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Precision dairy farming (Dairy 4.0): Sensor technologies, artificial intelligence and the pursuit of farm-level sustainability

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Abstract

Modern dairy production faces significant global pressures arising from increased demand, resource constraints and climate change mitigation targets, necessitating a transformation toward high efficiency, sustainable systems. This review synthesizes advancements in Precision Dairy Farming (PDF), frequently termed 'Dairy 4.0,' focusing on the synergistic integration of Internet of Things (IoT) sensors, Artificial Intelligence (AI) and advanced data analytics. A systematic literature appraisal (2018–2025) evaluated the performance of key technologies including wearable sensors, in-line milk analyzers and computer vision systems which provide real time, individual animal monitoring critical for proactive management. The central mechanism driving Dairy 4.0 is the application of Machine Learning (ML) and Digital Twin (DT) frameworks to translate heterogeneous sensor data into actionable, predictive management strategies. The analysis demonstrates that PDF systems substantially enhance economic viability, with precision feeding slashing costs by 15- 25% and automated health monitoring reducing veterinary expenses by up to ten to fifteen thousand rupees per cow annually. Crucially, PDF accelerates environmental stewardship by optimizing resource use, contributing to a 19% reduction in carbon footprint and aiding progress toward net-zero commitments. However, widespread adoption is impeded by challenges related to data interoperability, rural connectivity, model robustness under variable conditions and significant capital costs, particularly for smallholder farms. Future research must prioritize the integration of Explainable AI (XAI) with mechanistic models, standardize data exchange protocols and develop equitable policy frameworks to unlock the full potential of sustainable Dairy 4.0 globally.

Keywords: Precision dairy farming, dairy 4.0, IoT, sensors, artificial intelligence, digital twin

1. Introduction

1.1 Contextualizing Global Dairy Production Challenges

The global agricultural sector is under increasing pressure to sustainably meet the escalating demand for food while mitigating its environmental footprint. Dairy farming, in particular, operates within a challenging economic landscape defined by volatile milk and feed prices, tight profit margins, and widespread labour shortages (Jafri, 2024) ^[18]. Beyond these operational difficulties, the industry faces intense scrutiny regarding its contribution to climate change, largely through enteric methane emissions and manure management, which necessitate radical transformation (Peterson, 2021) ^[31].

In India, the dairy industry has begun to adopt clearer sustainability targets, recognising that long-term viability depends on the adoption of data-driven and resource-efficient management practices. A recent Life Cycle Assessment conducted by Singh *et al.* (2024) ^[35] reported that milk production systems in the state of Punjab generated approximately 1,689 kg CO₂-eq per 1,000 L of milk, whereas comparable systems in Rajasthan emitted around 2,550 kg CO₂-eq, highlighting significant efficiency gaps across regions.

Further, a comprehensive evaluation of nine commercial dairy processing plants by Sharma *et al.* (2024) ^[33] found that the Indian dairy processing sector has an average total water footprint of 9.0 L per kg of milk processed, with nearly 89% of this footprint originating from indirect,

energy-related water use. These findings underscore the need for India's dairy sector to strengthen sustainability interventions, reduce greenhouse-gas emissions, and improve water and land resource efficiency across both smallholder and commercial-scale operations.

1.2. Defining Precision Dairy Farming (PDF) and the Dairy 4.0 Paradigm Shift

Precision Dairy Farming (PDF) is fundamentally defined as the technological and methodological application of data-centric approaches to enhance the efficiency, productivity, and sustainability of dairy systems (Dar *et al.*, 2024) [11]. This paradigm involves deploying advanced systems, including the Internet of Things (IoT) sensors, automated machinery such as Automated Milking Systems (AMS), and sophisticated Artificial Intelligence (AI) algorithms. The core objective of PDF is to transition farm management from conventional,

reactive, herd-level decision-making to a proactive, individualized strategy (Dar *et al.*, 2024; Tadele *et al.*, 2025) [11, 40].

The concept of 'Dairy 4.0' represents the latest phase of PDF (Fig. 1), where technology integration is comprehensive and often facilitated by advanced conceptual frameworks, notably the Digital Twin (DT) (Xing *et al.*, 2025; Dawn *et al.*, 2024) [44, 12]. This advanced stage is characterized by unified, predictive ecosystems that enhance overall operational efficiency (Gkouskou, 2020) [14]. Studies evaluating the impact of such technological adoption suggest profound efficiency gains, reporting potential increases in milk yield by up to 30% and reductions in feed costs by 25% (Dar *et al.*, 2024; Tadele *et al.*, 2025) [11, 40]. These technologies also improve animal health monitoring, reduce workloads, and enhance the financial security of farming operations (Tadele *et al.*, 2025) [40].

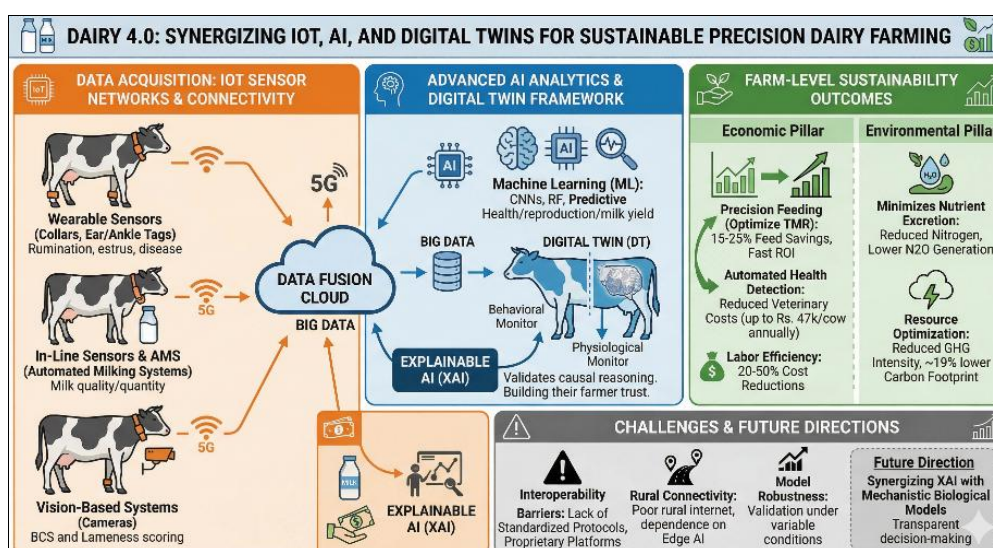


Fig 1: Conceptual Framework of the Dairy 4.0 Ecosystem: Integrating Sensor Networks, AI Analytics, and Sustainability Outcomes

1.3. Scope and Objectives of the Review

This scientific review draws on peer-reviewed literature published between 2018 and 2025 to synthesise recent advances in sensor technologies and AI analytics which underpin the "Dairy 4.0" paradigm. First, it critically evaluates performance, reliability and application domains of real-time monitoring and decision-support technologies within modern dairy systems (Hassoun *et al.*, 2023; de Oliveira *et al.*, 2024) [16, 13]. Second, it conducts a multidimensional assessment of the impact of these technologies — across economic viability, environmental footprint reduction and animal welfare/social dimensions — drawing on recent analytics studies (Palma *et al.*, 2025; Malik *et al.*, 2023) [30, 26]. Third, the paper identifies key technological, economic and ethical bottlenecks limiting broad deployment of Dairy 4.0, and proposes a strategic agenda for future research and policy.

2. Methodology / Literature Search Strategy

2.1. Search Protocol and Inclusion Criteria

A systematic literature search was conducted to identify recent, high-quality scientific contributions relevant to Precision Dairy Farming and digital technologies in livestock systems. Following the methodological approaches used by Antognoli *et al.* (2020) [4] and Vázquez-López *et al.* (2021) [43], the search covered peer-reviewed research published between 2018 and 2025 to ensure contemporary relevance.

The search strategy used combinations of structured keywords such as "Precision Dairy Farming," "Precision Livestock Farming," "IoT dairy," "wearable sensors cattle," "computer vision dairy cows," "Digital Twin livestock," "machine learning dairy," "sustainable dairy farming," and "dairy farm economics and technology." This keyword methodology aligns with established review protocols in digital livestock research (Antognoli *et al.* 2020 & Vázquez-López *et al.* 2021) [4, 43].

2.2. Data Extraction and Critical Analysis

Data extraction prioritized quantitative metrics relevant to technological efficiency and sustainability performance, following approaches used by Antognoli *et al.* (2020) [3]. Extracted information included sensor-based detection accuracies for key events (e.g., estrus, lameness, rumination), reliability metrics of monitoring systems, economic indicators such as Return on Investment (ROI) and feed-cost reductions, as well as environmental outcomes including greenhouse-gas (GHG) emission intensities and resource-use efficiency (Steenefeld & Hogeveen, 2015; Knapp, 2014) [39, 22].

The critical analysis adopted a comparative and synthetic framework by evaluating performance across different sensor modalities such as computer vision systems, accelerometer-based wearables, acoustic sensors, and in-line milk analyzers and across AI analytical approaches including Convolutional Neural Networks (CNNs), Random Forests (RF), and Long

Short-Term Memory (LSTM) models (Hall-Solorio, 2025) [15]. This enabled a structured comparison of both detection accuracy and operational feasibility in commercial dairy environments.

A central analytical objective was to distinguish simple correlations from causal mechanisms linking technological adoption—such as precision feeding systems, automated health detection, and real-time behavioral monitoring—to measurable improvements in sustainability outcomes. Studies such as Knapp *et al.* (2014) [22] and Benjamin *et al.* (2019) [4] demonstrate how precision feeding and automated decision systems can yield reductions in methane emissions, improved feed efficiency, and enhanced farm-level productivity, thereby contributing to the foundational understanding of the Dairy 4.0 impact.

3. Main Thematic Sections: Technology, Analytics, and Impact

3.1. Foundation of PDF: Real-Time Sensor Networks and IoT Infrastructure

3.1.1. Wearable and Acoustic Sensors for Health and Reproduction

The foundation of Precision Dairy Farming relies on continuous, individual-animal monitoring, primarily facilitated by the extensive deployment of wearable sensors (Lee *et al.*, 2021; Lamanna, Bovo & Cavallini, 2025) [25, 24]. Activity collars, rumination tags and associated devices gather high-resolution, real-time data on cow behaviour, including movement, eating duration and rumination patterns (Lamanna *et al.*, 2025) [24]. These data streams are crucial for effective herd management, as changes in behaviour serve as vital indicators for the detection of estrus cycles, early stages of disease and shifts in metabolic status, requiring timely intervention (Shorten *et al.*, 2023) [34]. Further innovation in monitoring includes the use of advanced acoustic detection systems: research using acoustic sensors and signal-processing techniques has shown promising accuracy in differentiating cow behaviours via methods such as Mel-frequency cepstral coefficients (MFCC) and machine learning classification (Shorten *et al.*, 2023) [34].

3.1.2. In-Line Sensors and Automated Milking Systems (AMS)

In-line sensors integrated into Automated Milking Systems (AMS) provide instantaneous data regarding milk quantity and quality, proving essential for early disease detection (Kunes *et al.*, 2021) [23]. Optical sensors are widely utilized for real-time milk quality analysis, leveraging the principles of light scattering and absorbency to identify physical changes in the milk stream (Kunes *et al.*, 2021) [23]. These optical measurements can detect contamination, monitor shifts in fat concentration, or indicate abnormalities such as blood, enabling rapid segregation of affected animals and prompt corrective action, which is vital for maintaining udder health (Kaur *et al.*, 2023) [20]. The comprehensive data generated by in-line sensors has profound implications beyond daily operational management, specifically in genetic improvement. The introduction of the sensor-based Milking Speed (MSPD) trait provides an objective, reliable genetic selection tool (Kaur *et al.*, 2023) [20]. This system eliminates the subjectivity inherent in century-old human classification scores by leveraging datasets comprising millions of individual milking observations. MSPD delivers Predicted Transmitting Abilities (PTA) measured in pounds-per-minute, achieving an average reliability of 69% for proven bulls, representing a significant

paradigm shift toward data-driven genetic selection focused on improving parlor throughput and operational efficiency (Kaur *et al.*, 2023) [20].

3.1.3. Vision-Based Systems for Locomotion and Body Condition Scoring (BCS)

Computer vision systems are rapidly transforming the monitoring of subjective animal health metrics, offering automated and objective scoring of lameness, locomotion and Body Condition Score (BCS) (Neupane, 2025 & Jiang, 2022; Higaki *et al.*, 2024) [29, 19, 17]. By deploying RGB and depth cameras, these systems collect visual data that, when processed by advanced Machine Learning (ML) models, can facilitate the noninvasive, accurate detection of subtle health indicators, such as early digital dermatitis (Paudyal *et al.*, 2025; Jiang *et al.*, 2022) [1, 19]. This capability shifts health management from reactive treatment to preventative, continuous surveillance (Paudyal *et al.*, 2025).

Despite their potential, the performance of vision-based systems is subject to critical technical constraints (Higaki *et al.*, 2024) [17]. The reliability of cameras is highly dependent on ambient lighting conditions and can be compromised by obstructions from barn structures, stalls, or other animals, demanding substantial high-speed internet connectivity and significant computing power for real-time image processing (Higaki *et al.*, 2024; Smink *et al.*, 2024; Rao *et al.*, 2025) [17, 38, 32]. The reliance on diverse sensor types—wearable, acoustic, optical, and visual—confirms that a complete physiological and behavioral status of a dairy cow necessitates the convergence of multiple technologies (Condotta *et al.*, 2026) [10]. This technological diversification highlights a shift in focus: the challenge is no longer primarily acquiring data but effectively managing the resulting data heterogeneity and ensuring precise synchronization across all disparate, proprietary platforms to enable truly integrated analysis (Bouwman *et al.*, 2023; Cabrera *et al.*, 2021; Rao *et al.*, 2025) [7, 9, 32].

3.2. Artificial Intelligence and Predictive Dairy Management

3.2.1. Machine Learning for Predictive Health and Reproduction

The exponential growth of sensor data collected in Dairy 4.0 necessitates advanced analytical methodologies provided by Artificial Intelligence (AI) and Machine Learning (ML). ML, leveraging statistical methods such as Random Forests (RF) and Convolutional Neural Networks (CNNs), is instrumental in processing complex, multidimensional datasets to accurately forecast disease events and animal performance (Condotta & Tedeschi, 2026) [10].

Practical applications of ML demonstrate its transformative potential in farm efficiency. Models have been successfully deployed for robotic milking systems to identify suboptimal performance indicators, such as excessive idle time or milking failures (Neupane & Paudyal, 2025) [29]. Furthermore, AI-powered models are capable of preemptive detection of heat stress, mastitis, and lameness, enabling farmers to apply individualized, timely interventions, thereby reducing health costs and improving animal welfare outcomes (Paudyal *et al.*, 2025). Deep learning architectures, such as the YOLOv11 model, are also being used for non-traditional analysis, classifying dairy cows into milk yield categories based solely on image analysis of the udder region (Martinez *et al.*, 2024). This vision-based approach yielded a mean Average Precision (mAP@50) of 0.558 for the low-yield class, demonstrating

the feasibility of tailoring nutrition based on predicted productivity.

3.2.2. Data Fusion and the Digital Twin (DT) Framework

The Digital Twin (DT) framework is emerging as a critical architectural component of Dairy 4.0, representing a dynamic, virtual counterpart of the physical farm system, which includes animals, environment, and equipment (Cabrera & Fadul-Pacheco, 2021) [9]. DTs integrate real-time data streams—from feed intake records to individual sensor data—to enable real-time monitoring, predictive analytics, and simulation (Ametefe *et al.*, 2024; Neethirajan & Kemp, 2021) [1, 28]. This capability allows farmers to simulate management strategies, such as altered feeding regimes, before deployment, optimizing resource use and enhancing productivity (Ametefe *et al.*, 2024) [1]. DT systems significantly contribute to systemic resilience by facilitating adaptive decision-making, particularly in the face of climate variability (Brown-Brandl, 2025) [8]. Continuous

monitoring enables specific, individualized interventions, such as adjusting cooling strategies during heat stress events, which directly impact welfare outcomes (Brown-Brandl, 2025) [8]. Beyond animal management, DTs incorporate environmental modeling; for example, models can predict milk urea values, which are then transformed using empirical equations to estimate urinary urea nitrogen (UUN) and ammonia (NH3) emissions, offering an indirect yet practical means of assessing and optimizing environmental performance (Zhou *et al.*, 2024) [45].

3.2.3. Data Synthesis and Performance Metrics

The convergence of sophisticated sensors and advanced AI algorithms has resulted in quantifiable improvements across core dairy management metrics. These technologies provide a level of precision and objectivity previously unattainable through manual monitoring. Table 1 summarizes key technological applications and their demonstrated performance metrics in recent literature.

Table 1: Performance and Application of Key Sensor and AI Technologies in PDF (2018–2025)

Management Focus	Technology Type	AI Algorithm	Reported Metric/Accuracy	Primary Function
Reproduction (Estrus)	Acoustic/Wearable Sensors	BP Neural Network	Up to 97.62% Accuracy	Timely insemination, reduced calving intervals (Singh <i>et al.</i> , 2025) [36]
Health (Lameness, Stress)	Computer Vision/Depth Cameras	CNNs, Machine Learning	Early, Noninvasive Detection	Shift from reactive treatment to proactive care (Paudyal <i>et al.</i> , 2025)
Production (Milk Yield)	Image-Based Udder Detection	YOLOv11 Architecture	mAP@50 up to 0.558 (Low-Yield)	Targeted nutritional and grouping strategies (Botsoglou <i>et al.</i> , 2025) [6]
Genetics/Efficiency	In-line Milking Sensors	Predictive Transmitting Abilities	69% Reliability for Proven Bulls (MSPD)	Objective selection for parlor throughput (Antanaitis, 2021) [2]
Environmental	Multi-Sensor Fusion	Digital Twin (DT) Framework	Real-time Scenario Simulation	Optimization of resource consumption (feed, water, energy) (Ametefe <i>et al.</i> , 2024 [1])

3.3. Farm-Level Sustainability: Multi-Dimensional Impact Assessment

3.3.1. Economic Sustainability and Labor Efficiency

Precision Dairy Farming drives measurable enhancements in economic viability, primarily by reducing costs associated with inputs and mitigating losses due to health issues (Dar *et al.*, 2024) [11]. Precision feeding systems are noted for the fastest Return on Investment (ROI), typically achieved within 2–4 years, largely through optimizing Total Mixed Rations (TMR) and individualized cow rations, resulting in feed cost reductions ranging from 15% to 25% (Cabrera *et al.*, 2021) [9]. The integration of AI-powered health detection systems and automated monitoring substantially decreases reliance on reactive veterinary care (Cabrera *et al.*, 2021) [9]. Early adopters have reported savings on health costs of up to Rs. 47000/- per cow annually by catching subclinical diseases like mastitis and lameness before they escalate. Furthermore, the automation enabled by technologies such as robotic milking and advanced tracking systems addresses the persistent labor shortage challenge, with some reports indicating labor cost reductions of 20% to 50%. For large-scale operations, these efficiencies are critical competitive advantages.

3.3.2. Environmental Sustainability and Resource Footprint Reduction

PDF technologies are indispensable tools for mitigating the environmental impact of the dairy sector and achieving ambitious climate goals (Borhan & Khanaum, 2022) [5]. The efficiency gains derived from data-driven management directly translate into reduced resource usage: the sector’s historical progress included a 19% reduction in carbon

footprint and a 30% reduction in water use per unit of milk, a trend accelerated by PDF adoption. Specifically, precision feeding minimizes nutrient excretion into the environment (Kebreab, 2024) [21]. By precisely balancing protein and energy in individual diets, farmers can reduce excess nitrogen excretion, which subsequently lowers the generation of Nitrous Oxide (N2O), a potent greenhouse gas (Kebreab, 2024) [21]. Optimized herd management and improved feeding strategies, informed by PDF data, have demonstrated the potential to close existing yield gaps and reduce GHG emission intensities by a significant margin, ranging from 6.5% to 27.4% (Tadele *et al.*, 2025) [40]. This measurable reduction in GHG emission intensity strategically positions PDF technologies as essential assets for achieving compliance with stringent global climate policies, making PDF adoption a strategic imperative driven by both environmental and regulatory pressures (Tedeschi, 2024) [41]. DTs further aid this process by allowing scenario testing to optimize water and energy use, fostering sustainable practices (Ametefe *et al.*, 2024) [1].

4. Challenges & Gaps in Current Knowledge

4.1. Technical Impediments: Interoperability, Data Fusion, and Connectivity

Despite the sophistication of individual sensor technologies, the practical integration of PDF systems faces severe technical hurdles (Smink, 2024) [38]. A paramount issue is the lack of standardized data exchange protocols. Farmers utilize equipment from numerous vendors (e.g., milk processing data from 11 different equipment manufacturers). This results in data heterogeneity and fragmentation, making

the seamless integration and fusion of high-resolution data streams—necessary for advanced DT modeling—exceptionally challenging (Cabrera, 2021) ^[9].

Furthermore, the physical deployment of advanced PDF systems is constrained by infrastructural limitations, particularly poor rural connectivity (Dar *et al.*, 2024) ^[11]. Real-time processing and analysis often require stable, high-speed connections, which are unreliable in remote farming areas (Higaki *et al.*, 2024) ^[17]. To circumvent this, complex computational tasks must rely on Edge AI for local inference, but implementing such systems requires high infrastructure costs and significant on-farm computing power. For highly complex applications like DTs, challenges such as managing high barn noise and achieving millisecond-level data synchronization are major obstacles that restrict full real-time predictive capabilities (Cabrera *et al.*, 2025) ^[9].

5. Future Research Directions

5.1. Integration of Explainable AI (XAI) with Mechanistic Biological Models

A critical direction for future research involves integrating Explainable AI (XAI) with established, biologically grounded mechanistic models (Mallinger *et al.*, 2025) ^[27]. Current ML models often function as "black boxes," providing predictions without transparent causal reasoning. The future demand is to move beyond mere prediction toward comprehensive explanation and accountability (Mallinger *et al.*, 2025) ^[27].

This integration would require developing hybrid modeling approaches where XAI validates algorithmic recommendations—such as a specific dietary change or intervention—against physiological plausibility based on known digestion or metabolic science (Mallinger *et al.*, 2025) ^[27]. This synergy will achieve two vital objectives: first, it builds necessary farmer trust by clarifying the *rationale* behind algorithmic decisions; second, it ensures system adaptability and reliability under novel or unprecedented farm conditions (e.g., sudden feed ingredient changes) where correlation-based ML models might otherwise fail (Mallinger *et al.*, 2025) ^[27].

6. Conclusion

Precision Dairy Farming (Dairy 4.0) represents a transformative shift in livestock management, replacing conventional, reactive practices with proactive, data-driven strategies. By integrating IoT sensor networks, Digital Twins, and advanced machine learning, these systems optimize both individual animal health and overall herd productivity. This technological synergy delivers profound economic benefits—such as significantly reduced feed and veterinary costs—while advancing environmental sustainability by minimizing greenhouse gas emission intensities and resource footprints to meet stringent global climate targets.

Despite these proven advantages, widespread global adoption is currently impeded by severe infrastructural and technical bottlenecks, most notably fragmented data interoperability across proprietary vendor platforms and inadequate rural internet connectivity. To fully realize the sustainable potential of Dairy 4.0, the industry must establish standardized data exchange protocols. Furthermore, future research must move beyond opaque, "black-box" algorithms by integrating Explainable AI (XAI) with biologically grounded mechanistic models. This hybrid approach will ensure that data-driven interventions are physiologically valid, transparent, and ultimately trusted by dairy producers.

Conflict of Interest

Not available

Financial Support

Not available

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