



Current Trends and Innovations in Animal Husbandry Dairy Technology

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ABSTRACT

The global dairy industry is undergoing a transformative shift driven by technological innovations, precision farming, and sustainability imperatives. This review paper critically examines the current trends and emerging innovations in animal husbandry dairy technology, encompassing precision dairy farming, robotic milking systems, Internet of Things (IoT)-based livestock monitoring, advanced reproductive and genomic technologies, non-thermal dairy processing methods, artificial intelligence applications, and circular economy frameworks. The integration of wearable biosensors, automated milking systems, and AI-powered analytics has significantly enhanced milk yield, animal welfare, and operational efficiency. Genomic selection and CRISPR-based gene editing are revolutionizing breeding strategies, while non-thermal processing technologies such as high-pressure processing are redefining product quality and safety. This review synthesizes recent literature to provide a holistic understanding of how these innovations are shaping the future of sustainable dairy production worldwide.

Keywords: Precision Dairy Farming; Robotic Milking Systems; Genomic Selection; Non-Thermal Processing; Sustainable Dairy Production

INTRODUCTION

The dairy industry represents one of the most significant sectors in global agriculture, contributing substantially to food security, rural livelihoods, and economic development. According to the Food and Agriculture Organization (FAO, 2023), global milk production has exceeded 930 million tonnes annually, with demand projected to grow by

1.7% per year through 2030. However, this sector faces unprecedented challenges, including rising labour shortages, increasing feed costs, stringent environmental regulations, climate change impacts, and evolving consumer demands for safe, nutritious, and sustainably produced dairy products.

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In response to these multifaceted challenges, the dairy industry has embraced a suite of technological innovations that collectively define the era of *precision dairy farming* (Bewley, 2015). The precision livestock farming market is projected to grow from USD 7.94 billion in 2025 to USD 12.12 billion by 2030, at a compound annual growth rate (CAGR) of 8.8% (Markets and Markets, 2025). This growth reflects the rapid adoption of Internet of Things (IoT) sensors, artificial intelligence (AI), robotic milking systems, advanced reproductive technologies, and data-driven decision support systems across dairy operations of all scales.

The transition from traditional herd-level management to individual animal monitoring represents a paradigm shift in dairy farming philosophy. Wearable sensors now enable real-time data collection on each animal, facilitating informed decisions regarding health, nutrition, reproduction, and overall herd management (Cabrera et al., 2020). Concurrently, advances in genomic science, embryo transfer technology, and gene editing tools such as CRISPR-Cas9 are accelerating genetic progress at unprecedented rates (Heo et al., 2021). On the processing front, non-thermal technologies like high-pressure processing (HPP) are preserving the nutritional integrity of dairy products while ensuring food safety (Stratakos et al., 2019).

2. Precision Dairy Farming and IoT Applications

2.1 Wearable Sensor Technologies

Precision dairy farming (PDF) refers to the application of technology-driven systems that enable real-time monitoring and management of individual animals within a herd (Rutten et al., 2013). The cornerstone of PDF lies in wearable sensor technologies, which have evolved from simple pedometers to sophisticated multi-parameter monitoring devices. Modern sensor systems include smart collars, ear tag-based accelerometers, noseband pressure sensors, and intra-ruminal

boluses that continuously track a wide array of physiological and behavioural parameters (Lopatka et al., 2023).

Smart collars, such as those manufactured by Merck, now incorporate advanced sensors and AI-powered algorithms to monitor chewing behaviour, rumination patterns, body temperature, and activity levels (New York Times, 2025). These collars can detect early signs of illness up to 48 hours before clinical symptoms manifest, enabling proactive treatment that reduces veterinary costs by USD 300-500 per cow annually (The Bullvine, 2025). Rumen boluses, such as the SmaXtec system, provide continuous monitoring of rumen pH, temperature, and activity, offering insights into digestive health and feed efficiency (Lopatka et al., 2023).

The RumiWatch noseband sensor system has been validated as an effective scientific monitoring device for automated detection of rumination and eating behaviours in dairy cows. Studies have demonstrated sensitivity of 88.9% and specificity of 93.3% for predicting the commencement of calving within three hours in multiparous cows (Lopatka et al., 2023). Such precision in calving prediction enables timely intervention, reducing dystocia-related losses and improving calf survival rates.

2.2 IoT Architecture and Data Integration

The Internet of Things framework in dairy farming encompasses a network of interconnected sensors, communication gateways, cloud-based data platforms, and decision support software. Data from wearable sensors, milking robots, automated feeders, and environmental monitors are aggregated on centralised farm management platforms such as Lely Horizon, providing real-time visualisation of key performance indicators including milking frequency, milk yield per cow, cow activity, and feed intake (CCF, 2025).

Cloud-based platforms supported by 5G connectivity enable farmers to access

dashboards, collaborate with veterinarians, and manage multiple sites remotely (MarketsandMarkets, 2025). The integration of RFID-based animal identification with sensor

data creates comprehensive digital profiles for each cow, supporting data-driven management decisions throughout the animal's productive life.

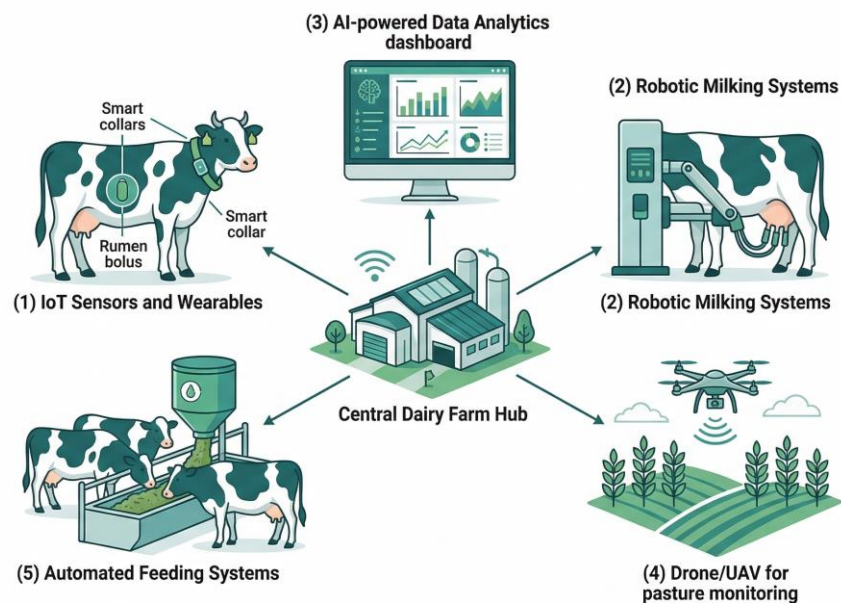


Figure 1: Components of Precision Dairy Farming Technology

3. Robotic Milking Systems and Farm Automation

3.1 Automated Milking Systems (AMS)

Robotic or automatic milking systems (AMS) have steadily increased in popularity since the installation of the first commercial unit in 1992 in the Netherlands. By 2015, over 25,000 AMS units had been installed worldwide, and adoption has continued to accelerate globally (University of Nebraska-Lincoln, 2017). A single robotic milking unit typically services approximately 60 cows and costs between USD 150,000 and USD 200,000, with complete system installations ranging from USD 300,000 to USD 460,000 for two-unit setups (CCF, 2025).

Modern AMS employ advanced robotic arms with laser guidance and 3D camera systems to precisely locate and attach teat cups to individual cows. Companies such as Lely have developed “I-flow” cow traffic systems where cows enter and exit the robot in a straight-through pattern, minimising stress and maximising voluntary milking frequency. GEA’s “In-Liner Everything” technology consolidates udder stimulation, cleaning,

milking, and post-dipping within the teat cup, streamlining the entire process (CCF, 2025).

The benefits of AMS are well documented. In a survey of 10 United States dairies and 15 Canadian dairies that had installed AMS, 70% reported a decrease in hired labour costs (University of Nebraska-Lincoln, 2017). Early adopters report slashing labour costs by 20-50% and lifting milk yields by 10-20% due to increased milking frequency and reduced cow stress (The Bullvine, 2025). Inline sensors continuously monitor milk flow from each quarter, along with somatic cell count (SCC) and conductivity, enabling immediate detection of mastitis or abnormalities and automatic diversion of abnormal milk to prevent contamination of the bulk tank.

3.2 Precision Feeding Systems

Feed costs constitute 50-60% of total dairy production expenses, making precision feeding one of the most impactful technologies for farm profitability. AI-driven precision feeding systems optimise total mixed ration (TMR) formulations and individual cow rations based on real-time data regarding lactation stage,

body condition score, and milk production parameters (The Bullvine, 2025).

These systems typically deliver feed savings of 15-25% per cow, translating to annual savings of USD 200-400 per animal. Real-time ration adjustments prevent USD 50-75 per cow losses caused by nutritional imbalances. Industry analyst Lucas Fues from RaboResearch notes that this technology improves feed conversion efficiency by 15-20%, representing a crucial competitive advantage in tight margin environments (The Bullvine, 2025). Precision feeding systems demonstrate the fastest return on investment among dairy technologies, typically paying for themselves within 2-4 years.

3.3 Computer Vision and Camera-Based Monitoring

Camera-based monitoring represents a non-contact, non-invasive approach to livestock surveillance. Systems such as CattleEye utilise security cameras positioned above milking parlour exits to capture video of each cow, which is then analysed by AI algorithms in the cloud to assess locomotion scores and detect lameness (CattleEye, 2023). DeLaval's Body Condition Score Camera employs 3D imaging technology using infrared ray dot patterns to automatically assess body condition, providing objective and consistent scoring without manual handling (Lopatka et al., 2023).

These vision-based systems save an estimated USD 420 per cow annually through early lameness detection and intervention, while simultaneously ensuring compliance with animal welfare standards (CattleEye, 2023). The elimination of wearable hardware requirements reduces costs and maintenance burden, making these solutions particularly attractive for large-scale operations.

4. Advanced Reproductive and Genomic Technologies

4.1 Genomic Selection

Genomic selection has fundamentally transformed dairy cattle breeding since becoming commercially available in 2008. The technology uses single nucleotide polymorphism (SNP) chip testing to evaluate the genetic potential of animals at a young age,

enabling more accurate breeding value predictions and dramatically shortening generation intervals (CDCB, 2024). Since its introduction, over 8 million U.S. dairy animals have been genotyped for dozens of key genetic traits related to milk production, quality, feed efficiency, reproductive viability, and cow health (CoBank, 2024).

The impact has been remarkable. While the U.S. dairy herd is only 1% larger than in 2008, milk production has climbed by 19.2% and butterfat has risen an impressive 32.2% from 2008 levels (CoBank, 2024). Data from the Net Merit dollar (NM\$) index indicates that genomic selection has delivered USD 70 in additional value per cow per year, based on the difference between the USD 13.50 in annual genetic improvement prior to genomics and the USD 83.33 annual genetic gain from 2010 to 2022 (CoBank, 2024). Future directions include genomic evaluations for methane emissions, with the Council on Dairy Cattle Breeding (CDCB) working with the Foundation for Food and Agriculture Research to develop national evaluations for environmental sustainability traits.

4.2 Embryo Transfer and In Vitro Fertilisation

Embryo transfer (ET) technology has evolved from a niche practice to a transformative tool for large-scale dairy operations. In 2021, over 1.4 million embryos were transferred into cows worldwide for breeding purposes, with the number of laboratory-produced (IVP) embryos now substantially exceeding those produced through conventional superovulation protocols (The Bullvine, 2025). One veterinary clinic serving large-scale farms reported increasing from approximately 500 embryo transfers annually to over 1,700 in 2023, illustrating the rapid adoption trajectory.

ET enables dairy producers to improve herd genetics at substantially lower cost than purchasing elite animals. The technology allows multiple top-quality calves to be produced from a single exceptional cow in a year, dramatically accelerating genetic progress across large herds (Four Star Veterinary Service, 2025). ET also offers

advantages in challenging conditions, boosting pregnancy rates by up to 10% during hot weather compared to artificial insemination (AI), which is particularly valuable in tropical and subtropical dairy regions (The Bullvine, 2025). In vitro fertilisation (IVF) further enhances these capabilities by combining DNA testing with laboratory techniques to create embryos from elite donors using oocyte aspiration without requiring superovulation protocols (Trans Ova Genetics, 2025).

4.3 CRISPR-Cas9 Gene Editing

The CRISPR-Cas9 system represents the frontier of genetic improvement in dairy cattle. This genome editing technology functions as “molecular scissors” that can make precise cuts in DNA at targeted locations, enabling researchers to disable genes, insert new DNA sequences, or correct mutations (UC Davis CLEAR Center, 2025). Applications in dairy cattle include the elimination of horn

development genes to improve animal welfare by removing the need for painful physical dehorning procedures, enhancement of disease resistance traits such as tuberculosis resistance, and modification of milk composition through targeted manipulation of casein and lactoglobulin genes (Heo et al., 2021).

Notable achievements include the introduction of the human lysozyme gene into the bovine beta-casein locus, resulting in transgenic cattle that secrete human lysozyme in their milk with antimicrobial properties against *Staphylococcus aureus* (Heo et al., 2021). Myostatin gene editing has been explored for increasing muscle growth and meat yield in dual-purpose dairy breeds. While regulatory frameworks for gene-edited livestock remain evolving, the potential for CRISPR to enhance productivity, disease resistance, and animal welfare in dairy cattle is substantial (UC Davis CLEAR Center, 2025).

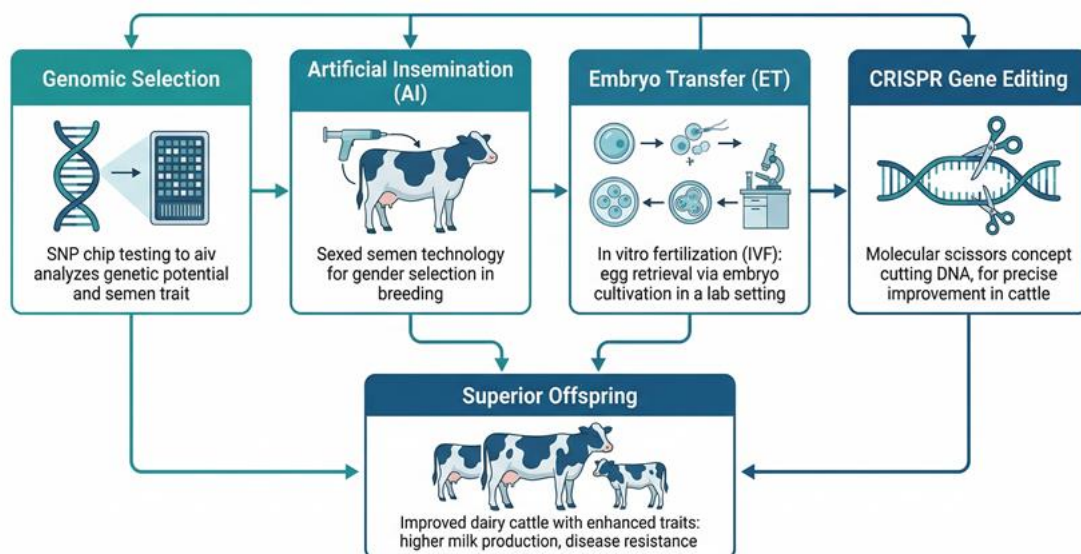


Figure 2: Advanced Reproductive and Genomic Technologies in Dairy Cattle illustrating the integration of genomic selection, artificial insemination, embryo transfer, and CRISPR gene editing for producing superior offspring.

5. Artificial Intelligence and Digital Twin Technologies

5.1 AI Applications in Dairy Farm Management

Artificial intelligence is revolutionising dairy science by enabling more precise and informed decision-making. The Dairy Brain project, initiated at the University of Wisconsin–

Madison, exemplifies how AI can be integrated into dairy operations by leveraging real-time data from milking equipment sensors, feed intake monitoring systems, and animal health tracking devices (Cabrera et al., 2020). AI algorithms analyse complex datasets to optimise feeding strategies, predict disease

onset, identify optimal breeding times, and detect peak lactation periods.

Machine learning applications in dairy encompass machine vision for automated quality inspection, smart environmental sensors for barn climate control, activity collar data analysis for health monitoring, thermal imaging cameras for mastitis detection, and digitised supply chain systems for inventory management (Psecommunity, 2025). AI-driven solutions provide economic benefits through enhanced operational efficiency, reducing costs associated with labour, medical interventions, and feed wastage while maximising productivity through more accurate prediction of animal performance parameters.

One million U.S. dairy cows are now under AI surveillance, and farms utilising these technologies report 20% increases in milk production alongside 25% reductions in input costs (The Bullvine, 2025). The DairyPrint model, developed through the Dairy Brain initiative, enables farms to monitor and manage their carbon footprint, contributing to both profitability and environmental sustainability (Cabrera and Fadul-Pacheco, 2024).

5.2 Digital Twin Technology

Digital twin technology represents the next frontier in dairy farm management. A digital twin is a continuously updated virtual representation of the entire farm system—from individual animals to infrastructure—created using real-time data from sensors, telemetry, and other digital tools. Scotland's Rural College (SRUC) has launched farm-twin, the world's first open-source digital twin platform specifically designed for dairy farming (SRUC, 2025).

The farm-twin platform integrates multiple streams of data from different vendors and visualises them through intuitive dashboards, providing farmers with a comprehensive view of their entire operation. The system supports predictive analytics, enabling early detection of health issues or productivity drops. For example, it can combine milk yield trends with live health data

to detect early signs of illness, triggering automated shedding gate responses to isolate affected animals while notifying farmers (SRUC, 2025). The Digital Future Farm (DFF) project at Wageningen University further demonstrates how digital twin technology can map nitrogen flows in near real-time, improving nutrient efficiency and reducing environmental impact (Agrifood TEF, 2025).

5.3 Drone and UAV Applications

Unmanned aerial vehicles (UAVs) are emerging as valuable tools in dairy farming operations. Farmers traditionally spend 50-60% of their time manually monitoring cattle, a burden that drone technology can significantly reduce (3Laws, 2024). Drones equipped with multispectral cameras can assess vegetation health, providing data on soil fertility, pest infestation, and nutrient deficiencies in pasture lands. Research by the USDA suggests this technology can improve pasture yields by up to 25% through optimised grazing management (3Laws, 2024).

Applications extend to spot spraying for weed control using AI-driven identification systems, pasture quality assessment replacing manual plate meter surveys, and real-time cattle tracking across extensive grazing areas (DJI Agriculture, 2024; Farming Connect, 2025). The ability to navigate complex terrain and access areas inaccessible to ground-based equipment makes UAVs particularly valuable for managing pastoral dairy systems.

6. Innovations in Dairy Product Processing

6.1 Non-Thermal Processing Technologies

Non-thermal processing technologies represent a paradigm shift in dairy preservation, offering alternatives to traditional heat-based pasteurisation that better preserve sensory and nutritional qualities. High-pressure processing (HPP) has emerged as the most widely implemented non-thermal food preservation technology, offering two key advantages: elimination of post-packaging contamination risk and preservation of quality attributes through non-thermal mechanisms (Hiperbaric, 2025).

HPP at 600 MPa (6,000 bar) for 3 minutes extends raw milk shelf life up to 30

days at 4°C while maintaining Enterobacteriaceae counts below the detection limit (Hiperbaric, 2025). Recent meta-analyses (2021-2025) demonstrate that HPP can extend dairy product shelf life up to six-fold (e.g., from 10 to 60 days) while reducing pathogens by up to eight log cycles and preserving more than 90% of key vitamins including A, C, D, E, K, and all B-group vitamins (PubMed, 2025). Applications in cheese production show that HPP extends shelf life of fresh cheese, mozzarella, and paneer products up to 90 days at 4°C (Hiperbaric, 2025).

Pulsed electric field (PEF) technology employs short bursts of high-voltage electrical pulses to inactivate microorganisms while maintaining product freshness. Ultrasonication utilises high-frequency sound waves to achieve microbial inactivation and can simultaneously improve the homogenisation of dairy products. UV-C treatment provides germicidal benefits through ultraviolet light exposure. These complementary technologies offer dairy processors a toolkit for preserving product quality while meeting food safety requirements (Frontiers in Sustainable Food Systems, 2022).

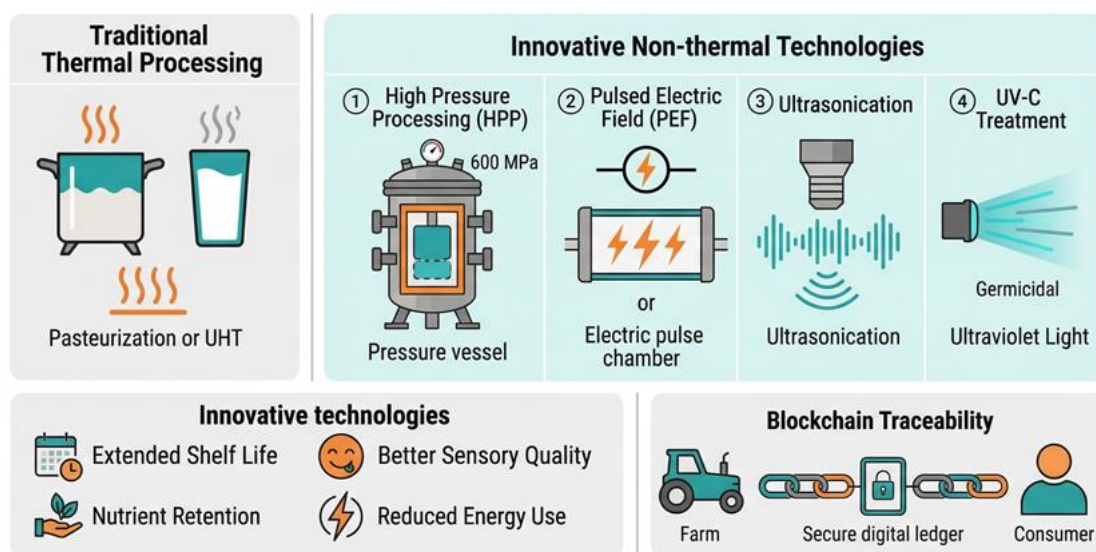


Figure 3: Innovative Dairy Processing Technologies comparing traditional thermal methods with non-thermal processing approaches including HPP, PEF, ultrasonication, and UV-C treatment, along with blockchain-enabled traceability systems.

6.2 Blockchain Traceability in Dairy Supply Chains

Blockchain technology is being increasingly applied to enhance traceability and transparency in dairy supply chains. The technology provides an immutable distributed ledger that tracks products from farm to consumer, verifying the source of milk, ensuring quality at collection points, and maintaining records throughout processing and distribution (TracexTech, 2023). The U.S. Food and Drug Administration’s “New Era for Smarter Food Safety Blueprint” published in 2020 recommends standardisation of critical tracking events and key data elements, with blockchain identified as a key enabling

technology for achieving these objectives (USDA, 2021).

Blockchain-powered solutions enable automated reporting for regulatory audits (Kosher, USDA, Department of Transportation), facilitate rapid tracing during foodborne illness emergencies, and build consumer trust through verifiable product provenance. The integration of blockchain with IoT sensors throughout the dairy value chain creates a comprehensive quality assurance framework that connects farm-level data with consumer-facing information (USDA, 2021).

7. Sustainability and Circular Economy in Dairy Farming

7.1 Methane Reduction Strategies

Methane, a potent greenhouse gas with nearly 80 times the warming power of carbon dioxide over 20 years, represents the dairy industry's most significant environmental challenge. Agriculture is responsible for nearly 40% of human-caused methane emissions, with the majority originating from livestock production (EDF, 2025). The Dairy Methane Action Alliance (DMAA), comprising leading global food and dairy companies including Danone, Agropur, Idaho Milk Products, and Savencia Fromage & Dairy, is driving industry-wide commitments to reduce methane emissions (EDF, 2025).

Danone has demonstrated notable progress, reducing methane emissions from its fresh milk supply chain by 25% against a 2020 baseline, moving toward its target of 30% reduction by 2030 (EDF, 2025). California dairy farms have reduced greenhouse gas emissions by more than 45% over the past 50 years through implementation of anaerobic digesters, alternative manure management projects, and solar energy installations (Dairy Cares, 2024). Feed additives such as 3-nitrooxypropanol (3-NOP) and seaweed-based supplements have shown promise in reducing enteric methane emissions by 20-30% without affecting milk production or animal health.

7.2 Circular Economy and Biogas Production

The integration of biogas plants into dairy farming exemplifies circular economy principles by converting organic waste into renewable energy while producing nutrient-rich digestate for crop fertilisation. Anaerobic digestion systems process manure and agricultural residues to produce biogas primarily composed of methane and carbon dioxide, which can be used for electricity generation, heating, or upgraded to biomethane for grid injection (Ag Proud, 2024).

This circular model addresses multiple environmental challenges simultaneously. Inadequate manure management leads to nitrous oxide emissions, which have approximately 300 times the global warming potential of carbon dioxide (Ag Proud, 2024). Biogas plants mitigate these emissions while transforming a waste management burden into a revenue-generating asset. The digestate produced through anaerobic digestion serves as an enhanced organic fertiliser with improved nutrient availability, completing the cycle back to crop and pasture production. More than 150 California dairy farms have additionally adopted solar energy generation, reducing reliance on fossil fuels and further enhancing the sustainability profile of dairy operations (Dairy Cares, 2024).

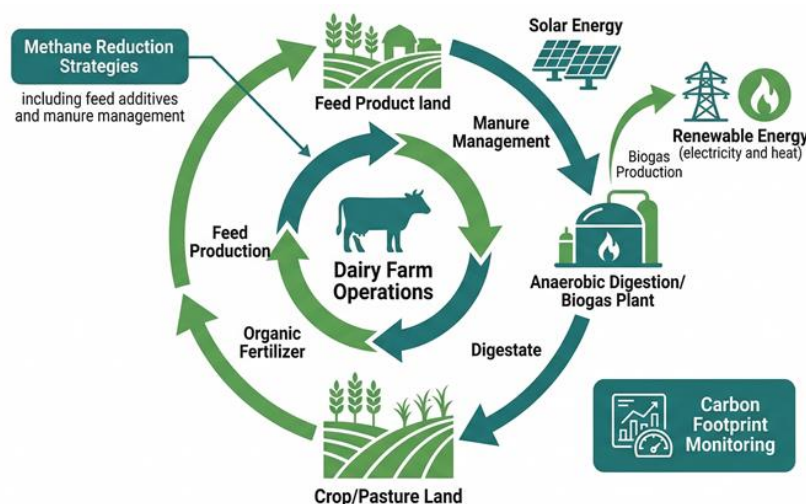


Figure 4: Circular Economy and Sustainability Framework in Modern Dairy Farming depicting the closed-loop system of manure management, biogas production, renewable energy generation, digestate recycling, and carbon footprint monitoring.

8. Challenges and Future Perspectives

Despite the transformative potential of these technologies, several challenges impede widespread adoption. The high initial capital investment required for robotic milking systems (USD 150,000-200,000 per unit), precision feeding infrastructure, and advanced sensor networks places these technologies beyond the reach of many small and medium-scale dairy operations, particularly in developing countries (University of Nebraska-Lincoln, 2017). Technical knowledge and expertise represent major barriers, as specialised training is required for proper implementation and efficient operation of AI and IoT systems (Sciencedirect, 2025).

Data interoperability remains a significant challenge, as different vendors often use proprietary formats that limit the integration of data from multiple sources. The farm-twin open-source approach represents one solution to this challenge, emphasising that open-source systems ensure transparency, foster innovation, and lower barriers to adoption (SRUC, 2025). Cybersecurity concerns, rural connectivity limitations, and the ethical and regulatory frameworks surrounding gene-edited livestock also require resolution as these technologies mature.

Future perspectives include the development of national genomic evaluations for methane emissions (CoBank, 2024), the integration of digital twin technology with autonomous farm machinery, advancement of CRISPR applications for disease resistance and milk composition enhancement, and the democratisation of AI tools to make them accessible to farms of all sizes. The convergence of these technologies promises to deliver a dairy production system that is simultaneously more productive, more sustainable, and more responsive to animal welfare and consumer expectations.

CONCLUSION

The dairy industry stands at a pivotal juncture where technological innovation is fundamentally reshaping every aspect of

production, from genetic improvement and animal management to milk processing and supply chain transparency. Precision dairy farming, powered by IoT sensors and AI analytics, has transitioned dairy management from intuition-based to data-driven decision making, delivering measurable improvements in milk yield (10-20% increases), labour efficiency (20-50% cost reductions), and animal health outcomes. Robotic milking systems have matured from experimental technology to industry standard, with over 25,000 units deployed globally and demonstrated returns on investment within 2-5 years.

Genomic selection has delivered transformative genetic gains, increasing U.S. milk production by 19.2% and butterfat by 32.2% since 2008, while embryo transfer and CRISPR gene editing continue to accelerate the pace of genetic improvement. Non-thermal processing technologies, particularly high-pressure processing, are redefining dairy product safety and quality standards by extending shelf life up to six-fold while preserving over 90% of key vitamins. The emergence of digital twin platforms and blockchain traceability systems represents the next evolutionary step toward fully integrated, transparent dairy value chains.

Critically, these innovations are increasingly aligned with sustainability imperatives. Circular economy models integrating biogas production, solar energy, and precision nutrient management demonstrate that environmental stewardship and economic viability are complementary rather than competing objectives. The 25% reduction in methane emissions achieved by leading dairy companies validates the effectiveness of coordinated industry action. As these technologies become more accessible and affordable, their transformative potential extends to dairy operations of all scales, promising a future where precision, sustainability, and profitability converge to meet the growing global demand for safe, nutritious dairy products.

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Conflict of Interest

The authors report no conflicts of interest.

Author Contributions

All authors participated in drafting, revising, and approving the manuscript.

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