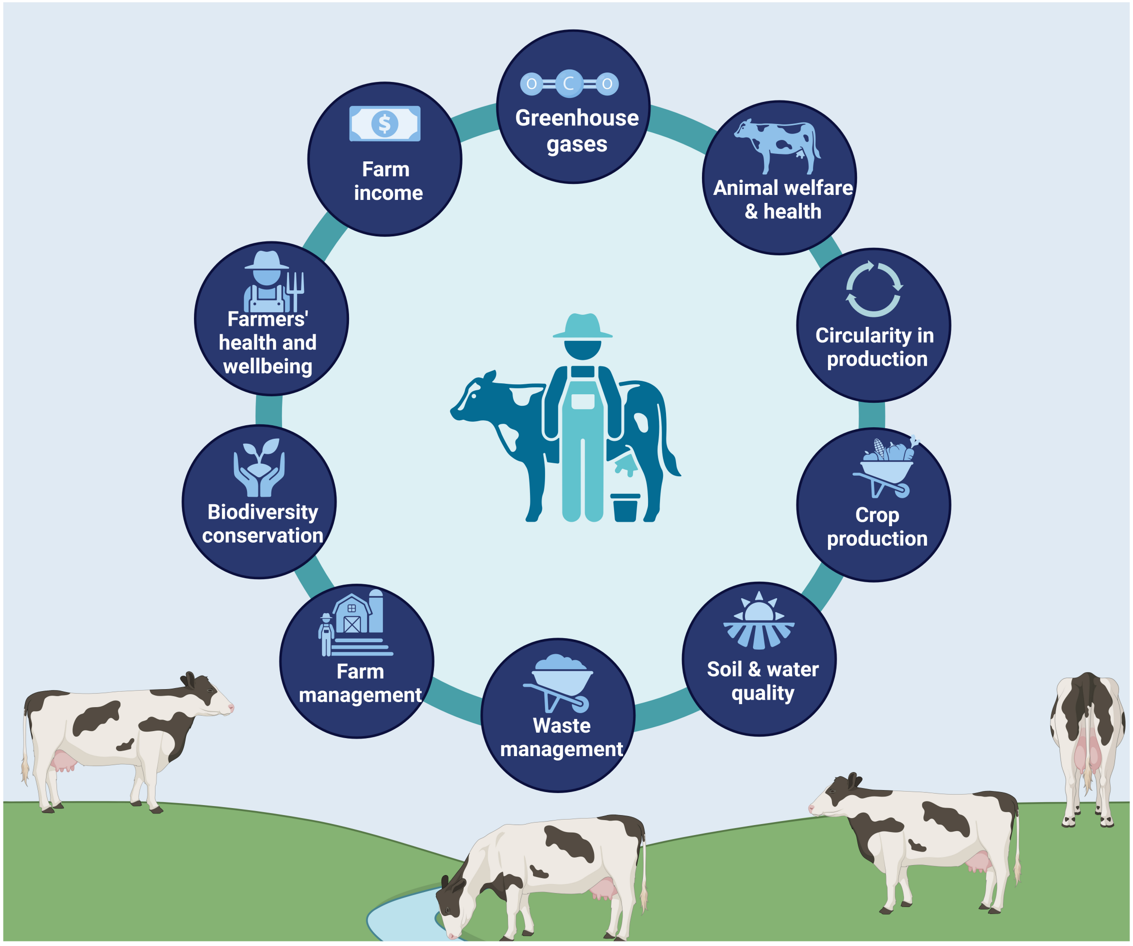

FIGURE 4
A systems-based approach to managing raw milk quality for sustainable dairy production. Created in BioRender. Priyashantha, H. (2025) https://BioRender.com/k65z336.

milk, minimizes environmental impacts, and promotes economic viability, addressing the needs of both producers and consumers. The systems-based approach integrates lean, agile, sustainable, resilient, and nutrition paradigms to enhance milk quality across the dairy supply chain (Talukder et al., 2021). By systematically evaluating key performance indicators from procurement to processing and distribution, the framework ensures that nutritional value, environmental sustainability, and operational efficiency are prioritized. This approach facilitates the production of high-quality milk products while addressing public health needs, thereby adding value to dairy products and supporting sustainable supply chain management.

This systems-based approach integrates biological, technological, environmental, economic, and social components to optimize the dairy supply chain. A Bulgarian case study by Kirilova and Vaklieva-Bancheva (2017) on curd production highlighted this, using interconnected models for production, logistics, and environmental impact assessment. Key findings emphasized milk fat content as a critical variable balancing product quality, profitability, and environmental performance. Environmental metrics, such as biological oxygen demand and CO_2 emissions, are monetized to align sustainability with economic goals. CO_2 emissions significantly drive costs, advocating for greener energy adoption. A case study by Shamsuddoha et al. (2023) in Bangladesh demonstrated the application of system dynamics modeling to design sustainable supply chain frameworks. By incorporating waste management loops, the study transformed dairy by-products into value-added products like biogas and fertilizers, reducing environmental impact and enhancing economic viability. Additionally, integrating reverse logistics and optimizing feed intake ratios promoted resource efficiency, improving milk production and overall profitability. This approach highlighted the importance of aligning stakeholder collaboration, government regulations, and evolving consumer demands for organic and sustainable dairy products.

3.1 Biological inputs and animal health

The foundation of raw milk quality lies in farm-level practices (Priyashantha and Lundh, 2021), where animal health and welfare play key roles. Implementing strategies like genetic

FIGURE 5
Milking parlor hygiene and milking technology are crucial for ensuring milk quality and safety. **(A)** The current state of the milking parlor shows significant areas for improvement. The dairy cows appear dirty, and the cleanliness of the milking parlor is not optimal, highlighting the need for better hygiene practices and technological upgrades. **(B)** The current state of the milking parlor reflects good management and attention to hygiene. The dairy cows appear clean, and the parlor environment is well-maintained, demonstrating adherence to best practices and the effective use of modern milking technologies.

selection enables the breeding of livestock with desirable traits such as improved milk quality, enhanced disease resistance, and adaptability to changing environmental conditions (Brito et al., 2021). These advancements have significantly increased productivity in the dairy industry while reducing the total number of cattle. However, intensive selection for traits like milk yield has led to challenges, including diminished genetic diversity and negative impacts on animal health, fertility, and resilience. Moving forward, the industry must prioritize breeding goals that incorporate traits for animal welfare, environmental efficiency, and robustness, alongside milk quality.

Integrating local and crossbreeding strategies, diversifying production systems, and leveraging advanced phenotyping and genomic tools can drive sustainable dairy farming. Research comparing indigenous cattle breeds, Thamankaduwa White (TW) and Lankan cattle (LC), with Friesian and Jersey cows highlighted the superior textural, sensory, and microstructural qualities of set-yogurts made from indigenous milk (Weerasingha et al., 2022). Promoting the use of native livestock breeds not only supports high-quality dairy and meat production but also conserves genetic diversity, fosters rural livelihoods, and enhances the system's ability to withstand economic and environmental disruptions (Priyashantha and Vidanarachchi, 2024).

Nutritional optimization improves milk quality by adjusting ruminant diets to enhance composition while reducing environmental impacts like methane emissions. Strategic feeding, such as using diverse forages and supplements, affects milk fat, fatty acids, and sensory properties (Ponnampalam et al., 2024). Pasture-based systems boost omega-3 and conjugated linoleic acid levels, while concentrate diets increase fat and omega-6. Omega-3-rich oils enhance nutrition, and enriched diet also promotes immune response (Bragaglio et al., 2015), though lipid oxidation must be managed. Using agricultural by-products supports sustainability and improves milk quality. These strategies should align with ruminants' growth needs for sustainable, high-quality milk production. Increasing dietary concentrate supplementation in dairy cows enhances milk production, reduces greenhouse gas emissions per unit of milk, and boosts farm profitability (Dida et al., 2024). Farms supplementing with $\geq$3 tons concentrate dry matter/cow per year observed a 14% reduction in emission intensity and a 73% increased in milk production compared to those with $\leq$1 tons concentrate dry matter/cow. This strategy benefits both the environment and dairy farmers, though further studies on carbon sequestration and nutrient excretion are needed for improved decision-making.

Advanced health monitoring tools, including wearable sensors and diagnostic technologies integrated with the Internet of Things, enable real-time, accurate monitoring of individual dairy cows, improving farm management and animal welfare. These technologies, part of precision livestock farming, allow for the early detection of illnesses like mastitis, preventing severe health issues and enhancing milk quality and yield. By continuously monitoring indicators such as lameness, body condition, and mastitis, farmers can make data-driven decisions that optimize both animal welfare and farm productivity, addressing the challenges of larger dairy herds and improving sustainability (Silva et al., 2021; Tangorra et al., 2024). These measures ensure not only the health of the animals but also the sustainability of milk production systems.

3.2 Milking practices and hygiene

Proper milking practices and hygiene standards are critical in maintaining raw milk quality (Figure 5). The increasing global interest in raw milk consumption, driven by health benefits, taste, and support for local agriculture, has led to the development of strict safety protocols to ensure hygienic production. Various systems as reviewed by Berge and Baars (2020), such as the German Vorzugsmilch and the Raw Milk Institute's risk management program in North America, demonstrated that raw milk can be produced safely with high standards of hygiene and biosecurity, reducing risks of microbial contamination and zoonotic diseases. These systems highlighted the importance of good animal husbandry practices, hygienic milking techniques, and regular microbial testing to ensure the safety and quality of raw milk for direct consumption. This involves regular maintenance of milking equipment to ensure efficiency and prevent contamination. Standard operating procedures for pre- and post-milking sanitation reduce microbial risks and improve overall milk hygiene.

Over the past century, the dairy farming has embraced technology to enhance yield and efficiency, including the introduction of AMS. The adoption of AMS and robotics has further enhanced consistency in milk extraction, reduced labor demands, and minimized human-induced contamination (Hogenboom et al., 2019). AMS can increase milk production, reduce labor, and improve cow welfare by allowing voluntary milking. However, its benefits can be compromised by management challenges, such as cows not milking voluntarily. A review by Jacobs and Siegford (2012) comparing AMS to conventional parlors demonstrated no significant effect on milk composition, but AMS can increased free fatty acids in milk, impacting quality. Hygienic aspects like somatic cell count and mastitis detection can also vary. Authors also suggested AMS can support high milk quality when integrated with appropriate hygiene and management practices, including proper teat cleaning and mastitis monitoring. By maximizing these technologies, producers can maintain high standards of milk quality while improving operational efficiency.

3.3 Processing and transport

The quality of raw milk is dynamic and begins to degrade soon after harvesting. Effective systems for processing and transport are crucial for preserving milk's integrity, particularly in the context of non-bovine milk, which plays a vital role in food security and economic development (Deshwal et al., 2021). As global demand for minimally processed fresh foods rises, innovative food processing methods have demonstrated significant potential in enhancing microbial safety, extending shelf life, and preserving milk's nutritional and functional properties with minimal quality degradation. While conventional methods like pasteurization and ultra-high temperature processing ensure milk safety, they may cause nutritional losses and changes in color and flavor. Emerging technologies, including high-pressure processing, ultrasound, and microwave heating, offer significant potential to enhance microbial inactivation, extend shelf life, and preserve nutritional value while minimizing adverse effects. Unlike traditional thermal methods, which can lead to nutritional losses and undesirable flavor changes, high-pressure processing maintains essential components, including aroma-related and nutritional elements, while improving the organoleptic properties of milk and dairy products (Ozaybi, 2024).

Temperature control is essential in preventing microbial growth, and cold chain logistics ensures the safety and quality of perishable goods. While it reduces food waste and supports industries like pre-cooked dishes, the significant carbon emissions from cold storage pose sustainability challenges (Niu et al., 2024). Shifting to eco-friendly refrigerants, such as hydrocarbons, hydrofluorocarbons, R744 (carbon dioxide), hydrofluoro olefin, and nanorefrigerants (Kasaeian et al., 2018) can reduce environmental impact, and cold storage systems with large heat capacities offer potential for energy storage. In regions lacking reliable cold chains, such as parts of Sub-Saharan Africa and South Asia, solar-powered milk chillers and lactoperoxidase enzyme systems have been explored as viable technologies to maintain milk quality during transport and storage (FAO, 2021). These methods help preserve milk for several hours without refrigeration, supporting safety in informal dairy industries. Real-time monitoring technologies, such as Internet of Things-enabled sensors, track critical parameters like temperature, pH, and microbial counts during storage and transportation, enhancing milk quality control (Dragone et al., 2024). A sensor-driven system integrates machine learning to identify anomalies and ensure traceability, improving safety and quality in the dairy supply chain. This system provides early detection of issues, highlighting specific cow characteristics and enabling predictive quality control. Blockchain technology provides a transparent and traceable system for quality assurance, enabling stakeholders to ensure compliance and enhance consumer trust. Research indicated that blockchain-enabled food traceability significantly increased trust in the organic food chain, positively influencing consumer purchase behavior (Duong et al., 2024). Furthermore, consumer knowledge about blockchain amplified the system's effects on trust and purchasing decisions, highlighting the importance of blockchain literacy in fostering consumer confidence.

3.4 Quality assurance and compliance

Quality assurance systems are essential for managing risks and ensuring compliance with regulatory standards, especially in milk production. Incorporating Hazard Analysis and Critical Control Points (HACCP) principles enables systematic monitoring of risks throughout the dairy supply chain. This approach ensures the safety and quality of milk by identifying critical control points in the production, processing, and distribution stages (Stanley et al., 2011). The application of HACCP in organic food supply chains, including dairy, helps manage both food safety hazards and organic integrity, enhancing overall quality assurance. Furthermore, specialized HACCP training manuals and workshops tailored to the dairy industry support the effective implementation of these systems to maintain high milk quality standards testing protocols for parameters such as somatic cell count, microbial load, and antibiotic residues ensure that milk meets safety and quality benchmarks.

Aligning dairy production practices with international standards, such as Codex Alimentarius, is a critical strategy for facilitating access to global markets and ensuring the economic sustainability of dairy operations. This alignment helps dairy farmers meet food safety, quality, and sustainability expectations, which are increasingly important for both consumers and regulatory bodies. In regions like East Africa, where informal dairy markets dominate, incorporating these international standards into local production practices can drive the integration of small-scale, informal producers into the formal markets (Kilima et al., 2024). By aligning local supply chains with international benchmarks, dairy operations can gain access to export opportunities, enhance product quality, and improve competitiveness on the global setup. Furthermore, the co-operative model, which can help marginalized stakeholders meet sustainability standards through capacity building and certification, is particularly effective in aligning smallholder farmers with international practices. By combining policy support, investments in training, and the adoption of globally recognized standards, dairy producers can ensure both economic sustainability and the broader development of the dairy industry.

In organic farming systems, stringent quality control is necessary due to strict residue-free requirements governing veterinary inputs and feed additives. The varying adoption rates of organic dairy practices across European countries highlight the importance of aligning farming practices with sustainability standards. As illustrated by Verburg et al. (2022), in the Netherlands, challenges in the diffusion of organic dairy farming can be attributed to insufficient market formation, inadequate governmental support, and the lack of financial incentives for farmers. A more consistent, systemic approach to supporting organic and sustainable dairy practices, e.g., diversified certification systems and financial subsidies can facilitate compliance with sustainability standards, promote quality assurance, and ultimately drive the economic sustainability of dairy operations.

3.5 Integrating sustainability

A systems approach integrates sustainability into raw milk production at farm level, with quantifying environmental impacts such as greenhouse gas emissions, water use, and land changes (Fan et al., 2022). While LCA supports sustainability decision-making, challenges remain in refining its impact assessment methods and adapting them to regional contexts. Additionally, LCA currently lacks integration of social indicators, although efforts to broaden its scope are ongoing. Conventional LCA frameworks have been criticized for their limited ability to capture socio-economic dimensions such as labor conditions, rural livelihoods, and equity. To address these gaps, complementary tools like Social Life Cycle Assessment (S-LCA), Prospective Life Cycle Assessment (pLCA), Shared Socioeconomic Pathways (SSPs), Life Cycle Costing (LCC), and hybrid LCA approaches are being developed to incorporate broader sustainability metrics (Hackenhaar et al., 2024; Nurdiawati et al., 2025). Future research should focus on developing region-specific data, improving functional units to reflect broader product aspects, and integrating LCA with other models to address economic and societal factors. These efforts will enhance LCA's effectiveness in supporting sustainable agricultural decisions.

Renewable energy solutions, like solar-powered milking systems, help reduce carbon footprints, while repurposing cattle manure for biogas production offers significant environmental and economic benefits (Figure 6). In Indonesia, biogas from cattle manure can replace coal-powered electricity and liquid petroleum gas, cutting carbon emissions by up to 6.78 tons per village per day (Kusmiyati et al., 2023). It also reduces the need for urea fertilizers by 44% and can save households and the national budget millions in energy and fertilizer costs. This approach enhances energy security, supports sustainable agriculture, and contributes to a greener future. This circular economy approach minimizes waste and enhances resource efficiency. The transition toward sustainable economies requires improved resource efficiency, and the dairy industry in Latin America has continued to grow without a clear sustainable energy and waste management plan as highlighted by Villarroel-Schneider et al. (2022). This study proposes integrated waste-to-energy solutions, focusing on biogas production from cattle manure. It highlights technology solutions such as biodigesters, power generators, and combined heat and power systems, which can meet energy demands (e.g., cooking gas, electricity, refrigeration, and hot water) while also providing organic fertilizers.

Adopting cost-effective practices like precision feeding and resource optimization enhances profitability while promoting sustainability (Figure 6). Incentive-based programs tied to short-term economic benefits boost adoption rates, with long-term success driven by perceived farm and environmental benefits (Piñeiro et al., 2020). Further, education and extension services are crucial in empowering smallholder farmers to adopt sustainable practices. Tailored policies that consider the target population's needs and the trade-offs between economic, environmental, and social outcomes are key to fostering long-term sustainable practices.

Transparent sustainability labeling on food products can guide consumers toward more informed and sustainable choices (Figure 6). While consumer understanding of sustainability information is often limited, effective labeling, particularly when backed by trusted authorities, can influence attitudes and purchasing behavior (Cook et al., 2023). Labels with intuitive visual cues, like traffic light colors, have proven to be more impactful, encouraging a higher willingness to pay for sustainably sourced products. Addressing health concerns, such as antibiotic residues and nutritional quality, also enhances consumer confidence in milk products.

3.6 Modeling and decision support

Advanced modeling tools, including System Dynamics, Agent-Based Models, and Multi-Criteria Decision Analysis, are instrumental in analyzing complex systems. These tools simulate the impacts of various interventions, identify trade-offs among sustainability objectives, and optimize resource distribution (Ding et al., 2018). Such tools can support informed decision-making for policymakers, producers, and stakeholders, ensuring that interventions align with both quality and sustainability goals.

A systems-based approach to raw milk quality control integrates multiple dimensions of dairy production, ensuring optimal outcomes for quality, sustainability, and economic

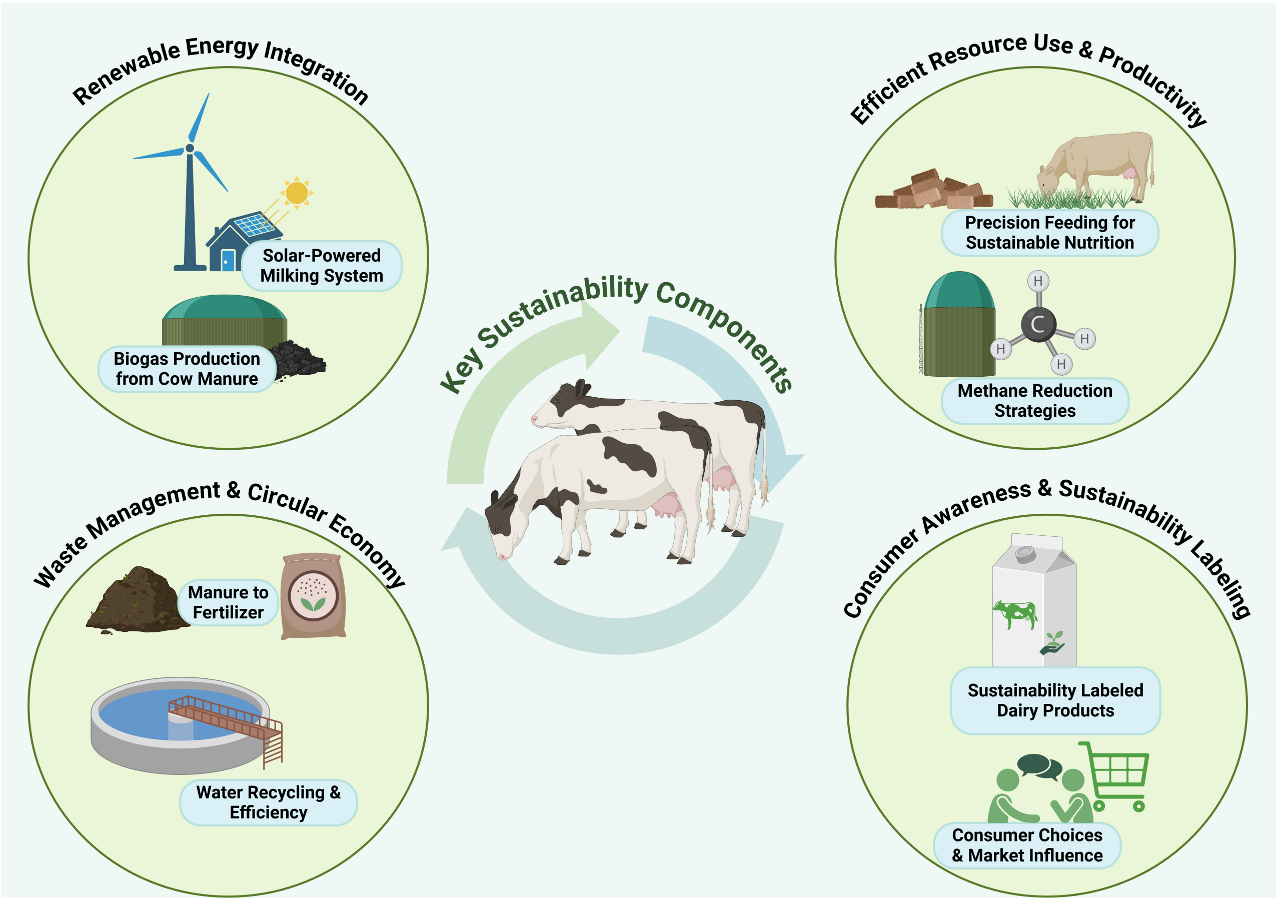

FIGURE 6
A circular systems approach for sustainable dairy production; Illustrating the integration of renewable energy, waste management, precision feeding, and sustainable resource use in dairy farming to enhance efficiency, reduce environmental impact, and support a resilient dairy value chain. Created in BioRender. Priyashantha, H. (2025) https://BioRender.com/e85z862.

viability. Collaborative quality control between dairy farmers and processors, supported by government intervention, can effectively address market failures and improve dairy product quality (Yang et al., 2023). Implementing advanced preventive strategies for farmers and advanced inspection strategies for processors, backed by subsidies or penalties, creates synergies that optimize quality control. Government and/or industrial support, including subsidies for advanced strategies and penalties for non-compliance, enhance collaboration and ensures the safety and profitability of dairy products. By addressing interdependencies across the supply chain, this holistic methodology aligns dairy production with global sustainability goals, including environmental conservation, economic resilience, and social equity (Manzoor et al., 2024). Effective food waste management, including redistribution, recovery, and reuse strategies, minimizes surplus and provides economic and environmental benefits. Overcoming challenges like technological limitations, inaccurate forecasts, and food standards is key to shifting consumption and production patterns. Through continuous innovation and collaboration, this approach not only reduces waste but also supports SDGs related to hunger, sustainable agriculture, economic growth, and climate action, transforming the dairy industry into a model of sustainable agricultural practice.

4 Data-driven efforts in the dairy industry for improving milk quality and sustainability

The dairy industry's reliance on data-driven methodologies to enhance milk quality and sustainability marks a significant evolution in its operational framework as illustrated in Figure 7. By integrating diverse data sources, such as herd activity monitors, weather patterns, and milking records, and applying advanced algorithms like artificial intelligence and machine learning, dairy farms can improve decision-making tools to enhance management efficiency, animal welfare, and economic outcomes (Cabrera and Fadul-Pacheco, 2021). However, addressing challenges in data governance, quality, and integration through robust data warehouses and collaborative approaches is critical to unlocking the full potential of precision dairy farming for sustainable practices and ensuring milk quality.

LCA have enabled the sector to comprehensively evaluate environmental impacts across the value chain, from "cradle to grave" (Fan et al., 2022). These assessments provide insights into emissions, resource use, and energy efficiency, forming a robust

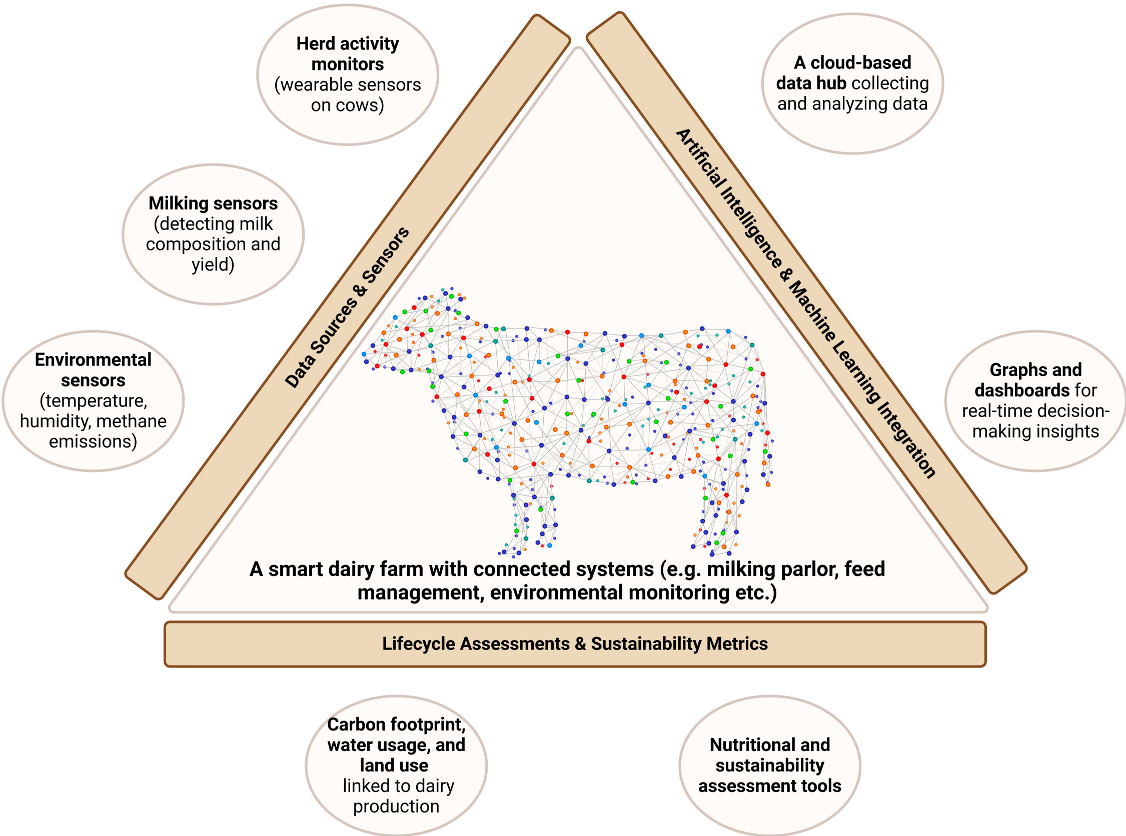

FIGURE 7
Data-driven innovations in dairy farming to enhance milk quality and sustainability through precision farming, AI, and LCA. Created in BioRender. Priyashantha, H. (2025) https://BioRender.com/d39w604.

foundation for sustainability benchmarking. The incorporation of health-focused metrics, such as nutritional quality through indices and sustainability measures can exemplifies a holistic approach to sustainability in dietary assessments (Bôto et al., 2024). These methodologies ensure that environmental gains, evaluated through carbon footprint, water footprint, land use, and related sustainability indicators are achieved without compromising the nutritional value, health benefits, or economic viability of food systems (Shabir et al., 2023). Effective food supply chain management, incorporating sustainable energy sources, energy-efficient equipment, and biodegradable packaging, plays a pivotal role in reducing greenhouse gas emissions and preserving natural resources. By optimizing processes such as food production, preservation, and packaging, these approaches strive to balance the competing demands of environmental conservation, resource efficiency, and affordability, ensuring a holistic framework for sustainable food systems. Additionally, advanced technologies like precision agriculture and real-time monitoring systems optimize resource use while maintaining high milk quality. Moreover, sector-wide collaboration and transparency, driven by standardized data frameworks, foster consistency and comparability across geographic and economic contexts.

However, there are limitations to these data-driven efforts. While a strong emphasis on quantifiable metrics, such as greenhouse gas emissions per calorie, provides valuable insights, it often overlooks multifaceted considerations like cultural acceptability, ecosystem biodiversity, and the unintended consequences of technology adoption, including e-waste and resource inequities (Dwivedi et al., 2022; Shabir et al., 2023). Addressing climate challenges requires not only technological innovation but also responsible digitalization, which balances environmental trade-offs with societal needs. These complexities highlight the need for a holistic and inclusive approach that integrates measurable outcomes essential for achieving true sustainability while avoiding unintended harm to marginalized communities and ecosystems.

Sustainable milk production solutions are often extrapolated from industrialized contexts where state-of-the-art technologies and infrastructure are available. In doing this, however, such models may inadvertently overlook the specific constraints that characterize low- and middle-income countries, where dairy production is a lifeline for rural livelihoods but is constrained by limited access to digital infrastructure, financial capital, and technological inputs (Cowie et al., 2020). A singular focus on emissions reduction risks sidelining no less important issues of milk affordability and nutritional access, thereby compounding food insecurity and economic vulnerability. To counter this, Cowie et al. (2020) propose a "Responsible Rural Research and Innovation" agenda fostering the development of regionally tailored solutions, attuned to socio-cultural processes, rural infrastructures, and technological change's broader implications for milk yield and quality.

Data reliability across diverse dairy systems varies significantly, with inconsistencies in collection methods, particularly in developing regions, undermining global assessments and comparisons (Riera et al., 2023). Moreover, the absence of universally accepted sustainability indicators further complicates benchmarking and progress measurement. This emphasizes the need for inclusive approaches that integrate diversity and sustainability assessments to address these challenges effectively. Future frameworks should incorporate diverse metrics, including sociocultural, economic, and health-related indicators while leveraging artificial intelligence and the Internet of Things to analyse complex data streams (Neethirajan, 2023). Investments in capacity building and technology transfer to low- and middle-income countries, along with collaborative efforts to standardize data collection and bridge technological gaps, are essential for equitable and globally representative strategies. Policymakers should leverage data-driven insights to create adaptive regulations that balance environmental, economic, and nutritional priorities (Mana et al., 2024). Further, integrating behavioral and societal dynamics into these strategies can improve sustainability interventions by addressing consumer preferences, producer challenges, and broader societal trends.

5 Sustainability challenges and the role of milk quality

5.1 Environmental impact

The dairy farming is a significant contributor to greenhouse gas emissions, water consumption, and land use. According to the FAO, dairy farming (mainly cattle) accounts for ∼4% of global greenhouse gas emissions, largely due to enteric fermentation, manure management, and feed production (FAO, 2021). Ruminant livestock farming, including cattle, goats, and sheep, are major contributors to global greenhouse gas emissions. Together, they account for up to 18% of global emissions when assessed through LCA, with cattle being the dominant source (O'Mara, 2011). Accordingly, Asia, Africa, and Latin America produce nearly half of global ruminant products but are responsible for almost 69% of enteric methane emissions, highlighting significant regional inefficiencies in emission intensity. Improving milk quality can mitigate these impacts per unit of milk by reducing spoilage and enhancing processing efficiency. For instance, milk with lower microbial contamination requires fewer resources for pasteurization and processing, leading to reduced energy and water use. Additionally, premium-quality raw milk increases the yield of dairy products like cheese and yogurt, thereby reducing the environmental footprint per unit of product.

5.2 Animal welfare

Milk quality is directly linked to the health and wellbeing of dairy animals. Stress, poor nutrition, and inadequate housing increase somatic cell counts in milk, compromising its quality, reducing shelf life, and signaling potential mammary health issues in dairy animals (Alhussien and Dang, 2018). Moreover, proper management, nutrition, and hygiene practices are essential to maintain low somatic cell counts and ensure better milk quality. Prioritizing animal welfare through proper feeding, housing, and healthcare not only enhances milk quality but also aligns with ethical farming practices. According to Karlsson et al. (2023), Sweden's dairy industry illustrates how high animal welfare standards, such as reduced veterinary treatments and improved disease management, align with enhanced milk quality and sustainability, emphasizing the interconnectedness of welfare and productivity.

5.3 Resource efficiency

Milk meeting hygiene and compositional standards optimizes the use of resources across the dairy value chain. From farm to consumer, milk that meets quality standards reduces the need for additional inputs such as cleaning agents, antibiotics, or energy-intensive processing, contributing to more sustainable production systems (Figure 8). In Sweden, innovative practices like precision feeding and real-time milk testing enhance resource efficiency, enabling high-quality raw milk production with minimal inputs and waste (Krizsan et al., 2021). These approaches align with the country's national food strategy, which aims for self-sufficiency, sustainability, and reduced environmental impact, while meeting consumer demand for high-value, nutrient-rich dairy products. Further, efficient feeding and methane mitigation strategies also help reduce greenhouse gas emissions, supporting climate goals and sustainable dairy practices.

5.4 Economic viability

For farmers, premium-quality raw milk often commands higher market prices, improving profitability and incentivizing sustainable practices. For processors, such milk enhances yields and returns in value-added products like cheese and yogurt. Furthermore, farm-level sustainability and ecosystem service provision can further improve the environmental and economic performance of dairy systems. As demonstrated by Robert Kiefer et al. (2015), carbon footprints of dairy farms vary significantly depending on allocation methods used in LCA, ranging from 1.99 kg to 0.68 kg CO_2eq/kg fat and protein corrected milk, particularly when ecosystem services and multifunctionality (e.g., biodiversity conservation, landscape stewardship) are accounted for. These findings underscore the importance of adopting broader sustainability metrics beyond production volume, thereby reinforcing the value of premium-quality milk in systems that deliver both product and public goods. However, dairy farmers' satisfaction with prices depends on factors like price transparency, price-quality ratio, and fairness, rather than just the price itself (Simões et al., 2024). These multidimensional aspects influence satisfaction with dairy processors and supply chain

FIGURE 8
Cheese processing factory utilizing premium-grade raw milk for sustainable and efficient dairy product manufacturing.

coordination. Improved business relations, built on trust and transparency, can further enhance satisfaction and loyalty in competitive markets. In developing regions, initiatives focused on improving milk quality, such as training programs and testing access, can help smallholder farmers engage in formal markets, boosting their income. A study by Ma et al. (2024) showed that market participation significantly enhances farmers' income, wellbeing, and dietary diversity, with e-commerce playing a key role in expanding market access. Policies that support better market linkages, address farmers' preferences, and reduce market power imbalances can drive rural economic growth and poverty reduction.

5.5 Consumer trust and health

As consumer awareness of food safety and nutrition rises, demand for high-quality dairy products grows. Ensuring milk quality not only builds consumer trust but also supports public health and long-term market stability. Research has demonstrated that consumers are willing to pay a premium for attributes like milk quality, safety, and sustainability, which can enhance the market value of dairy products (Madududu et al., 2024). Additionally, consumer perceptions of milk quality vary, with a focus on both technical and subjective attributes, highlighting the importance of communication and education to align expectations across stakeholders (Castellini et al., 2023).

5.6 Food waste and milk quality

Poor milk quality, often due to microbial contamination, significantly contributes to food waste, as contaminated milk is discarded during processing. In the United States, about a quarter of dairy products are lost or wasted annually, with premature spoilage caused by microbes like *Pseudomonas* and *Paenibacillus* being a major factor (Martin et al., 2021). Hence, reducing microbial spoilage through strategies such as on-farm contamination control and advanced microbiological techniques can help decrease waste and improve the sustainability of the dairy industry. High microbiological and compositional quality of raw milk reduces spoilage and increases shelf life of dairy products. Advanced technologies, such as rapid microbial detection and in-package sensors, have been key in reducing milk waste in industrialized countries. These methods provide faster, more reliable results at a lower cost than traditional techniques, enabling real-time monitoring of spoilage and pathogens throughout the dairy supply chain (Ziyaina et al., 2020). This enhances milk quality, and processing efficiency, and helps reduce waste while improving safety and marketability.

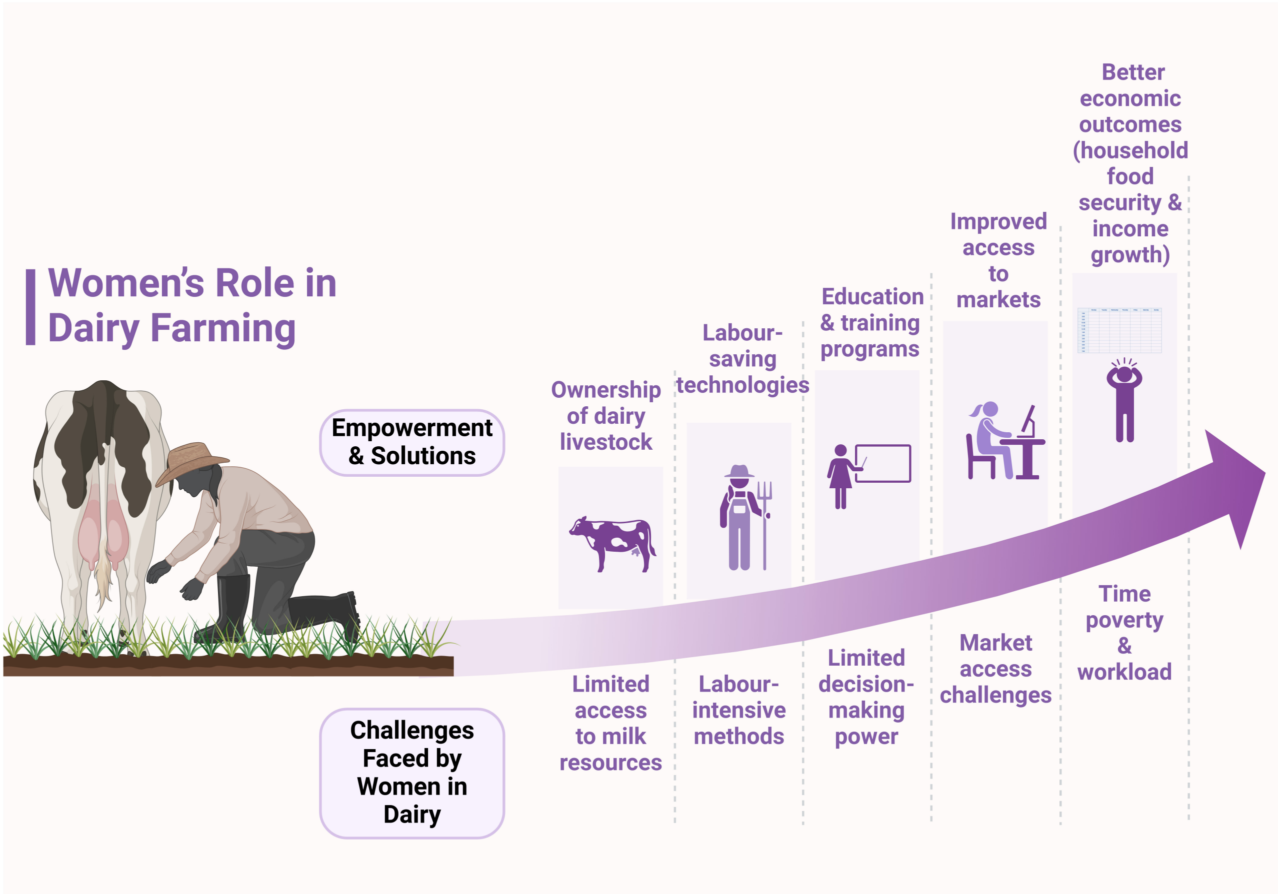

FIGURE 9
Women in dairy play a crucial role in milk production, processing, and rural livelihoods, facing challenges that can be addressed through empowerment strategies and sustainable solutions. Priyashantha, H. (2025). Women in dairy. https://app.biorender.com/profile/template/details/t-683644eeb976383f304b7701-women-in-dairy.

5.7 Women in dairy (inclusive dairy farming)

Women play a strategic role in dairy farming, especially in developing regions, where they manage milk safety, value addition, and marketing (Figure 9). They are key contributors to milk processing, including butter and ghee production (Nagasha et al., 2024). However, women face challenges in accessing sufficient milk, using labor-intensive methods, and limited market access, with men typically controlling the decision-making process (Figure 9). Addressing these challenges through training and better market access can enhance women's roles, strengthen rural livelihoods, and improve dairy production. Empowering women through education and resources to improve milk quality can lead to better economic outcomes and sustainable practices. Supporting women with dairy livestock assets can enhance their economic empowerment, improving household incomes and food security (Bain et al., 2018). However, women's involvement in dairy farming also increases their labor burden, often leading to time poverty, especially when they lack decision-making power (Figure 9). Empowering women in dairy farming can reduce these burdens, but interventions must address gender inequalities and structural challenges, such as access to water and labor-saving technologies, to ensure the benefits are equitable and sustainable.

5.8 Climate change and milk quality

Climate change–induced temperature increases, and unpredictable weather patterns have critical implications for dairy farming, notably through the impact of heat stress on milk yield and composition. Heat stress in dairy cattle has been consistently associated with reductions in dry matter intake and overall energy balance, leading to measurable declines in milk yield and quality. Specifically, energy-corrected milk (ECM) output can decrease by up to 20% under high temperature-humidity index (THI) conditions (Chen et al., 2024). Unlike raw milk or fat- and protein-corrected milk (FPCM), ECM reflects the energy density of milk, integrating fat and protein contributions. As heat stress diminishes nutrient intake and metabolic efficiency, it leads to reductions in milk fat and protein percentages, thereby disproportionately affecting ECM relative to raw milk volume or FPCM output. Furthermore, breed-specific variation in thermal tolerance has been observed. Jersey and Brown Swiss breeds, for instance, display greater resilience to heat stress than Holsteins, attributable to physiological traits such as smaller body mass, increased sweating rates, and adaptive feed conversion efficiency under thermal load (Safa et al., 2019; Lovarelli et al., 2024; Habimana et al., 2023; West, 2003).

Heat stress in dairy animals can reduce milk quality, primarily by lowering protein content, as demonstrated by Chen et al. (2024). For example, heat stress leads to a decrease in dry matter intake and energy-corrected milk yield, particularly as the temperature-humidity index increases, with reductions of 4.13% in dry matter intake and 3.25% in energy-corrected milk for every unit increase in temperature-humidity index. However, milk fat content often remains unaffected (Chen et al., 2024; Vroege et al., 2023). Adaptation strategies, such as climate-controlled housing and the use of heat-tolerant breeds, are essential to mitigate the effects of extreme heat and maintain milk production in the face of climate change.

6 Plant-based alternatives and milk quality: sustainability and scientific perspectives

The rise of plant-based alternatives, i.e., almond, oat, soy etc., emphasizes a significant shift in consumer priorities toward sustainability. These options typically demand fewer natural resources and generate lower greenhouse gas emissions compared to traditional milk. However, the environmental benefits of plant-based alternatives vary by crops and regions. According to Kandhway et al. (2025), almond farming is highly water-intensive, and climate change is expected to further increase its water demands. Warming temperatures may extend the growing season, raising water use by 1–3%. While almond milk has a lower greenhouse gas footprint compared to dairy, its significant water consumption makes it less sustainable than other plant-based options, such as soy or oat milk, especially in water-scarce regions. Despite fortification, these substitutes lack the nutritional complexity of dairy, including essential proteins, fats, and bioactive compounds critical for human health, nutrient bioavailability, and functional food applications.

Advancements in artificial milk production, including precision fermentation and mammary epithelial cell culture, aim to replicate dairy milk's key components without livestock (Eisner, 2024). These technologies promise to reduce methane emissions, land use, and zoonotic risks while enabling production in diverse regions. Yet, they face substantial challenges, such as replicating the intricate colloidal systems of casein micelles, milk fat globule membranes, and bioactive components like immunoglobulins present in dairy. High energy demands, industrial input reliance, and potential waste by-products limit their current scalability and raise environmental and socioeconomic questions.

Traditional dairy farming is evolving with innovative practices like methane-reducing feed additives, regenerative agriculture, and water-efficient techniques (Neethirajan, 2024). These advancements aimed to reduce environmental impacts while supporting rural livelihoods and biodiversity. The integration of circular agricultural practices, such as waste management and carbon sequestration, further enhances sustainability, fostering a more environmentally aligned dairy industry. This shift is essential in addressing the ecological footprint of the dairy industry, ultimately contributing to climate change mitigation efforts.

From a nutritional standpoint, traditional dairy remains unparalleled. Its proteins, including caseins and whey, provide a balanced amino acid profile and possess various bioactive properties like antimicrobial and anti-lipidemic effects. These proteins, along with peptides released during digestion, contribute significantly to health benefits such as satiety, immune modulation, and gut health. While plant-based and artificial alternatives contribute to food diversity, traditional dairy's complex matrix, with its superior digestibility and nutrient bioavailability, continues to offer a nutritionally rich, functionally beneficial, and sustainable option (Auestad and Layman, 2021; Weaver, 2021).

A recent review by Khanpit et al. (2024) examined the environmental impacts of animal-based milk (cattle, buffalo, goat, and sheep) and plant-based liquids (almond, oat, soy, pea, and coconut) through LCA studies, establishing a universal framework for comparison. Plant-based liquids generally showed a lower global warming potential, acidification, and land use, while animal-based milk outperforms plant-based liquids in water footprints and energy use. Authors have identified as key mitigation areas include enteric fermentation, manure management, and feeding strategies for animal-based milk in dairy farming, and emissions from processing, packaging, and transportation for plant-based liquids. However, limitations in data and variations in LCA methodologies highlighted the need for standardized research to reduce uncertainties and improve sustainability across milk systems.

7 Case studies in milk quality and sustainability

7.1 The Netherlands: sustainable dairy chain initiative

The Netherlands' Sustainable Dairy Chain initiative, launched in 2010, integrates milk quality into its comprehensive sustainability framework (van Erve, 2025). By fostering collaboration among dairy organizations, farmers, and societal stakeholders, the initiative focuses on four key objectives; climate-neutral development, livestock health and welfare improvement, grazing preservation, and biodiversity protection. Milk quality is central to the initiative, supported by advanced technologies like real-time monitoring systems that track somatic cell counts and bacterial loads. These technologies enhance information sharing, collaboration, and transparency in the supply chain, reducing waste and improving customer satisfaction. These systems ensure high milk quality while optimizing herd health and reducing antibiotic use. Additionally, tools such as the annual nutrient cycle assessment help farmers manage feed and fertilizer use, indirectly enhancing milk composition and safety. For example, the introduction of grazing premiums and the establishment of the Grazing Foundation have played significant roles in promoting sustainable practices and improving milk quality. The Grazing Foundation, established in 2007, financially supports farmers who continue grazing practices and provides advice through trained grazing advisors (Runhaar et al., 2020).

7.2 India: Amul and smallholder farmers

In India, Amul, one of the largest dairy cooperatives, partners with millions of smallholder farmers to enhance milk quality and promote sustainable production practices. Amul's initiatives include training programs on hygienic milking practices, providing access to veterinary services, and deploying bulk milk chillers to preserve milk quality in rural areas (Makwana et al., 2022). These efforts have significantly reduced spoilage, improved farmer incomes, and ensured a steady supply of quality milk for processing, demonstrating the importance of grassroots-level interventions in developing regions.

7.3 New Zealand: pasture-based dairy systems

New Zealand's dairy industry exemplifies the synergy of sustainability and milk quality through its pasture-based systems. Cows grazing on nutrient-rich ryegrass and clover pastures produce milk with higher fat and protein content, enhancing product quality (Luo and Ledgard, 2021). However, the New Zealand's dairy sector is also responding to significant socio-ecological issues due to increasing intensification and global demand for high-quality milk powder (Bojovic and McGregor, 2025). Existing research identifies the need for sustainable changes, identifying three key pathways: de-intensification, diversification, and the development of dairy alternatives (e.g., plant-based and precision fermentation). Increased inputs, including targeted nitrogen fertilizers and externally sourced feeds, have improved nitrogen utilization efficiency, reducing nitrogen losses per unit of milk while supporting higher milk solids production.

7.4 Sweden: integrated approaches to milk quality

Sweden's dairy industry integrates sustainability and milk quality through advanced technologies and environmental stewardship, setting a benchmark in modern dairy farming. Farms prioritize low SCC and microbial loads, crucial indicators of hygiene and udder health, to meet stringent EU standards. Dairy farmers are recognized annually by the Federation of Swedish Farmers (LRF) with the LRF Gold Medal for consistently maintaining and delivering high-quality milk to their respective dairies (LRF Dairy, 2025). The Swedish dairy industry has made significant advances in sustainability, where the methane emission reduction in the dairy sector was achieved through improved feed efficiency, increased milk yield, technological advancements, organic farming practices, reduction in dairy cow numbers, and supportive legislative changes. These strategies collectively led to a 36% decline in total enteric methane emissions from 1990 to 2020 (Karlsson et al., 2023). However, challenges remain in ecosystem support due to reduced semi-natural grasslands, requiring future policies to balance emission reductions with biodiversity preservation.

Seasonal variations in Swedish milk (non-seasonal calving dairy farming systems) composition, including fluctuations in fat, protein, and lactose levels, are carefully managed through advanced farm practices to ensure consistent quality year-round. For example, fat and protein content are typically lowest in August, while casein micelle size and proteolytic activities, such as plasmin and plasminogen, vary significantly throughout the year (Priyashantha et al., 2021b). These fluctuations highlight the complexity of milk production systems, particularly during outdoor grazing periods when milk attributes like casein micelle size are smallest. Despite these variations, research showed that as long as raw milk meets minimum quality criteria, its impact on cheese ripening time and product texture remains limited, emphasizing the importance of robust farm management and process control in maintaining high-quality dairy production.

7.5 Global: comprehensive performance indicators

A review by Fiorillo and Amico (2024) explored the role of milk quality and sustainability in the dairy industry, focusing on the need for a holistic approach to economic sustainability. The dairy sector, while integral to global food systems, faces growing challenges due to competition, particularly in saturated markets. Current economic performance indicators used by dairy farms are found to be insufficient, lacking the necessary depth to measure the complex interaction of variables that contribute to long-term sustainability. The authors emphasized the adoption of additional indicators across dimensions like operational efficiency, strategic investments, and financial strength, which are essential to maintaining competitiveness and quality. It calls for the development of a comprehensive set of sector-specific indicators to inform decision-making and strengthen supply chain resilience. Furthermore, integrating these indicators across various stakeholders in the dairy supply chain, such as processors and distributors, can foster greater collaboration, increase investments, and drive innovation for sustainable growth.

8 Linking milk quality to the Sustainable Development Goals (SDGs)

Premium-quality raw milk plays a critical role in achieving multiple SDGs, as illustrated in Figure 10. It contributes to SDG 2 (Zero Hunger) by addressing malnutrition through the provision of essential nutrients and to SDG 3 (Good Health and WellBeing) by ensuring safe consumption and improving public health. The active participation of women in dairy farming supports SDG 5 (Gender Equality) by enhancing economic empowerment and promoting gender-inclusive livelihoods. Additionally, the dairy sector generates employment opportunities, aligning with SDG 8 (Decent Work and Economic Growth). Sustainable dairy practices contribute to SDG 12 (Responsible Consumption and Production) by minimizing waste and improving resource efficiency, while efforts to reduce greenhouse gas emissions and enhance climate resilience support SDG 13 (Climate Action).

FIGURE 10
The premium-quality raw milk plays a critical role in achieving multiple SDGs, as illustrated in this figure, raw milk in achieving Sustainable Development Goals (SDGs) through improved nutrition, economic empowerment, responsible production, and climate resilience. Created in BioRender. Priyashantha, H. (2025) https://BioRender.com/n29n318.

According to FAO (2021) fact sheet, milk's global significance is evident as one of the most produced and valuable agricultural commodities, contributing 10% to agriculture and 27% to the global livestock value. Fresh milk, primarily from cattle, dominates production, with growing demand in developing countries improving public health and livelihoods. Dairy supports over 150 million farmers, particularly in rural areas, by providing income, food security, and resilience. Women play a key role, owning dairy animals in 25% of cattle-keeping households (FAO, 2021), fostering gender empowerment (SDG 5). Dairy's affordability and nutrient density make it a foundation for combating hunger and malnutrition, particularly among vulnerable groups such as children and pregnant women. As nutrient-rich dairy products contribute essential proteins, vitamins, and minerals, they align with SDG 2 (Zero Hunger and SDG 3 (Good Health and WellBeing). For pregnant and lactating women, high-quality, nutrient-dense diets that include milk are associated with improved maternal and neonatal outcomes, reducing complications and supporting optimal child development (Marshall et al., 2022). Evidence highlights the urgency of promoting affordable, nutrient-dense foods like milk as a foundational component of public health strategies to address global nutritional inadequacies and advance equity in maternal and child health.

The dairy sector supports the livelihoods of over one billion people globally, generating up to 5.7 full-time jobs per 100 L of milk traded (FAO, 2021). However, its rapid growth has intensified challenges such as zoonotic risks, environmental degradation, and greenhouse gas emissions. Addressing these issues requires innovative solutions in feeding practices, waste management, and methane reduction, ensuring economic viability while safeguarding public health, animal welfare, and the environment (Grout et al., 2020; Neethirajan, 2024). Balancing these priorities is critical for sustainable development in the dairy industry. By advancing sustainable practices, the dairy industry can drive progress across SDGs 1 (No Poverty), 5 (Gender Equality), 6 (Clean Water and Sanitation), 8 (Decent Work and Economic Growth), 12 (Responsible Consumption and Production), 13 (Climate Action), and 15 (Life on Land). Collaboration and investments in sustainable dairy are key to fostering a future that balances nutrition, livelihoods, and environmental health.

9 Conclusion

The sustainability of the global dairy sector focuses on prioritizing milk quality as an integral component of environmental, economic, and social strategies. Premium-quality raw milk reduces the need for energy-intensive processing, restricts waste, and supports circular economy models by enabling resource-efficient production and utilization of by-products. The integration of precision technologies, climate-adaptive farming practices, and consumer-driven quality assurance programs enhances the sector's ability to address climate challenges and meet evolving market demands. Scientific advancements, including genomics and artificial intelligence, offer unprecedented opportunities to optimize milk quality and yield while mitigating environmental impacts. However, achieving global sustainability requires tailored solutions that address regional disparities in resources, infrastructure, and policy frameworks. Collaboration across the dairy value chain (from farmers to policymakers) is essential to ensure equitable progress. By embedding milk quality into sustainability initiatives, the dairy industry can play a central role in addressing global food security, reducing greenhouse gas emissions, and fostering economic resilience. These efforts will establish a scientifically robust and ethically sound pathway for a sustainable dairy future.

Author contributions

HP: Conceptualization, Data curation, Formal analysis, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

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Generative AI statement

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