



International Journal of Veterinary Sciences and Animal Husbandry



ISSN: 2456-2912
NAAS Rating (2026): 4.61
VET 2026; 11(7): 249-256
© 2026 VET
www.veterinarypaper.com
Received: 22-04-2026
Accepted: 28-05-2026

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Smart dairy farming: Automation, artificial intelligence and precision livestock technologies: Current advances, challenges and future perspectives

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DOI: <https://www.doi.org/10.22271/veterinary.2026.v11.i7d.3629>

Abstract

The global dairy industry is undergoing a technological transformation driven by rapid advances in automation, Artificial Intelligence (AI), the Internet of Things (IoT), robotics, cloud computing, and Precision Livestock Farming (PLF). Increasing herd sizes, labour shortages, growing concerns regarding animal welfare, environmental sustainability, and the demand for high-quality milk have accelerated the adoption of digital technologies for real-time monitoring and decision-making. Unlike conventional dairy management, smart dairy farming utilizes interconnected sensing devices, wearable technologies, automated milking systems, computer vision, machine learning algorithms, and decision-support platforms to monitor individual animals continuously and optimize farm operations. These technologies enable early detection of diseases, precision feeding, reproductive management, behavioural assessment, milk quality monitoring, and environmental control, thereby improving productivity while simultaneously enhancing animal welfare and reducing production costs. Recent advances in AI and deep learning have further expanded the capability of precision dairy systems by facilitating predictive analytics, image-based disease diagnosis, automated behavioural recognition, and intelligent resource management. Nevertheless, challenges associated with high installation costs, interoperability among digital platforms, data ownership, cybersecurity, algorithm validation, and technology adoption by smallholder farmers continue to limit widespread implementation. This review critically examines the evolution of smart dairy farming, major automation technologies, artificial intelligence applications, precision livestock technologies, economic implications, sustainability benefits, existing limitations, and future research opportunities. Rather than merely describing available technologies, the review synthesizes current scientific evidence and identifies critical research gaps necessary for developing resilient, economically viable, and sustainable dairy production systems.

Keywords: Artificial intelligence, automation, dairy farming, internet of things, robotics

Introduction

Increasing herd sizes and declining labour availability have encouraged the adoption of Precision Livestock Farming (PLF) technologies to reduce repetitive tasks and improve herd monitoring (Hostiou *et al.*, 2017) ^[15], while growing expectations for environmentally, economically, and socially sustainable dairy production have accelerated the integration of sensors, automation, and decision-support technologies (Lovarelli *et al.*, 2020) ^[25]. PLF integrates engineering, sensor technologies, animal science, and information systems to continuously monitor individual animals and support data-driven management decisions (Wathes *et al.*, 2008; Norton *et al.*, 2019) ^[31], emphasizing real-time assessment of physiological, behavioural, health, production, and welfare parameters (Berckmans, 2017) ^[7]. Smart dairy farming extends PLF through the integration of automation, Internet of Things (IoT), artificial intelligence (AI), robotics, cloud computing, and advanced data analytics (Akbar *et al.*, 2020; Yousfi and M'Sadak, 2025) ^[1, 43], facilitating continuous data acquisition, transmission, and analysis for evidence-based decision-making (Taneja *et al.*, 2019; Akbar *et al.*, 2020) ^[1, 38]. Wearable sensors, RFID, accelerometers, rumination collars, rumen boluses,

thermal imaging, and computer vision generate high-frequency data for precision management (Rutten *et al.*, 2013; Lamanna *et al.*, 2025; Han *et al.*, 2022) [13, 21, 36], enabling early detection of diseases, reproductive disorders, metabolic disturbances, and behavioural abnormalities (Rutten *et al.*, 2013; Han *et al.*, 2022) [13, 36].

AI-driven machine learning and deep learning are increasingly investigated for health prediction, reproductive monitoring, lameness detection, and milk production forecasting (Slob *et al.*, 2021; Kaur *et al.*, 2023a) [18], while automated milking, feeding, and sensor-actuator systems can reduce labour requirements and support precision

management (Jacobs and Siegford, 2012; Kaur *et al.*, 2023a) [16]. However, expanding sensor networks generate large, heterogeneous datasets requiring advanced integration and analytics (Bahlo *et al.*, 2019; Cockburn, 2020) [4, 11]. Although these systems can improve monitoring of health, welfare, productivity, and resource use (Cockburn, 2020) [11], widespread adoption remains constrained by investment costs, interoperability, data integration, management, and ownership issues (Bahlo *et al.*, 2019) [4]. Furthermore, machine-learning models require larger integrated datasets and further validation to improve reliability and generalizability across commercial production systems (Cockburn, 2020) [11].

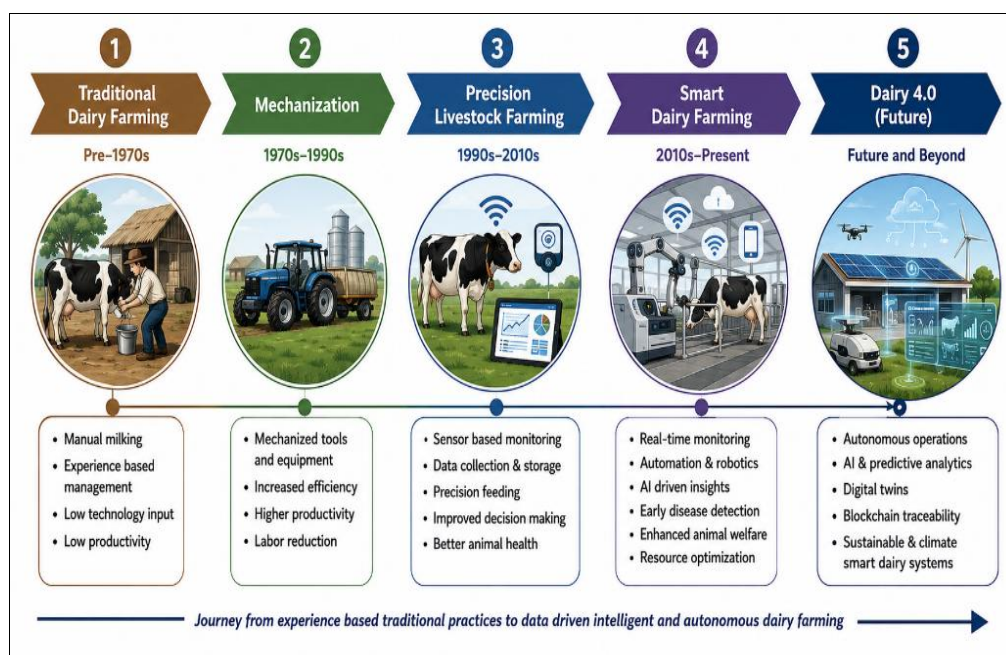


Fig 1: Evolution of dairy farming

1. Automation and robotics in smart dairy farming

Automation has emerged as an important component of the digital transformation of dairy farming, replacing or assisting repetitive manual operations through automated, sensor-based, and increasingly data-driven systems (Jacobs and Siegford, 2012; Kaur *et al.*, 2023b) [16, 19]. Beyond conventional mechanization of individual farm tasks, modern automated systems increasingly integrate sensors, communication technologies, data-processing tools, and decision-support systems to monitor animals and farm processes and support management decisions based on continuously generated data (Kaur *et al.*, 2023b) [19]. This transition has contributed to a shift from labour-intensive operations toward precision management, with opportunities to improve labour efficiency, production management, animal monitoring, and resource utilization (Jacobs and Siegford, 2012; Romano *et al.*, 2023) [16]. Recent technological developments have extended automation across multiple dairy operations, including automatic milking and feeding, while sensor-based technologies increasingly support health, behavioural, and reproductive monitoring, contributing to the development of more integrated precision dairy farming systems (Mottram, 2016; Kaur *et al.*, 2023b) [19, 29].

1.1 Automatic milking systems (AMS)

Automatic Milking Systems (AMS) are among the most important automation technologies adopted in modern dairy farming, allowing cows voluntary access to milking while generating individual-level data on milk production, milking

frequency, and other parameters useful for herd management (Jacobs and Siegford, 2012; Løvendahl and Chagunda, 2011) [16, 26]. Beyond reducing milking-related labour, data routinely collected by AMS and associated sensor technologies can support the detection and management of health disorders through changes in milk production, milking behaviour, and animal activity (King *et al.*, 2018; Tse *et al.*, 2018). Although AMS can reduce labour requirements and provide greater flexibility in milking management, their economic performance depends on factors such as system utilization, herd size, milk production, investment costs, and farm management (Rotz *et al.*, 2003; Bijl *et al.*, 2007; Jacobs and Siegford, 2012) [8, 16, 34].

1.2 Automated feeding systems

Automated feeding technologies improve feeding precision, reduce labour requirements, and enable consistent ration delivery, thereby supporting feed efficiency and animal performance (Monteiro *et al.*, 2021; Tangorra *et al.*, 2024) [28, 39]. Integration of automated feeding with sensors and data-driven technologies further enables precision nutrition through individualized feed allocation based on animal requirements and performance (Dell 'Unto *et al.*, 2025)

1.3 Automated manure management

Autonomous manure-scraping robots improve barn hygiene, reduce labour demand, and minimize exposure to pathogens associated with hoof and udder diseases (Benni *et al.*, 2021) [6]. Efficient manure management can further support nutrient

recovery and renewable energy production through anaerobic digestion, contributing to more sustainable dairy production systems (Atandi and Rahman, 2012) [3].

1.4 Automated environmental control

Sensor-based ventilation and cooling systems facilitate automated regulation of the barn microclimate, including temperature and humidity, helping to mitigate heat stress and its adverse effects on milk production and reproductive performance (Polsky and von Keyserlingk, 2017; Fournel *et al.*, 2017) [32]. Such environmental control strategies are particularly important in hot climatic conditions, where heat

stress represents a major constraint to dairy cattle productivity (Becker *et al.*, 2020) [5].

1.5 Advantages and limitations

Automation enhances labour efficiency, production consistency, disease surveillance, and precision management through continuous data acquisition (Jacobs and Siegford, 2012) [16]. However, high capital investment, maintenance costs, interoperability issues, and limited adoption by smallholder farmers remain major barriers to widespread implementation (Benni *et al.*, 2021) [6].

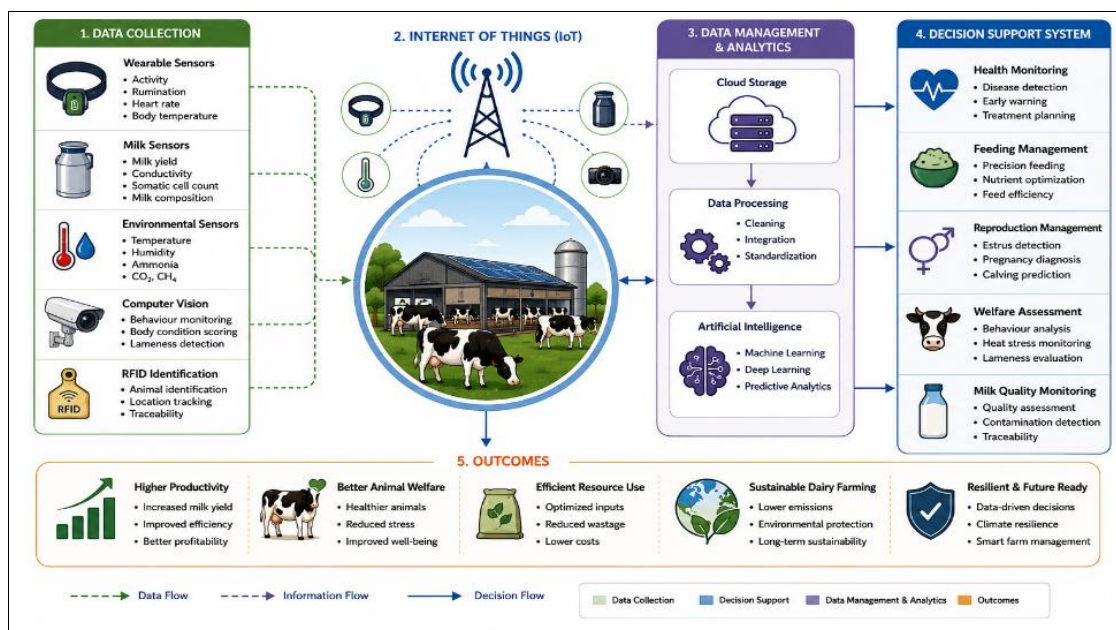


Fig 2: Integrated smart dairy farming framework

2. Artificial intelligence and machine learning in smart dairy farming

Artificial Intelligence (AI) and Machine Learning (ML) enable automated analysis of large, complex datasets generated by sensors and farm-management systems, supporting predictive decision-making and individual-animal precision management. By identifying complex relationships among behavioural, physiological, environmental, and production variables, AI-based approaches are increasingly applied to dairy cattle health monitoring, reproduction, feeding, and welfare assessment (Cockburn, 2020; Slob *et al.*, 2021; Kaur *et al.*, 2023a) [11, 18].

2.1 Machine learning algorithms in dairy farming

Supervised machine learning algorithms, including Random Forest (RF), Support Vector Machine (SVM), Artificial Neural Networks (ANN), and gradient-boosting methods, are increasingly applied to multidimensional agricultural and dairy datasets for prediction and classification tasks (Liakos *et al.*, 2018; Cockburn, 2020) [11, 22]. In dairy farming, these approaches have been investigated for predicting milk production, animal health, and other management-related outcomes. RF models offer robust ensemble-based classification and regression, while SVMs are effective for high-dimensional classification problems and ANNs are particularly suited to modelling complex nonlinear relationships. However, model performance is application- and dataset-dependent, and no single algorithm is universally superior (Cockburn, 2020) [11].

2.2 Deep learning applications

Deep learning has advanced automated analysis of images, videos, and time-series data in dairy farming. Convolutional Neural Networks (CNNs) and related computer-vision approaches have been applied to individual-animal identification and automated recognition of behaviours such as feeding, drinking, standing, and lying (McDonagh *et al.*, 2021). Emerging transformer-based and multimodal approaches offer further potential for real-time animal tracking, behavioural classification, and integration of heterogeneous data streams in precision dairy management. Computer vision has emerged as one of the fastest-growing technologies in dairy farming because it enables continuous, non-invasive monitoring of cattle. Integration of computer vision with deep learning has substantially improved detection accuracy while reducing labour requirements and observer bias. However, lighting variability, animal occlusion, and environmental complexity remain important technical challenges limiting commercial deployment (Antognoli *et al.*, 2025) [2].

2.3 AI-based health monitoring

Artificial Intelligence (AI) and machine-learning approaches enable integration of sensor and farm-management data for earlier identification of health abnormalities in dairy cattle. Predictive models using milk, behavioural, activity, and other sensor-derived data have shown potential for detecting conditions such as mastitis and lameness, supporting earlier intervention and improved health management (Post *et al.*,

2020; Shahinfar *et al.*, 2021) [33, 37]. Emerging ML-based approaches also show promise for identifying physiological responses to heat stress by integrating environmental,

behavioural, and physiological indicators (Džermeikaitė *et al.*, 2025).

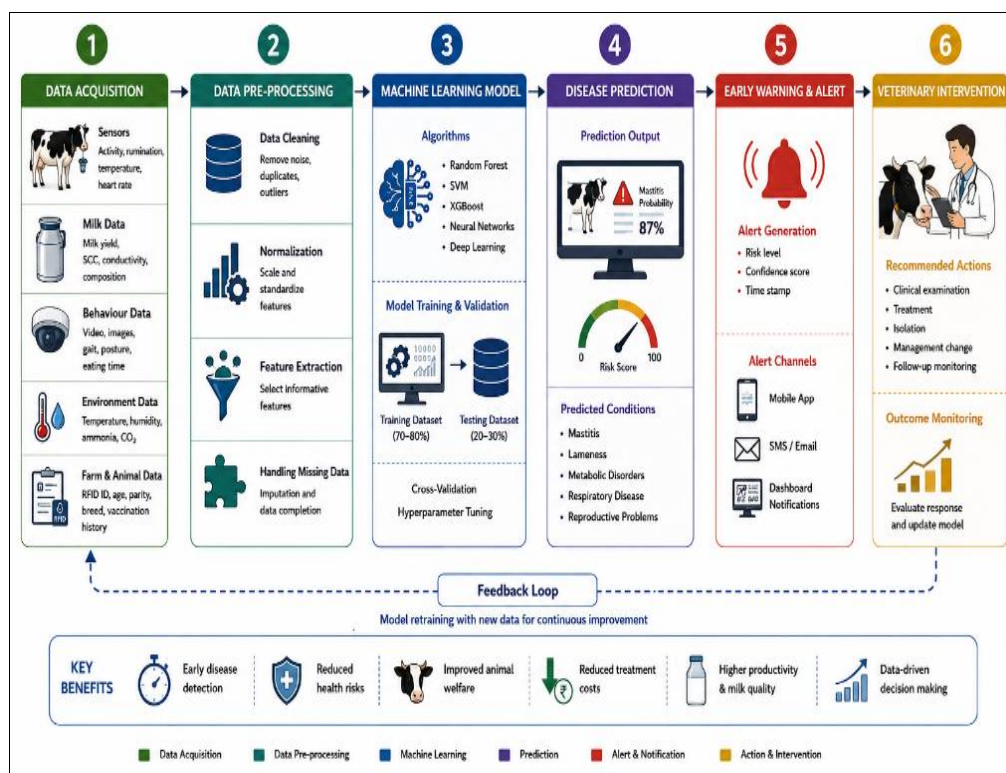


Fig 3: AI-Based disease prediction pipeline in dairy farming

2.4 AI in precision feeding and reproduction

AI and machine-learning approaches support precision nutrition by integrating production, behavioural, and sensor-derived data to predict individual feed intake and nutritional requirements, potentially improving feed efficiency and resource utilization (González *et al.*, 2018; Martin *et al.*, 2021) [27]. Similarly, sensor-based and machine-learning systems analyse activity and behavioural changes to support automated estrus detection and reproductive monitoring, reducing reliance on visual observation (Liu *et al.*, 2023) [24].

2.5 Emerging technologies

Digital twins are emerging as virtual representations of animals and farming systems that integrate real-time data with computational models to support monitoring, simulation, and predictive management (Neethirajan and Kemp, 2021) [30]. Emerging explainable AI (XAI), multimodal learning, and large language models (LLMs) may further enhance the interpretability, integration, and accessibility of AI-driven livestock management systems (Menezes *et al.*, 2024).

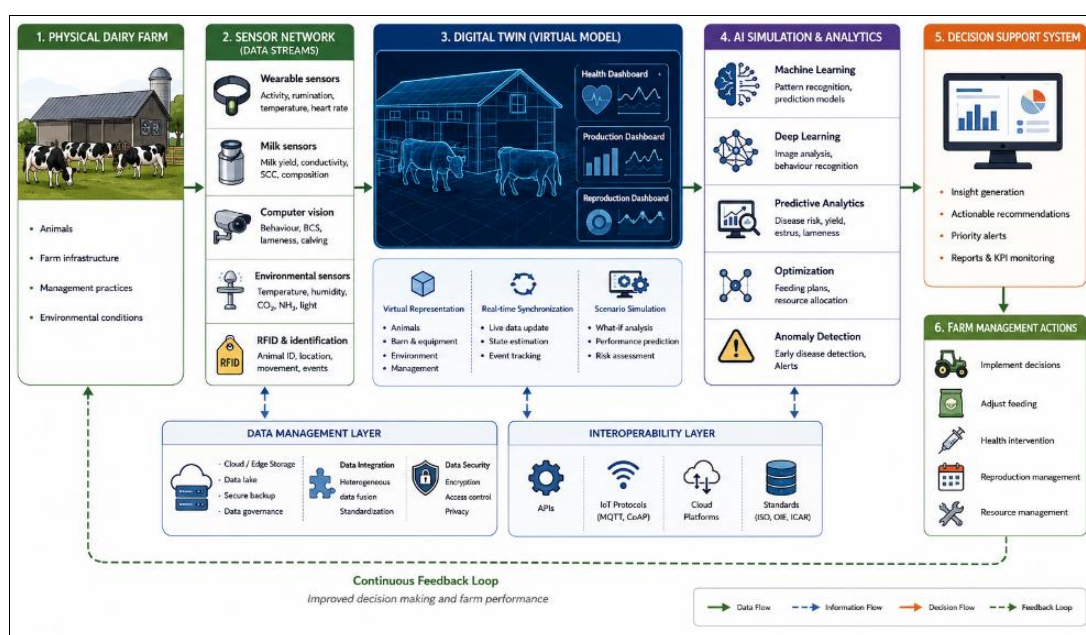


Fig 4: Digital twin architecture for dairy farms

2.6 Challenges and future perspectives

Despite significant progress, AI implementation in dairy farming remains constrained by limited availability and integration of high-quality datasets, interoperability among digital platforms, and insufficient external validation of predictive models. Future research should prioritize standardized data frameworks, larger and more diverse datasets, and robust validation across independent herds and production environments to improve model reliability and generalizability (Bahlo *et al.*, 2019; Cockburn, 2020; Slob *et al.*, 2021)^[4, 11].

3. Precision livestock farming (PLF) technologies and biosensors

Precision Livestock Farming (PLF) integrates sensors, automation, and data analytics for continuous, individual-animal monitoring and data-driven management. By assessing health, production, reproduction, behaviour, and welfare in real time, PLF enables earlier identification of deviations and supports timely management interventions (Berckmans, 2017; Norton *et al.*, 2019)^[7, 31]. Unlike conventional herd-level management, PLF utilizes continuously generated animal and environmental data to improve decision-making, productivity, and precision management (Rutten *et al.*, 2013; Kaur *et al.*, 2023b)^[36].

3.1 Wearable sensor technologies

Wearable sensors, including neck collars, ear tags, pedometers, accelerometers, and rumination monitors, enable continuous monitoring of activity, feeding, rumination, and locomotor behaviour in dairy cattle, supporting precision health and reproductive management (Rutten *et al.*, 2013; Mottram, 2016)^[29, 36]. Accelerometer-based systems can identify behavioural and activity changes associated with estrus, lameness, and health disturbances, facilitating earlier detection and reducing reliance on manual observation (Mottram, 2016; King *et al.*, 2018)^[29].

3.2 Rumination and feeding monitoring

Rumination and feeding behaviours are valuable indicators of dairy cattle health and welfare. Automated sensors enable continuous monitoring of rumination, feeding duration, and feeding frequency, facilitating early identification of behavioural deviations associated with health disturbances (Borchers *et al.*, 2016; Lamanna *et al.*, 2025)^[9, 21]. Sensor-based monitoring of feeding behaviour and feed intake can further support precision feeding and individualized nutritional management, with potential benefits for feed efficiency and farm profitability (Kaur *et al.*, 2023a)^[18].

3.3 Milk monitoring sensors

Automatic milking systems incorporate inline sensors that monitor parameters such as milk yield, flow rate, electrical conductivity, colour, and somatic cell count-related indicators, supporting automated surveillance of udder health and milk quality (Kamphuis *et al.*, 2008; Rutten *et al.*, 2013)^[17]. Integration of milk sensor data with machine-learning algorithms can further improve mastitis prediction and facilitate earlier management interventions (Tian *et al.*, 2024)^[40].

3.4 Identification and traceability technologies

Radio Frequency Identification (RFID) is widely used for automated individual-animal identification and provides a foundation for linking animal identity with production, health, feeding, reproductive, and movement records in precision livestock systems (Ruiz-Garcia and Lunadei, 2011; Caja *et*

al., 2016)^[10, 35]. Integration of electronic identification with digital farm-management platforms can enhance livestock traceability and facilitate more efficient animal monitoring and record management throughout the production chain (Ruiz-Garcia and Lunadei, 2011)^[35].

3.5 Internet of things (IoT) in dairy farming

The Internet of Things (IoT) interconnects sensors, automated equipment, and digital management platforms through communication networks, enabling real-time data exchange and integrated monitoring in dairy farms (Akbar *et al.*, 2020)^[1]. IoT architectures incorporating cloud and fog computing facilitate remote monitoring of animal behaviour and health and support data-driven decision-making, improving the flexibility and efficiency of dairy management (Taneja *et al.*, 2019)^[38].

3.6 Benefits and limitations of PLF technologies

Precision Livestock Farming (PLF) technologies enable continuous individual-animal monitoring, supporting improved health surveillance, reproductive management, labour efficiency, and welfare assessment (Rutten *et al.*, 2013; Berckmans, 2017)^[7]. However, wider adoption remains constrained by investment costs, technical complexity, data integration, and interoperability challenges (Bahlo *et al.*, 2019; Kaur *et al.*, 2023a)^[4, 18]. Future research should prioritize interoperable data standards, integration of heterogeneous data sources, and robust validation across commercial production environments to improve the reliability and scalability of PLF systems (Bahlo *et al.*, 2019; Cockburn, 2020)^[4, 11].

4. Challenges, research gaps and future perspectives

4.1 Technical challenges

The effectiveness of smart dairy farming depends on the accuracy, reliability, and completeness of sensor-generated data. Missing or erroneous data, sensor failures, and communication disruptions can compromise data quality and consequently reduce the reliability of automated monitoring and AI-based decision-support systems (Cockburn, 2020; Kaur *et al.*, 2023b)^[11, 19]. Interoperability is another major challenge, as heterogeneous technologies and data formats often limit seamless data exchange and system integration. Development of standardized and interoperable data frameworks is therefore essential for effective integration of sensors, automated systems, and farm-management platforms (Bahlo *et al.*, 2019)^[4].

4.2 Data management and cybersecurity

Smart dairy farming generates large volumes of heterogeneous animal, production, and environmental data, creating challenges related to data storage, processing, integration, and governance. Although cloud-based platforms facilitate data access and management, concerns regarding data privacy, ownership, security, and responsible data sharing remain important considerations in digital agriculture (Wiseman *et al.*, 2019)^[41]. Furthermore, limited interoperability and the lack of standardized data frameworks restrict seamless data exchange among digital technologies and management platforms (Bahlo *et al.*, 2019)^[4].

4.3 Adoption by farmers

Adoption of precision dairy technologies remains uneven and is influenced by economic, technical, and farm-specific factors. High investment costs, uncertainty regarding economic returns, technological complexity, and farmers' skills and perceptions can constrain technology adoption

(Drewry *et al.*, 2019; Lima *et al.*, 2020) ^[23]. These barriers may be particularly important for resource-constrained and smallholder production systems, where access to capital, digital infrastructure, and technical support is often limited.

4.4 Research gaps

Most AI models have been developed using datasets collected from a limited number of commercial farms, reducing their applicability across different breeds, management systems, and climatic regions. Greater emphasis should be placed on developing robust and externally validated algorithms capable of generalizing under diverse production environments (Liakos *et al.*, 2018; Liu *et al.*, 2023) ^[22].

Current research also focuses predominantly on disease detection and behavioural monitoring, whereas comparatively

fewer studies have investigated long-term sustainability, economic performance, greenhouse gas mitigation, and integration of multiple technologies into unified management platforms (Liu *et al.*, 2023) ^[24].

4.5 Future perspectives

Future smart dairy systems are likely to increasingly integrate AI, IoT, robotics, advanced analytics, and digital twins to support predictive and individualized management, automation, and improved production efficiency (Neethirajan and Kemp, 2021; Hassoun *et al.*, 2023) ^[14, 30]. Emerging technologies may further enhance real-time data integration and intelligent decision support; however, their practical scalability, interoperability, and effectiveness under commercial dairy conditions require further validation.

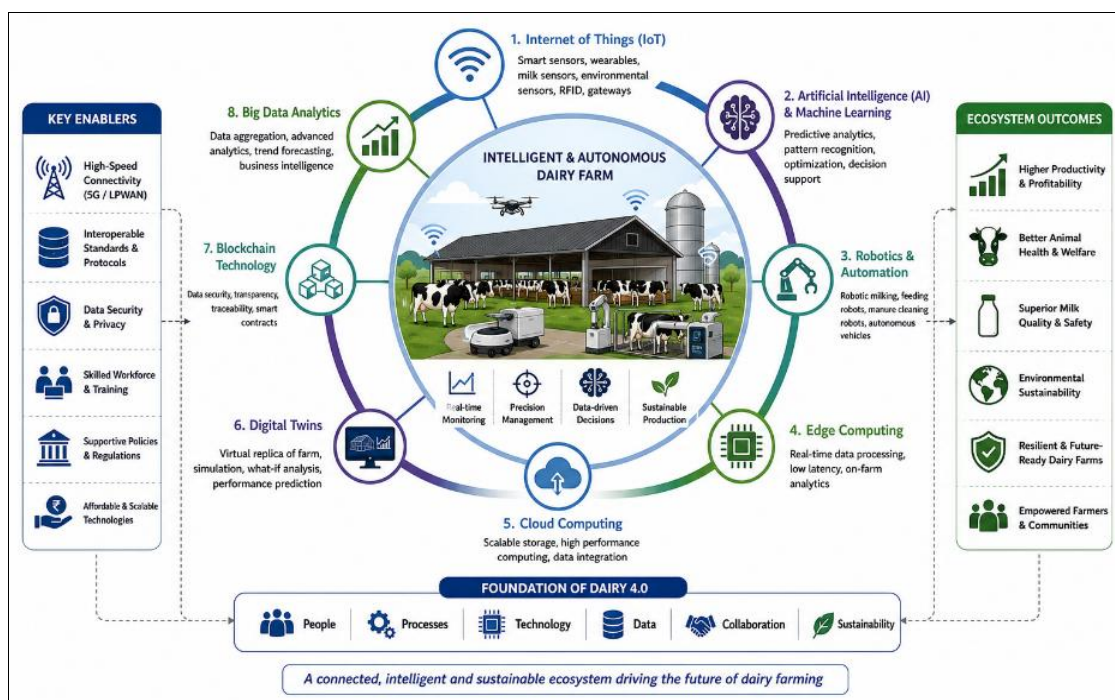


Fig 5: Future dairy 4.0 ecosystem

Conclusion and future outlook

Smart dairy farming represents a shift from conventional herd management toward automated, data-driven, and individual-animal-focused production systems. The integration of precision livestock farming technologies, IoT, biosensors, robotics, automation, and artificial intelligence enables continuous monitoring and supports timely decisions related to animal health, reproduction, feeding, welfare, and production. Automated milking and feeding systems further reduce labour demands while generating high-frequency data for precision management.

Advances in AI, machine learning, and computer vision are facilitating a transition from reactive toward predictive management through earlier identification of health and behavioural abnormalities. However, widespread implementation remains constrained by high investment costs, limited interoperability and data integration, concerns regarding data governance and security, and insufficient validation of AI models across diverse production environments.

Future research should prioritize interoperable digital infrastructures, standardized data frameworks, robust model validation, explainable and multimodal AI, and affordable technologies adaptable to different farm scales. Emerging

approaches such as digital twins may further strengthen predictive and individualized decision support, although their commercial applicability requires validation. Ultimately, the success of Dairy 4.0 will depend on developing reliable, economically viable, and farmer-oriented technologies that translate complex data into actionable decisions, supporting efficient, resilient, welfare-oriented, and environmentally sustainable dairy production.

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How to Cite This Article

Deb D, Verma MK, Diwakar V, Gangwar M. Smart dairy farming: automation, artificial intelligence and precision livestock technologies: current advances, challenges and future perspectives. *International Journal of Veterinary Sciences and Animal Husbandry.* 2026; 11(7): 249-256

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