Scientific Papers. Series D. Animal Science. Vol. LXIX, No. 1, 2026
ISSN 2285-5750; ISSN CD-ROM 2285-5769; ISSN Online 2393-2260; ISSN-L 2285-5750

PRECISION TECHNOLOGIES FOR DAIRY COW MANAGEMENT: A REVIEW OF WELFARE, HEALTH, AND SUSTAINABILITY OUTCOMES

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Abstract

Dairy cow farming is a strategic sector of agriculture, with a major impact on food production, the rural economy, and food security. In the context of increased production and increasing demands on animal welfare and sustainability, modern dairy farms are increasingly integrating advanced management technologies. This review synthesizes and analyses the main modern technologies used in dairy cow maintenance, including health and behaviour monitoring systems, precision nutrition technologies, automated milking systems, environmental management solutions, and digitally assisted reproductive technologies. The effects of these systems on cows' productivity, milk quality, health, and longevity of cows, as well as on the economic and environmental sustainability of farms, are assessed. Through the integrated approach to modern maintenance systems, this review contributes to clarifying the relationship between technology, animal welfare, and production efficiency, addressing gaps in the literature, where these issues are often treated separately.

Key words*: animal health monitoring, animal welfare, automatic milking systems (AMS), dairy cattle management, precision livestock farming (PLF).*

INTRODUCTION

In recent decades, dairy cattle production has undergone profound transformations: herd sizes have increased, input costs have escalated, and standards regarding milk quality and animal welfare have become increasingly stringent. In this context, traditional herd management methods based on the stockman's direct observation and empirical knowledge can no longer sustain an efficient and profitable dairy operation on their own. Given these considerations, it is understandable that a growing number of dairy farmers are turning to modern technologies that enable both the continuous collection and analysis of individual animal data and the timely adoption of evidence-based management decisions (Neethirajan, 2023).

Precision livestock farming (PLF) has evolved from simple automation systems primarily aimed at reducing labour requirements (Kelemen et al., 2016), towards complex solutions centred on the continuous monitoring of animal needs, particularly with regard to health and welfare. Data collected at farm level are intended to support the farmer's decision-making process, facilitating timely interventions adapted both to the animals' physiological status and to the operational efficiency objectives of the holding.

A wide range of systems are currently available that can be attached to cows or installed on the farm (motion sensor collars, ear tags, ingested boluses for ruminal temperature measurement, thermal cameras, and others). Precision livestock farming relies on individual animal monitoring through internet-connected sensors, with data transmitted directly to the farmer to support better management decisions for each cow (Tangorra et al., 2024). One of the most significant advantages of these systems lies in their ability to detect health disorders before they become clinically apparent. The onset of disease in dairy cows is accompanied by characteristic behavioural changes - reduced rumination time, decreased dry matter intake, diminished locomotor activity, and prolonged recumbency - changes that sensors can signal several days before a conventional clinical

diagnosis (Tsai et al., 2021). When milk production data and physiological indicators are combined with thermal imaging, the accuracy of early disease detection increases considerably compared with the use of any single data source in isolation (Michelena et al., 2025; Paulauskaite-Taraseviciene et al., 2026).

An equally important consideration is the housing environment in which cows are kept. Barn temperature, air quality, and resting area comfort directly influence animal health and milk yield. The temperature-humidity index (THI) is a widely used indicator of heat stress risk in dairy cattle. When THI exceeds the threshold of 68, automated systems activate fans and water sprinklers to cool the animals, without requiring any intervention from the stockman (Tangorra et al., 2024; Neculai-Văleanu et al., 2025). As herd sizes have grown, individual monitoring of each cow has become increasingly challenging, with real consequences for animal health and milk production. Precision livestock farming offers a practical solution for managing large herds without losing sight of the individual animal, while simultaneously improving the economic efficiency of the farm and reducing its environmental footprint (Kaur et al., 2023; Tangorra et al., 2024).

Although the scientific literature contains a growing number of studies on individual technologies - automatic milking systems, wearable sensors, artificial intelligence algorithms, and individually tailored nutrition - studies examining all of these together as an integrated system remain scarce. Despite this growing body of research, integrated assessments that simultaneously link outcomes in terms of animal welfare, productivity, and farm sustainability remain limited in the scientific literature. The aim of this review is to critically evaluate the main precision livestock farming technologies applied in dairy cattle operations, assessing their combined effects on animal welfare, health, productivity, and farm sustainability. By analyzing and synthesizing the available evidence in the scientific literature, this study contributes to filling an existing gap in the field, highlighting the importance of a holistic approach in which data on health, production, housing environment, and reproduction are correlated to support long-term economic efficiency and animal welfare (Stygar et al., 2021; Papakonstantinou et al., 2024; Defta et al., 2025).

MATERIALS AND METHODS

To achieve the objectives of this review, the following scientific databases were consulted: Web of Science, Scopus, PubMed, and ScienceDirect (Elsevier), which host the most relevant peer-reviewed studies on precision livestock farming applied in dairy cattle operations. Articles published primarily between 2015 and 2026 were selected to reflect the most recent technological developments in the field. A total of 312 articles were identified through database searches, of which 68 were included in the final analysis based on relevance and compliance with the inclusion criteria. Search strings included combinations of terms such as: “precision livestock farming” and “dairy cow”, “automated milking system” and “welfare”, “sensor” and “dairy cattle” and “health”, “machine learning” and “dairy”, and “smart farming” and “sustainability”. An extensive review of the scientific literature was conducted on the application of Precision Livestock Farming (PLF) technologies in dairy cow farms, with an emphasis on their impact on animal health, welfare, and sustainability.

The keywords used in the literature search included: precision livestock farming, dairy cow monitoring, automated milking systems, sensor technologies for dairy, animal welfare in dairy cows, smart farming in dairy, feeding automation for dairy cattle, and reproductive monitoring in dairy cows.

Following the construction of the reference database, a set of inclusion and exclusion criteria was applied to the selected articles.

Inclusion criteria:

- original research articles and review papers published in ISI-indexed journals;
- studies addressing technologies applied directly in dairy cow farming operations;
- research evaluating the impact on animal health, welfare, milk production, or farm sustainability;
- studies employing sensors, artificial intelligence, automated systems, or digital management platforms.

Exclusion criteria:

- publications with restricted access to full text;
- studies without direct relevance to the dairy cattle sector;
- articles of a purely theoretical nature, lacking practical applicability;
- non-scientific or unvalidated sources (reports not subject to peer review).

The selected articles were managed and organised using the Mendeley reference management software and classified according to the technological domain addressed.

Automatic milking technologies, housing and environment management, and reproductive management technologies. The schematic representation of these technologies consisted in the development of conceptual diagrams using the IPE software, facilitating the visualisation of the relationships between the different components of precision livestock farming systems.

RESULTS AND DISCUSSIONS

A. Health and welfare monitoring technologies in dairy cows

The monitoring of health and welfare in dairy cows has become a priority in modern farming operations. Until recently, stockmen relied almost exclusively on daily visual observation to identify potential health disorders in individual animals. Today, digital sensors, cameras, and artificial intelligence algorithms perform this task automatically, around the clock, for each cow individually (Neculai-Văleanu et al., 2025). Farms adopting these technologies are able to detect disease more rapidly, reduce milk yield losses, and lower treatment costs (Silva et al., 2021), which explains the growing uptake of such solutions in dairy cattle operations. Figure 1 illustrates the main categories of health and welfare monitoring instruments currently deployed in dairy cow operations, encompassing sensor-based, imaging, and AI-driven systems.

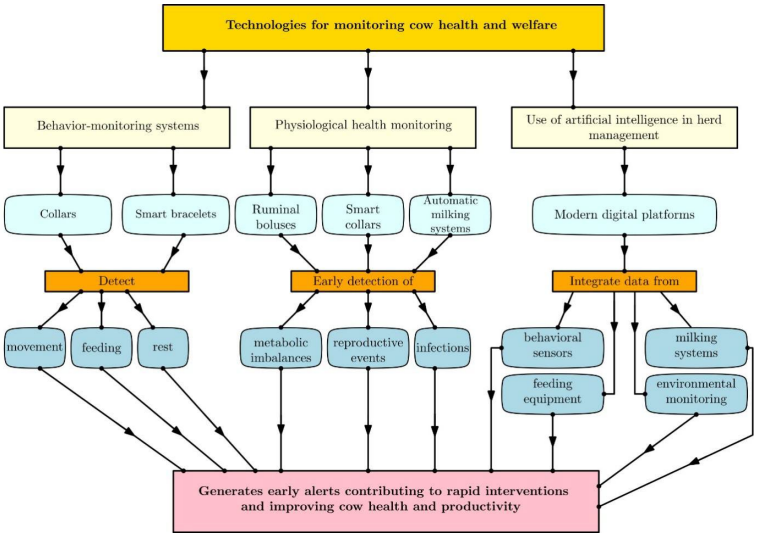

Figure 1. Schematic representation of health and welfare monitoring instruments in dairy cows
Own source (processed using IPE software)

a. Behaviour monitoring systems

The simplest and most widely used approach to monitoring the health status of dairy cows involves sensors attached directly to the animal's body. Smart collars and ear tags equipped with accelerometers continuously record the animal's activity - time spent feeding, ruminating, and lying down - automatically transmitting data to the farmer and generating alerts whenever an individual cow's behavioural patterns deviate from its established baseline (Lovarelli et al., 2022). Collars fitted with microphones add an additional layer of precision by acoustically differentiating rumination from primary ingestion (Alipio & Villena, 2023), while ear tags with integrated temperature sensors allow

fever detection without any physical contact with the animal. The limbs are monitored through pedometers or plantar pressure sensors, which identify gait abnormalities that may indicate pain or early-stage lameness (Lee & Seo, 2021).

The relevance of these devices increases substantially when they operate in parallel, with their data aggregated and analyzed on a shared digital platform. A decline in rumination time correlated with extended recumbency periods and reduced locomotor activity can thus signal the onset of disease several days before the appearance of visible clinical signs (Tsai et al., 2021).

Animal behaviour is a reliable indicator of health status, and deviations from normal behavioural patterns may signal underlying health disorders (Silva et al., 2021). For instance, a reduction in water intake may indicate heat stress or disease; increased locomotor activity is characteristic of oestrus, and a decline in rumination time may precede certain metabolic conditions (Tsai et al., 2021). Automated monitoring systems are capable of detecting these behavioural changes in real time, making them particularly valuable in large-scale dairy farming operations (de Oliveira et al., 2024).

b. Physiological health monitoring

The monitoring of physiological parameters through modern technologies - including ruminal boluses, smart collars, and automatic milking systems - enables the early detection of metabolic imbalances, reproductive events, and infectious conditions, facilitating timely interventions and contributing to improvements in animal health, milk yield, and milk quality (Lee & Seo, 2021; Michelena et al., 2025).

The most economically significant conditions in dairy farming - mastitis, lameness, and postpartum metabolic disorders - can be identified at an early stage through automated systems, before the onset of visible clinical signs. Mastitis is detected through an increase in milk electrical conductivity and a reduction in milk yield from the affected quarters (Michelena et al., 2025), and the integration of these data with behavioural changes reduces the rate of false alarms (Post et al., 2020; Mottram, 1997). Lameness is identified through changes in locomotion patterns and lying time (Swartz et al., 2024), and it can also be monitored through video-based systems with automated gait analysis (Sohan et al., 2025). Concurrently, postpartum metabolic disorders can be anticipated through declines in rumination time, locomotor activity, and milk yield, several days before clinical manifestation (Silva et al., 2021).

c. Application of artificial intelligence in herd management

Modern digital platforms integrate data from behavioural sensors, milking systems, feeding equipment, and environmental monitoring units, constructing a comprehensive profile for each individual cow. These profiles are analysed through machine learning algorithms capable of identifying patterns imperceptible to human observation and supporting the concept of a "digital twin" for the simulation of management decisions (Kaur et al., 2023; Cabrera, 2025; Rao et al., 2026). Such systems generate early health and reproductive alerts, including estimates of the optimal time for artificial insemination and the risk of culling, with high accuracy in mastitis prediction (Dharejo et al., 2025). Computer vision technologies further enable individual animal monitoring without the need for wearable devices (Mahato et al., 2025).

The integration of these technologies contributes substantially to animal welfare and farm sustainability through the early detection of mastitis and lameness, the reduction of antibiotic use and premature culling, and the anticipation of postpartum metabolic disorders based on behavioural and physiological changes (Silva et al., 2021; Stygar et al., 2021; Cabrera, 2025). Overall, the application of artificial intelligence transforms individual animal data into preventive management decisions, optimising veterinary interventions and extending the productive longevity of animals within the herd (Neculai-Văleanu et al., 2025).

All of the technologies described - behavioural sensors, ruminal boluses, and artificial intelligence platforms - do not operate in isolation. Their true value emerges only when they are connected within an integrated system that consolidates data from multiple sources and analyses them collectively.

A critical assessment of health and welfare monitoring technologies reveals both considerable advantages and significant limitations that must be acknowledged. On the

positive side, wearable sensors and AI-based platforms enable continuous, individual-level monitoring that substantially outperforms traditional visual observation, with reported sensitivities for oestrus detection ranging from 83% to 93% and mastitis detection accuracies exceeding 85% in well-validated systems (Stygar et al., 2021; Schilkowsky et al., 2021). Early disease detection reduces treatment costs, lowers antibiotic use, and decreases milk yield losses, generating measurable economic returns (Silva et al., 2021). However, several limitations constrain their practical impact. False positive rates remain non-negligible: alert systems based on a single parameter generate substantially more false alarms than multi-parameter platforms, imposing additional labour costs on farm staff who must investigate each alert (Post et al., 2020). Sensor accuracy is also affected by individual animal variability, breed differences, and parity, meaning that algorithms trained on one population may underperform when applied to another (Tsai et al., 2021). The economic viability of these systems depends heavily on herd size: on farms with fewer than 100 cows, the cost per animal of sensor infrastructure and data management software frequently exceeds the financial benefit from improved disease detection, limiting uptake to larger operations (Kaur et al., 2023). Furthermore, the lack of standardised communication protocols between sensor manufacturers prevents seamless data integration, requiring costly middleware solutions or manual data reconciliation (Tangorra et al., 2024).

B. Feeding and nutrition technologies

Nutrition is one of the most important factors influencing milk yield, metabolic health, and the welfare of dairy cows. Adequate feeding does not simply mean ensuring a sufficient supply of feedstuffs, but also the precise delivery of the appropriate nutrients, at the right time, to each production group or even to each individual animal (Neculai-Valeanu et al., 2025). Modern dairy operations that have adopted automated feed delivery systems report increases in milk yield, a reduction in the incidence of metabolic disorders, and lower feed costs (Tangorra et al., 2024). These outcomes make feeding automation one of the investments with the highest return on investment in modern dairy cattle production. Figure 2 illustrates the precision instruments used for feeding and nutrition management, including automated TMR systems, NIRS sensors, and feed monitoring platforms.

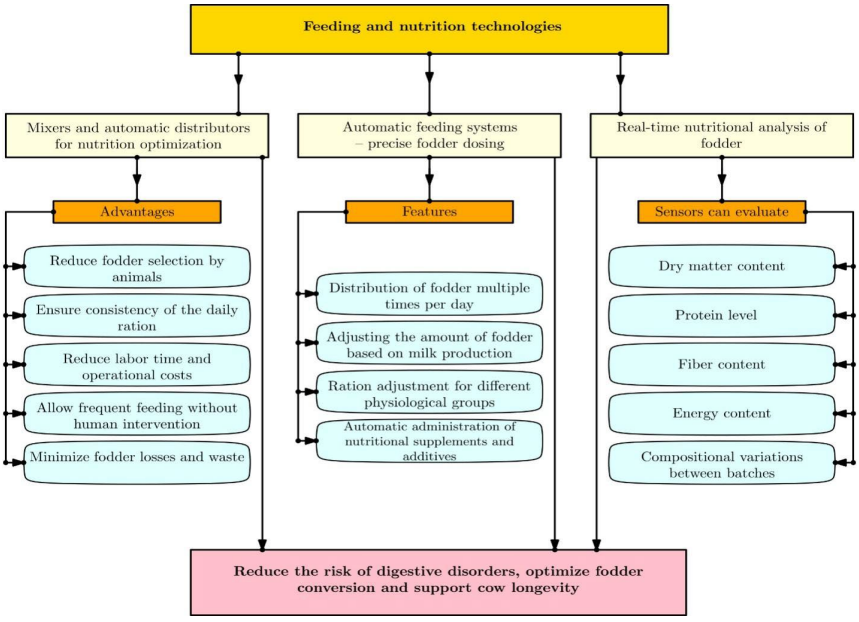

Figure 2. Schematic representation of precision instruments for feeding and nutrition technology
Own source (processed using IPE software)

a. Automatic feeding systems - precision feed delivery

Feeding dairy cows using a total mixed ration (TMR) ensures a uniform nutrient intake, stabilising ruminal fermentation, reducing the risk of acidosis, and stimulating voluntary dry matter intake (Romano et al., 2023). Automatic feeding systems (AFS) optimise this process through the automated preparation and delivery of feed several times per day, thereby increasing the frequency of feed access, reducing social competition at the feed bunk, and maintaining a stable ruminal pH (Mattachini et al., 2019; C Souza et al., 2025).

In addition, these technologies provide substantial operational benefits, considerably reducing labour requirements and energy consumption compared with conventional feeding systems, thus contributing to the efficiency and sustainability of modern dairy farming operations (Romano et al., 2023).

b. Automatic mixers and distributors for nutrition optimisation

The quality of a total mixed ration (TMR) depends not only on its composition but also on the homogeneity of the mix, as a non-uniform blend promotes feed sorting and increases the risk of digestive disorders (Chase & Fortina, 2023). In this context, feed pusher robots ensure continuous access to feed by redistributing it along the feed bunk, operating autonomously and completing multiple cycles per day (Tangorra et al., 2024).

Automated TMR preparation and delivery systems integrate mixing and feed distribution functions, enabling ration adjustments based on individual milk yield and the physiological status of the animals (Hun et al., 2023), drawing on data centralised within the farm's digital management platform (Mattachini et al., 2019; Hu et al., 2023). Furthermore, the monitoring of feeding behaviour through video-based systems and artificial intelligence provides detailed information on feed intake and feeding patterns, facilitating the early identification of health problems or adaptation difficulties (Yu et al., 2022).

c. Real-time nutritional analysis of feedstuffs

Variability in feedstuff composition represents a major challenge in ration formulation for dairy cows, as rations based on average values may lead to nutritional imbalances and milk yield losses (Evangelista et al., 2021). The use of near-infrared spectroscopy (NIRS) sensors enables rapid, real-time analysis of feedstuff composition and automatic adjustment of ingredient proportions to maintain optimal nutritive value (Evangelista et al., 2021; Yamada et al., 2024).

The integration of these technologies with in-line milk analysis provides detailed information on the metabolic status of individual cows, including the estimation of blood metabolites without invasive sampling methods, thereby facilitating continuous monitoring of nutritional balance (Giannuzzi et al., 2022). At a more advanced level, machine learning algorithms enable the formulation of individualised rations and nutritional grouping of animals, optimising milk production and reducing the environmental impact of dairy farming (Lee et al., 2025; Hu et al., 2023).

A comparative evaluation of precision feeding technologies highlights both their potential and their current constraints. Automated feeding systems (AFS) and TMR robots reduce labour requirements by an estimated 20-30% compared to conventional feeding and improve feed bunk access through multiple daily deliveries, stabilising ruminal pH and reducing the risk of subacute ruminal acidosis (Romano et al., 2023; Mattachini et al., 2019). NIRS-based real-time feedstuff analysis represents a significant advance over static ration formulation, accounting for natural variability in forage composition that conventional approaches ignore, with improvements in dry matter intake consistency reported in several studies (Evangelista et al., 2021). Nevertheless, the evidence base for fully individualised precision feeding remains limited. Souza et al. (2025) demonstrated that short-term historical production responses were insufficient to inform reliable supplementation decisions at the individual cow level, with neither of two tested precision feeding algorithms generating significant improvements in milk yield, feed efficiency, or income over feed cost compared to a conventional TMR. This finding challenges the assumption that individual cow data automatically translates into better feeding outcomes and underscores the need for more sophisticated data streams and longer training periods. The capital cost of fully integrated

precision feeding systems - including automated mixers, NIRS sensors, and individual cow identification infrastructure - represents a substantial financial barrier for many producers, particularly on small and medium-sized farms (Chase & Fortina, 2023).

C. Automatic milking technologies

Milking is the primary activity in any dairy farming operation and, at the same time, the most demanding in terms of time and labour. Whereas conventional milking was traditionally carried out two to three times per day at fixed hours with the direct involvement of farm staff, modern systems have fundamentally changed this approach (Gislon et al., 2024). The automation of the milking process represents one of the most significant technological transformations in modern dairy farming (Bull et al., 1996). Current systems aim not only to increase process efficiency, but also to improve animal comfort, reduce stress, and enable continuous monitoring of production and health parameters. Figure 3 summarises the main components of automatic milking technology, from animal identification and teat preparation to milk quality monitoring and data management.

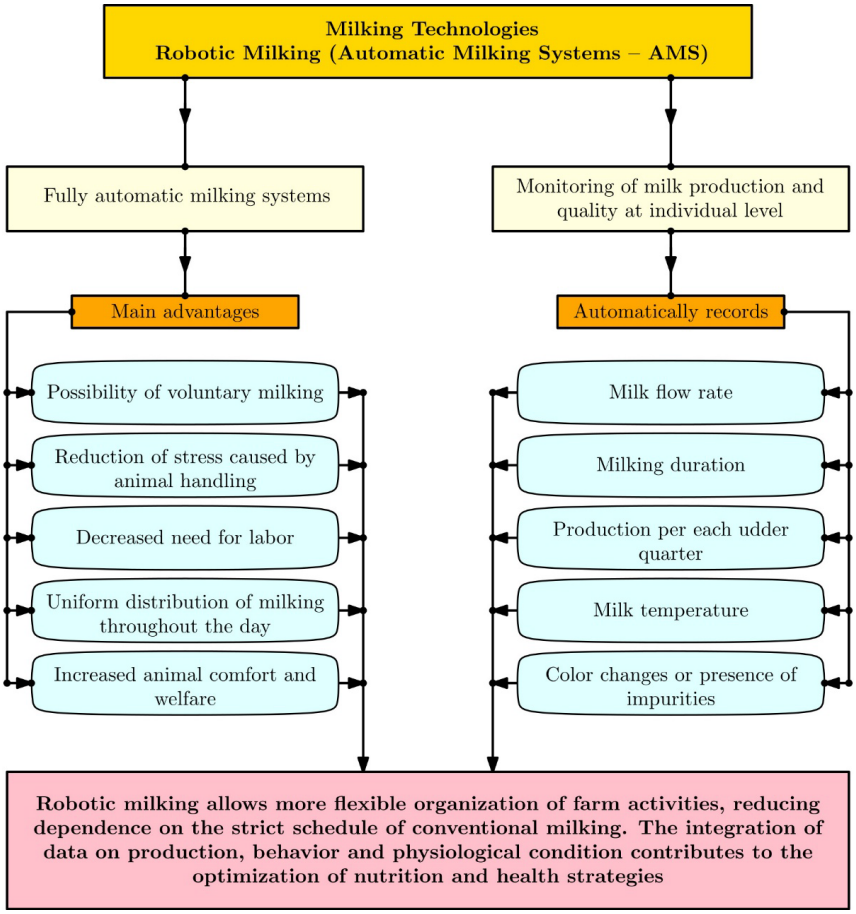

Figure 3. Schematic representation of precision instruments for milking technology
Own source (processed using IPE software)

Automatic milking systems (AMS) allow cows voluntary access to the milking unit, reducing stress and increasing milking frequency, with positive effects on milk yield and animal welfare (Lage et al., 2024). The entire process is fully automated - from animal identification and teat cleaning to teat cup attachment and milking monitoring - carried out without direct human

intervention (Aerts et al., 2022; Wang et al., 2023). Furthermore, cows spend less time waiting and more time resting and feeding, which contributes to reduced stress levels and improved behavioural expression (Lavrijsen-Kromwijk et al., 2024; Lage et al., 2024).

A major advantage of AMS is the continuous, individual monitoring of milk yield and milk quality through parameters such as milk quantity, flow rate, temperature, electrical conductivity, and visual changes in milk appearance (Cogato et al., 2021; Bausewein et al., 2022; Van Steenkiste et al., 2023). These data enable the early detection of mastitis through the correlation of multiple indicators, including a reduction in quarter milk yield and an increase in electrical conductivity, sometimes before the onset of clinical signs (Van Steenkiste et al., 2023; Zhang et al., 2023). Although detection accuracy varies between systems, these technologies significantly reduce the economic losses associated with mastitis (Bausewein et al., 2022; Van Steenkiste et al., 2023).

Furthermore, the integration of AMS data with other farm management systems enables reproductive monitoring, including oestrus detection and the analysis of hormones such as progesterone, contributing to the optimisation of artificial insemination timing and an improvement in conception rates (Jacobs & Siegford, 2012; Pan et al., 2025). In this way, AMS have become a central component of smart dairy farms, combining process automation with data analysis to improve overall herd performance and farm sustainability.

Automatic milking systems offer clear advantages in terms of labour savings, milking frequency, and individual cow monitoring, but a critical appraisal reveals important limitations. On the benefit side, AMS increase milking frequency from the conventional two to three times per day to four or more voluntary visits, which is associated with milk yield increases of 5-15% in cows that adapt readily to the system (Jacobs & Siegford, 2012; Cogato et al., 2021). The continuous recording of milk yield, electrical conductivity, and somatic cell count per quarter enables earlier mastitis detection than is achievable through conventional parlour milking (Bausewein et al., 2022). However, the sensitivity and specificity of AMS-based mastitis detection vary considerably across systems and farms, with reported sensitivity values for clinical mastitis ranging from 46% to 89%, indicating that AMS alone cannot replace structured herd health monitoring programmes (Bausewein et al., 2022). Cow traffic management in AMS systems - whether free, guided, or forced - significantly affects milking frequency, resting time, and social stress, and suboptimal traffic design can negate some of the welfare benefits associated with voluntary milking (Lavrijsen-Kromwijk et al., 2024). The capital investment for a single AMS unit ranges from approximately €100,000 to €180,000, with an additional requirement for adapted barn infrastructure, making the transition economically viable primarily for herds of 60 cows or more per robot under typical European milk pricing conditions (Lage et al., 2024). Furthermore, AMS dependency introduces operational risk: system downtime due to technical failure can rapidly compromise cow welfare, milk yield, and udder health in the absence of adequate contingency protocols.

D. Housing and environment management

Housing conditions have a direct impact on the health, welfare, and milk yield of dairy cows, as inadequate environments lead to reduced dry matter intake, decreased milk production, and an increased incidence of disease (Leliveld & Provolo, 2020). Consequently, modern livestock buildings are integrated into digital management systems and continuously optimised through technologies similar to those used for individual animal monitoring (Papakonstantinou et al., 2024).

Heat stress represents a major challenge in dairy cattle production, negatively affecting milk yield, fertility, and longevity, but can be mitigated through automated ventilation and cooling systems adapted to environmental conditions (Mihai et al., 2020). At the same time, the quality of flooring and resting areas influences the incidence of lameness, directly contributing to the maintenance of animal health and the reduction of premature culling from the herd (Losacco et al., 2025). Figure 4 presents the precision instruments deployed for housing management, covering climate control, environmental sensing, and resting area monitoring.

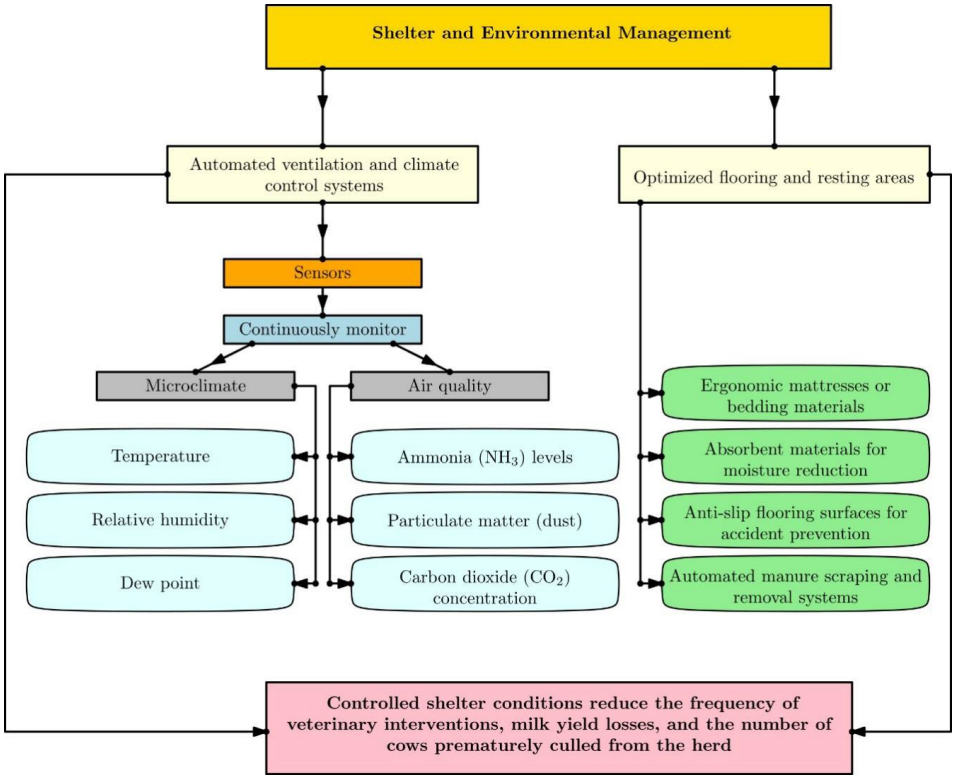

Figure 4. Schematic representation of precision instruments for housing management
Own source (processed using IPE software)

a. Automatic ventilation and climate control systems

Automatic ventilation and climate control systems are essential for maintaining animal health and milk quality, as poor air quality and elevated temperatures reduce dry matter intake and predispose animals to heat stress (Leliveld & Provolo, 2020). Heat stress risk is assessed using the temperature-humidity index (THI), where values above 72 indicate the onset of heat stress and values above 80 indicate severe effects on animal performance (Neves et al., 2022).

The integration of temperature and humidity sensors enables real-time monitoring and the automatic activation of ventilation and cooling systems when critical thresholds are exceeded (Provolo et al., 2025). Although natural ventilation is commonly used, modern solutions - such as high-volume low-speed (HVLS) fans and evaporative cooling systems - significantly reduce body temperature and physiological heat stress in dairy cows (Oliveira et al., 2025; Fournel et al., 2017).

Furthermore, the combination of microclimatic data with behavioural data from individual animals enables the precise identification of cows most affected by heat stress and the tailoring of cooling interventions accordingly, contributing to more efficient and individualised housing management (Fournel et al., 2017; Mylostyvyi & Izhboldina, 2025).

b. Optimised flooring and resting areas

The comfort of resting areas is essential, as dairy cows spend 10 to 14 hours per day in recumbency, a period that supports milk synthesis and limb health (Leliveld & Provolo, 2020). Inadequate surfaces or poorly dimensioned cubicles reduce lying time and increase the risk of integument injuries and lameness (EFSA AHAW et al., 2023).

Appropriate bedding materials, such as deep sand or rubber mats, improve resting comfort and reduce the incidence of limb disorders,

whereas slippery or abrasive flooring surfaces increase the risk of injuries, underscoring the importance of sound barn design (Andreasen & Forkman, 2012; Weerasinghe et al., 2021; B Sadiq et al., 2017).

c. Real-time environmental monitoring

Modern environmental monitoring systems in dairy farms employ IoT-based architectures in which sensors continuously collect data on microclimatic conditions and air quality and transmit them in real time to digital management platforms. These systems provide accurate and reliable long-term information, facilitating continuous surveillance of housing conditions (Leliveld et al., 2024).

The effectiveness of these technologies increases substantially when environmental data are correlated with individual behavioural indicators. For example, associating an increase in the temperature-humidity index (THI) with a reduction in feeding time or changes in resting patterns enables the rapid identification of heat stress and the automatic activation of corrective measures, reducing the rate of false alarms (Leliveld & Provolo, 2020; Leliveld et al., 2024).

The integration of environmental, behavioural, production, and health data within a single digital platform transforms monitoring from a simple measurement tool into an active decision-support system, contributing to the optimisation of farm management and the improvement of animal welfare (Tangorra et al., 2024).

A critical evaluation of housing and environmental management technologies reveals a clear gradient between the effectiveness of individual components and the complexity of fully integrated systems. Automated ventilation and cooling systems - particularly high-volume, low-speed (HVLS) fans combined with evaporative cooling - have demonstrated significant reductions in body temperature and physiological heat stress indicators, with reported improvements in milk yield of 4-8% under heat stress conditions when cooling is activated at THI thresholds above 68-72 (Oliveira et al., 2025; Fournel et al., 2017). Real-time THI monitoring through IoT sensor networks improves the timeliness and precision of cooling interventions relative to fixed timer-based systems, reducing unnecessary energy consumption and associated operating costs (Provolo et al., 2025). In terms of flooring and resting area design, deep sand bedding consistently outperforms rubber mats and concrete in reducing lameness prevalence and integument lesions, but its operational costs - in terms of sand procurement, manure separation, and maintenance - are substantially higher than those associated with alternative bedding materials (Andreasen & Forkman, 2012; Weerasinghe et al., 2021). A key limitation of current environmental monitoring systems is that most commercial solutions remain primarily descriptive: they report microclimatic conditions but lack validated decision rules that automatically translate environmental alerts into specific management actions. The integration of environmental data with individual animal behavioural data, while technically feasible, requires substantial investment in sensor infrastructure, data management platforms, and staff training, and its cost-effectiveness has not been rigorously evaluated across different farm types and climatic regions (Leliveld et al., 2024).

E. Reproductive management technologies

Reproductive performance is one of the most important economic drivers in dairy farming. Undetected oestrous events and extended calving to conception intervals generate significant economic losses and contribute to the premature culling of cows from the herd. In modern dairy cows, the oestrous period lasts on average 12 to 18 hours and occurs frequently at night, when farm staff are not present, resulting in a visual detection rate of only 34 to 40% under conventional observation (Das et al., 2023). Each missed oestrus represents a delay of 21 days until the next insemination opportunity (Adenuga et al., 2020). In modern dairy operations, digital technologies and automated systems enable precise monitoring of the reproductive cycle and the optimisation of artificial insemination programmes. Figure 5 illustrates the precision instruments used in reproductive management, from oestrus detection sensors to progesterone monitoring systems and reproductive decision-support platforms.

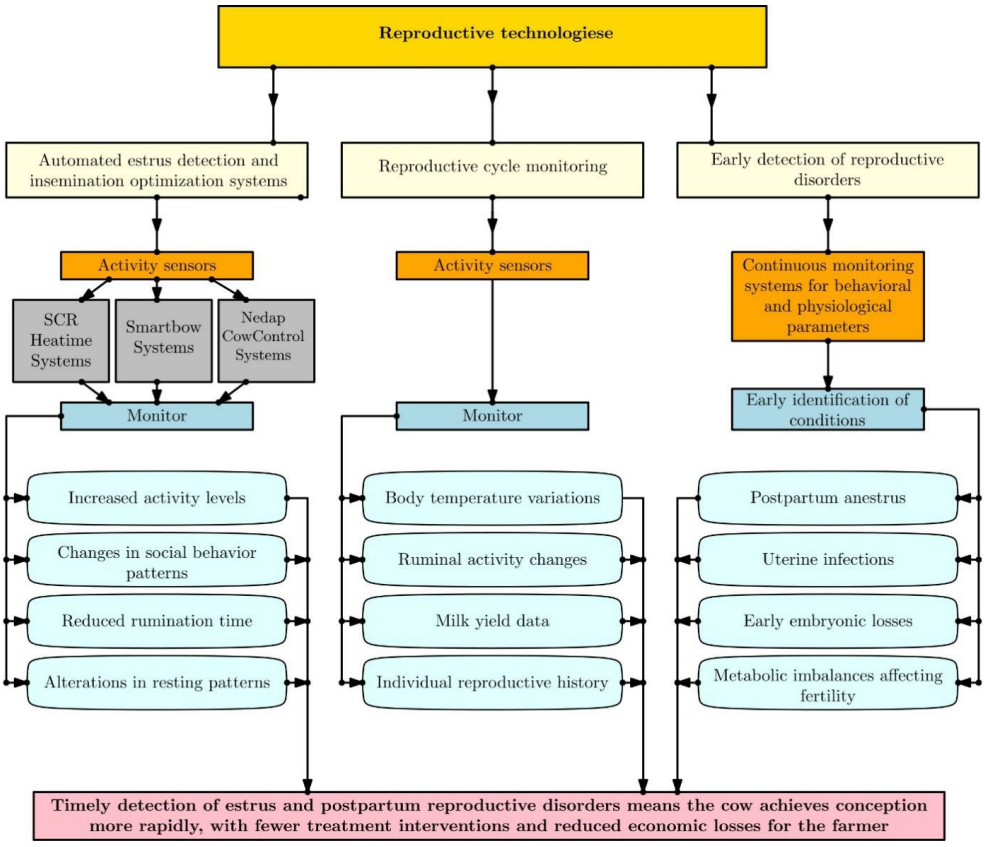

Figure 5. Schematic representation of precision instruments for reproductive management technology
Own source (processed using IPE software)

a. Automatic oestrus detection systems and insemination optimisation

Automatic oestrus detection systems use activity sensors - accelerometers mounted on collars or ear tags - to continuously monitor cow movement and compare it against each animal's individual baseline pattern. A sudden increase in locomotor activity, associated with a concurrent reduction in rumination time, automatically triggers an oestrus alert, regardless of the time of day (Antanaitis et al., 2020).

Systems such as SCR Heatime, Nedap CowControl, and Smartbow achieve a sensitivity of 83 to 93% and a specificity of 92 to 97%, contributing to an improvement in the pregnancy rate at 200 days in milk from 57% to 67-69% compared with visual observation (Schilkowsky et al., 2021).

For maximum reproductive efficiency, artificial insemination should be performed 11 to 16 hours after the onset of the detected oestrus, and these systems can automatically generate alerts indicating the optimal insemination window (Várhidi et al., 2024).

b. Reproductive cycle monitoring and early detection of reproductive disorders

Approximately 50% of dairy cows exhibit irregular ovarian cycles in the early postpartum period, and anovulatory anoestrus extending beyond 60 days significantly increases the calving-to-conception interval (Das et al., 2023). In this context, the Herd Navigator system (DeLaval) monitors milk progesterone concentration at each milking, estimating the resumption of ovarian cyclicity, the timing of oestrus, and gestational status, with an oestrus detection accuracy of 95 to 97% and conception rates of 42 to 50%, compared with 20 to 30% achieved through conventional methods (Adenuga et al., 2020; Antanaitis et al., 2020).

A further concern is represented by postpartum uterine diseases, which affect up to 40% of dairy

cows and reduce fertility by approximately 20% (Várhidi et al., 2024). Automated monitoring systems can detect metritis at an early stage through changes in rumination time, locomotor activity, and body temperature, occurring 1 to 3 days before the appearance of clinical signs (Zhou et al., 2022). Nguyen (2025), based on a study conducted on a herd of 3,747 cows equipped with SCR sensors, confirmed that automated alerts enable the early identification of genital tract infections and prompt veterinary intervention.

By integrating behavioural, hormonal, and reproductive data within a single digital platform, reproductive management becomes predominantly preventive in nature, reducing the interval to conception and improving the long-term reproductive sustainability of the herd (Das et al., 2023).

A critical appraisal of automated reproductive management technologies highlights both substantial performance gains and important implementation challenges. Activity-based oestrus detection systems achieve sensitivity values of 83-93% and specificity values of 92-97%, representing a marked improvement over visual observation rate of 34-40% (Schilkowsky et al., 2021; Das et al., 2023). When combined with progesterone-based cycle monitoring through systems such as Herd Navigator, conception rates of 42-50% have been reported, compared with 20-30% achieved through conventional reproductive management, with a corresponding reduction in the calving to conception interval and in the number of open days per cow (Adenuga et al., 2020; Antanaitis et al., 2020). These improvements translate directly into economic benefit: each additional open day costs a dairy farm an estimated €3-5 per cow, meaning that even modest reductions in calving-to-conception intervals generate measurable returns on investment (Adenuga et al., 2020). However, the cost of progesterone monitoring systems - which require dedicated milk sampling at each milking and specialised analytical equipment – is substantially higher than that of activity-based systems alone, and their cost-effectiveness depends on herd size and the baseline reproductive performance of the farm. A further limitation is that automated systems perform less reliably in cows with prolonged postpartum anoestrus, high body condition score losses, or concurrent subclinical health conditions, precisely the animals in which accurate reproductive monitoring is most needed (Das et al., 2023; Várhidi et al., 2024). Integration of reproductive data with health and nutritional platforms remains technically challenging and is not yet consistently achieved in commercial farm management software.

F. Limitations and challenges of PLF technologies

Despite the demonstrated benefits of PLF technologies, their widespread adoption is constrained by a set of persistent limitations. The initial investment costs for integrated sensor systems, automatic milking units, and digital management platforms remain high, limiting uptake particularly on small and medium sized farms. Furthermore, return on investment depends heavily on herd size, milk price, and the technical capacity of farm staff, making cost benefit assessments highly context specific (Adenuga et al., 2020; Romano et al., 2023).

A major research gap remains the lack of standardised data formats and measurement protocols across precision livestock farming technologies, limiting cross platform comparability and large-scale data integration. Limited interoperability between PLF systems from different manufacturers remains a key barrier to the effective integration of multi-source data for decision-making in dairy farming. The absence of universal communication standards means that data from milking systems, wearable sensors, and environmental monitors frequently cannot be consolidated without significant technical effort (Kaur et al., 2023; Tangorra et al., 2024).

Alert interpretation also presents challenges: false positive rates in disease detection remain non-negligible, and the effectiveness of automated alerts depends on the training and responsiveness of farm personnel. Machine learning algorithms developed on data from specific breeds or management systems may show reduced accuracy when transferred to different farm contexts, underscoring the need for broader validation studies (Dharejo et al., 2025; Stygar et al., 2021). Reliance on digital connectivity further introduces vulnerability in areas with limited network infrastructure, where

system downtime can result in data loss and delayed interventions

CONCLUSIONS

Precision livestock farming (PLF) technologies applied in dairy farming operations now cover all key aspects of dairy cattle management - animal health, nutrition, milking, housing conditions, and reproduction - delivering measurable outcomes in each of these domains. Their true value, however, emerges not when individual technologies are used in isolation, but when they are integrated within a shared platform that correlates data from multiple sources and supports better management decisions for each individual animal.

The adoption of these technologies contributes to improvements in milk yield and milk quality, a reduction in the incidence of stress-related conditions and disease, more efficient use of farm inputs, and a lower environmental impact. At the same time, their implementation presents challenges related to initial investment costs, staff training, equipment dependency, and the management of large volumes of data.

The main limitations of these technologies remain the high cost of implementation, the need for validation under diverse farm conditions, and reliance on digital connectivity. The integration of data from multiple sources also raises challenges related to platform compatibility and the training of personnel in alert interpretation. Future developments are expected to include the wider application of machine learning algorithms for individual-level disease prediction, the integration of genomic selection data with real-time physiological measurements, and the extension of the digital twin concept to the level of the dairy herd. The dairy farm of the future will not necessarily be larger or more automated - it will, above all, be better connected, with every management decision supported by objective, individual-animal data.

For farmers, the practical implication is that technology adoption should be approached incrementally and strategically: starting with systems that address the most economically significant pain points, mastitis detection, oestrus identification, heat stress management, before expanding towards fully integrated platforms. Staff training and change management are as critical as the technical infrastructure itself. For researchers, the priority should be the development of cross-platform validation studies, standardised welfare outcome metrics, and economic models that account for the diversity of farm sizes and management contexts across different regions.

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