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Advancements in Precision Livestock Farming: Technologies and Applications

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Abstract Precision livestock farming (PLF) has become a transformative method in modern agriculture, offering more efficient and sustainable production through advanced technologies while improving animal welfare. This study provides a comprehensive review of the key technologies supporting PLF, including sensor technologies, data analytics, artificial intelligence, the internet of things (IoT), and robotics, and explores the applications of PLF in health monitoring, disease prevention, precision feeding, reproductive management, and environmental sustainability. A case study of a dairy farm demonstrates the integration of these technologies and their impact on productivity and animal welfare. The study also discusses the challenges and limitations associated with PLF, such as technical, economic, and ethical barriers, emphasizing the future directions and emerging technologies of PLF, highlighting its potential for revolutionary impact on livestock farming. The findings underscore the importance of continued research and innovation to address challenges and fully harness the advantages of PLF.

Keywords Precision livestock farming; Sensor technologies; Data analytics; Dairy farming; Sustainability

1 Introduction

Precision livestock farming (PLF) refers to the use of advanced technologies and data-driven approaches to monitor and manage livestock production at an individual animal level (Vranken and Berckmans, 2017). Since its inception in the early 2000s, PLF has evolved significantly, driven by advancements in Industry 4.0 and the Internet of Things (IoT) (Morrone et al., 2022), The concept of PLF encompasses a range of technologies, including sensors, automated systems, and data analytics, aimed at improving the efficiency, productivity, and welfare of livestock (Halachmi and Guarino, 2016). Early applications of PLF, such as electronic milk meters and behavior-based estrus detection, have paved the way for more sophisticated systems that can monitor various physiological and behavioral parameters in real-time (Vaintrub et al., 2020).

The importance of PLF in modern agriculture cannot be overstated (Werkheiser, 2018). As global demand for animal products continues to rise, there is an increasing need for sustainable and efficient farming practices. PLF offers a solution by enabling farmers to optimize resource use, reduce waste, and improve animal health and welfare (Norton et al., 2019). By providing continuous and real-time monitoring of individual animals, PLF helps farmers make informed decisions that enhance productivity and sustainability (Monteiro et al., 2021). Moreover, PLF technologies can address economic pressures by allowing farmers to manage larger herds more effectively, thus bridging the gap between the farmer and the animal (Tzanidakis et al., 2021). The integration of PLF into livestock farming also supports the broader goals of environmental, economic, and social sustainability (Lovarelli et al., 2020).

This study provides a comprehensive overview of the advancements in PLF technologies and their research applications across different livestock production systems, exploring the current state of PLF, including the latest technological developments and their practical implementations in various farming contexts, examining the benefits and challenges associated with the adoption of PLF, with a focus on its impact on animal welfare, farm productivity, and sustainability, with the aim of highlighting the potential of PLF to transform modern livestock farming and identifing directions for future research and development.

2 Key Technologies in Precision Livestock Farming

2.1 Sensor technologies

Sensor technologies are fundamental to precision livestock farming (PLF), enabling the continuous monitoring of various parameters related to animal health, behavior, and environmental conditions. Wearable sensors, for instance, can track eating habits, rumination, body temperature, and activity levels, providing critical data for early disease detection and overall animal management (Džermeikaitė et al., 2023). These sensors can be attached to or implanted in animals, offering real-time data that helps farmers make informed decisions to enhance productivity and animal welfare (Gagliardi et al., 2021). Additionally, sensors are used in aerial and satellite-based systems to measure pasture quality and quantity, further supporting efficient livestock management (Tedeschi et al., 2021).

2.2 Data analytics and artificial intelligence

Data analytics and artificial intelligence (AI) play a crucial role in processing the vast amounts of data generated by sensor technologies. AI, particularly machine learning (ML), can analyze complex datasets to predict animal health issues, optimize feeding strategies, and improve overall farm management (Zhang et al., 2021). For example, ML models can predict fertility patterns and diagnose eating disorders in livestock using data collected from collar sensors (Liu et al., 2023). The integration of AI with traditional mechanistic models can lead to hybrid intelligent systems that enhance the sustainability and efficiency of livestock production (Sharma et al., 2021).

2.3 Internet of things (IoT) and connectivity

The internet of things (IoT) is a key enabler of precision livestock farming, facilitating the seamless connection and communication between various devices and systems on the farm. IoT sensors provide precise information about animal health and environmental conditions, which can be remotely monitored and analyzed (Benjamin and Yik, 2019). For instance, IoT-enabled wearable devices can transmit data on animal behavior and physiological parameters, allowing for real-time monitoring and management (Monteiro et al., 2021). The integration of IoT with data analytics and AI further enhances the ability to make data-driven decisions, improving farm productivity and sustainability (Akhter and Sofi, 2021).

2.4 Robotics and automation

Robotics and automation are transforming livestock farming by reducing the need for intensive manual labor and improving operational efficiency. Automated systems, such as milking robots and feeding machines, can perform repetitive tasks with high precision, ensuring consistent care and management of livestock. These technologies not only reduce labor costs but also enhance animal welfare by providing timely and accurate interventions. Additionally, the use of unmanned aerial vehicles (UAVs) and automated data collection systems enables farmers to monitor large areas and gather detailed information on animal health and environmental conditions. In summary, the integration of sensor technologies, data analytics and AI, IoT, and robotics and automation is driving significant advancements in precision livestock farming. These technologies collectively enhance the ability to monitor, manage, and optimize livestock production, contributing to improved productivity, sustainability, and animal welfare (Vaintrub et al., 2020).

3 Applications of Precision Livestock Farming

3.1 Health monitoring and disease prevention

Precision livestock farming (PLF) technologies have significantly advanced the ability to monitor animal health and prevent diseases. These technologies include sensors, cameras, and microphones that enable continuous and real-time monitoring of livestock. For instance, wearable Internet of Things (W-IoT) devices can provide precise and dynamic health data, which is crucial for early disease detection and intervention (Zhang et al., 2021). Additionally, PLF systems can monitor animal behavior and physical conditions, allowing for timely responses to health issues, thereby improving overall animal welfare and reducing the need for antibiotics (Figure 1) (Vranken and Berckmans, 2017). The integration of these technologies into livestock farming not only enhances animal health but also contributes to the sustainability of farming practices by minimizing the environmental impact of disease outbreaks (Monteiro et al., 2021).

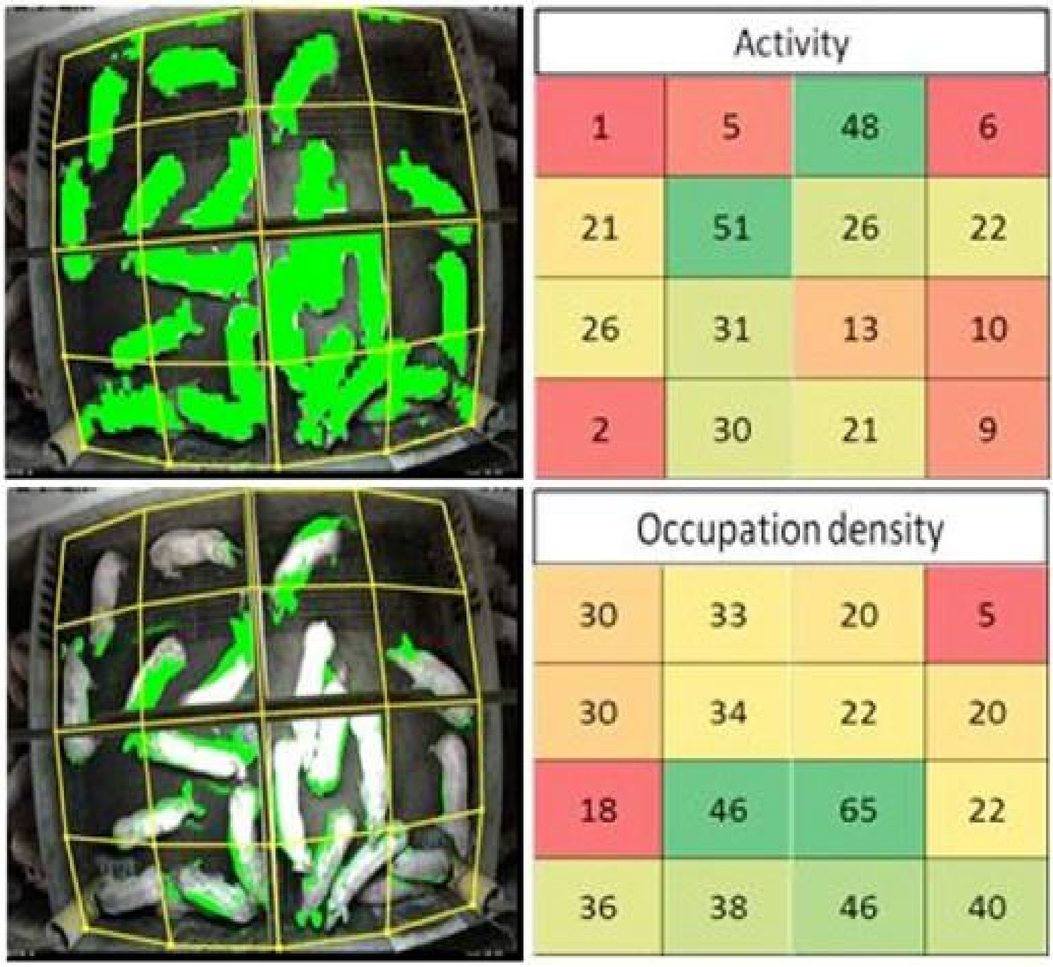

Figure 1 Camera-based system to monitor activity levels and occupation density levels in the pig pen (Adapted from Vranken and Berckmans, 2017)
Image capton: a system used for monitoring a pig pen, capturing information on the activity and occupation density of the pigs through cameras. This allows farmers to understand the activity levels and space utilization in different areas, optimizing management and improving animal welfare. This technology aids in real-time monitoring and adjustment of the farming environment (Adapted from Vranken and Berckmans, 2017)

Vranken and Berckmans (2017) found that a camera-based monitoring system is effective in assessing both activity levels and occupation density in pig pens. The system provides real-time visual data that helps in understanding the distribution and movement patterns of pigs within a pen. This monitoring technique is crucial for optimizing environmental conditions, improving animal welfare, and enhancing the overall management of pig farming operations. By analyzing activity and occupation density, farmers can adjust factors such as space allocation and feeding strategies to ensure that all animals are thriving under the most favorable conditions. This technology represents a significant advancement in precision livestock farming, enabling more accurate and efficient monitoring compared to traditional methods.

3.2 Precision feeding and nutrition management

Precision feeding is a key application of PLF that involves tailoring diets to meet the specific nutritional needs of individual animals. This approach is facilitated by advanced technologies such as sensors and automation systems that monitor feed intake and animal growth in real-time (Șonea et al., 2023). By optimizing feed efficiency, precision feeding reduces feed wastage and nutrient excretion, which in turn lowers the environmental footprint of livestock production (Silva et al., 2022). Moreover, precision feeding technologies can improve animal welfare by ensuring that each animal receives the appropriate nutrients, thereby enhancing their overall health and productivity. The adoption of these technologies is essential for achieving sustainable livestock production that meets the growing global demand for animal-derived food.

3.3 Reproductive management

PLF technologies also play a crucial role in reproductive management by providing detailed insights into the reproductive status and behavior of livestock. Sensors and monitoring systems can track estrus cycles, detect pregnancies, and monitor birthing processes, enabling farmers to make informed decisions about breeding and reproductive health (Morrone et al., 2022). These technologies help in optimizing breeding schedules, improving reproductive success rates, and reducing the time and labor required for manual monitoring (Benjamin and Yik, 2019). Additionally, the use of PLF in reproductive management can enhance genetic selection programs by providing accurate data on reproductive performance, thereby contributing to the overall improvement of livestock breeds (Lovarelli et al., 2020).

3.4 Environmental monitoring and sustainability

Environmental monitoring is another critical application of PLF, aimed at ensuring the sustainability of livestock farming. Technologies such as remote sensing and environmental control systems can monitor various environmental parameters, including temperature, humidity, and air quality, to create optimal living conditions for livestock (Silva et al., 2022). These systems help in reducing the environmental impact of farming by optimizing resource use and minimizing waste. Furthermore, PLF technologies can track and manage the carbon footprint of livestock operations, contributing to the development of carbon-efficient farming practices1. By integrating environmental monitoring with other PLF applications, farmers can achieve a balance between productivity and sustainability, ensuring the long-term viability of livestock farming (Banhazi et al., 2012).

4 Case Study: Implementation of PLF in Dairy Farming

4.1 Overview of the dairy farm case study

The case study focuses on the implementation of precision livestock farming (PLF) technologies in a dairy farm setting. PLF technologies have been increasingly adopted in dairy farming to enhance productivity, animal welfare, and sustainability. The farm in question has integrated various PLF tools to monitor and manage the health, behavior, and productivity of dairy cattle. This case study aims to provide insights into the practical application of these technologies and their impact on the farm's operations (Halachmi and Guarino, 2016).

4.2 Technologies used and their integration

The dairy farm utilized a range of PLF technologies, including individual cow activity sensors, automatic milking systems, and real-time health monitoring tools. These technologies were integrated into a cohesive system that allowed for continuous monitoring and data collection. For instance, accelerometers were used to track cow activity and detect lameness, while automatic milking systems provided data on milk yield and quality (Kaur et al., 2023). Additionally, sensors for monitoring environmental conditions within the barn were employed to ensure optimal living conditions for the cattle.

4.3 Impact on productivity, animal welfare, and sustainability

The implementation of PLF technologies had a significant positive impact on the farm's productivity, animal welfare, and sustainability. The continuous monitoring of cow health and behavior allowed for early detection of diseases and timely interventions, which improved overall herd health and reduced veterinary costs (Kaur et al., 2023). The automatic milking systems increased milking efficiency and consistency, leading to higher milk yields and better milk quality (Palma-Molina et al., 2023). Furthermore, the use of environmental sensors helped maintain optimal barn conditions, contributing to the well-being of the animals and reducing stress-related issues (Lovarelli et al., 2020). These improvements also translated into economic benefits, as healthier and more productive cows resulted in higher profitability for the farm (Figure 2) (Morrone et al., 2022).

Morrone et al. (2022) found that the global distribution of published articles on Precision Livestock Farming (PLF) varies significantly by species. Research on cattle is predominantly concentrated in North America and Europe, indicating a strong focus on improving cattle farming practices in these regions. In contrast, studies on swine are more prominent in China and parts of Europe, reflecting the economic importance and scale of swine production in these areas. Research on small ruminants, such as sheep and goats, is more dispersed, with notable contributions from Africa and Asia, which are regions where these animals play a critical role in local agriculture.

Poultry-related PLF research shows significant activity in Asia and Europe, underlining the importance of poultry in global food security and production systems. This geographic disparity in research focus highlights the varying priorities and agricultural practices across different regions of the world.

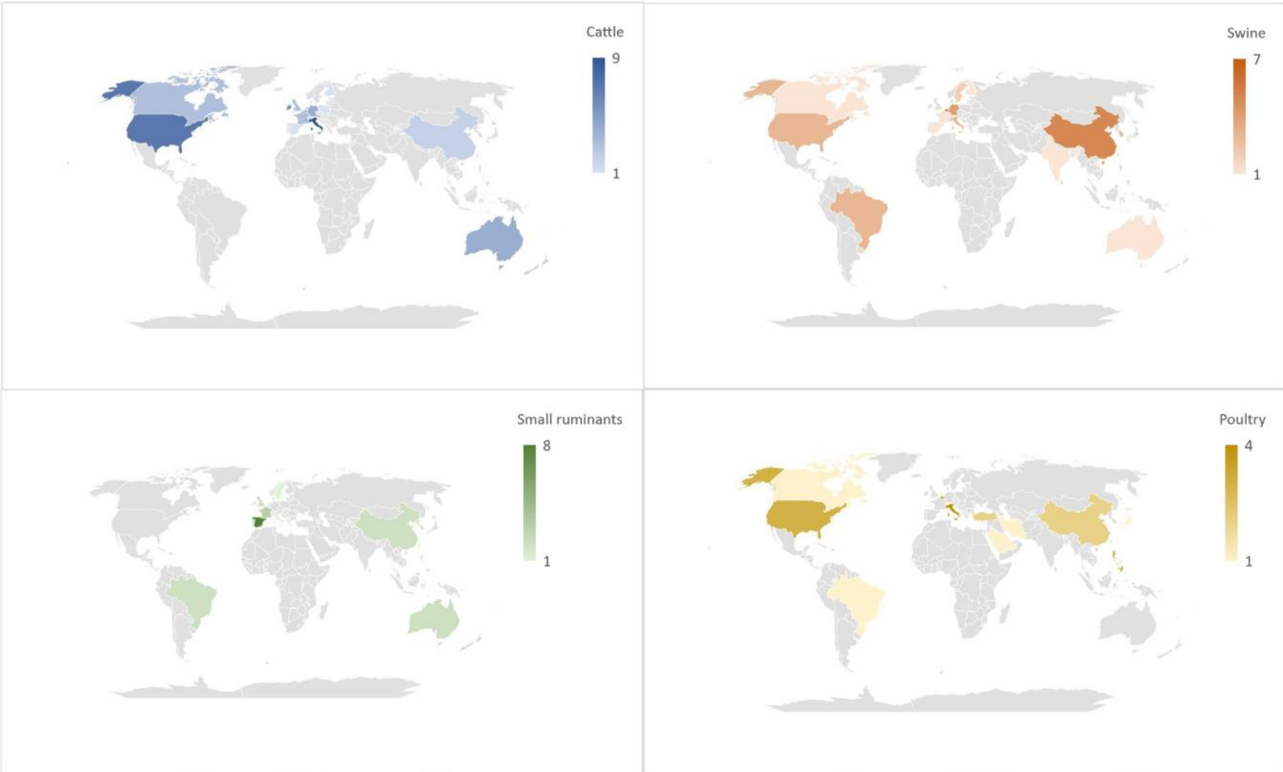

Figure 2 Number of articles related to PLF published worldwide in relation to the species (Adapted from Morrone et al., 2022)
Image caption: Blue: cattle; orange: swine; green: sheep and goat; yellow: poultry (Adapted from Morrone et al., 2022)

4.4 Lessons learned and best practices

Several lessons were learned from the implementation of PLF technologies on the dairy farm (Vaintrub et al., 2020). One key takeaway is the importance of proper training for farm staff to effectively use and maintain the new technologies. Ensuring that all personnel are familiar with the PLF tools and their functionalities is crucial for maximizing their benefits (Halachmi and Guarino, 2016). Another lesson is the need for regular maintenance and calibration of the sensors and systems to ensure accurate data collection and reliable performance (Stygar et al., 2021). Additionally, integrating PLF technologies with existing farm management practices and systems can enhance their effectiveness and streamline operations (Norton and Berckmans, 2017). Best practices include starting with a pilot implementation to identify potential challenges and gradually scaling up the use of PLF technologies as the farm staff becomes more comfortable with them (Norton et al., 2019).

5 Challenges and Limitations

5.1 Technical challenges

Precision livestock farming (PLF) technologies face several technical challenges that hinder their widespread adoption and effectiveness. One significant issue is the integration and reliability of various sensors and devices used for monitoring livestock. These technologies must operate continuously and accurately in diverse and often harsh farm environments, which can be challenging due to factors such as lack of infrastructure, electrical power, and communication networks, especially in extensive farming systems (Liu et al., 2023). Additionally, the vast amount of data generated by PLF systems needs to be processed and converted into actionable information for farmers, which requires sophisticated algorithms and robust data management systems (Vaintrub et al., 2020). The development of user-friendly interfaces and reliable backup solutions is also crucial to ensure that farmers can effectively utilize these technologies without extensive technical knowledge (Vranken and Berckmans, 2017).

5.2 Economic and adoption barriers

The economic barriers to adopting PLF technologies are significant, particularly for small and medium-scale farms. The initial investment required for purchasing and installing PLF systems can be prohibitively high, and the financial risk associated with adopting new technologies can deter farmers, especially those with limited resources (Menendez et al., 2022). Moreover, the economic benefits of PLF, such as reduced operational costs and improved productivity, may not be immediately apparent, making it difficult for farmers to justify the investment. The conservative nature of many farming communities, characterized by an older demographic, further complicates the adoption process, as these farmers may be less inclined to take financial risks or change established practices (Morrone et al., 2022). Additionally, the lack of collaboration among different disciplines, such as animal scientists, veterinarians, and technologists, can impede the development and dissemination of PLF technologies.

5.3 Ethical considerations

The implementation of PLF technologies raises several ethical concerns that need to be addressed. One major issue is the potential impact on the human-animal relationship. The use of automated systems to monitor and manage livestock could lead to a reduction in direct human-animal interactions, which may affect the welfare of the animals and the traditional role of farmers as caretakers. There are also concerns about the potential for PLF technologies to facilitate the management of production systems that may be harmful to animal welfare, such as those that prioritize productivity over the well-being of the animals. Furthermore, the consolidation of farms and the alienation of laborers due to increased automation could have broader social implications, including the loss of identity and relationships for both farmers and animals. Addressing these ethical considerations is crucial to ensure that PLF technologies are implemented in a way that promotes the welfare of animals and the sustainability of farming communities (Schillings et al., 2021).

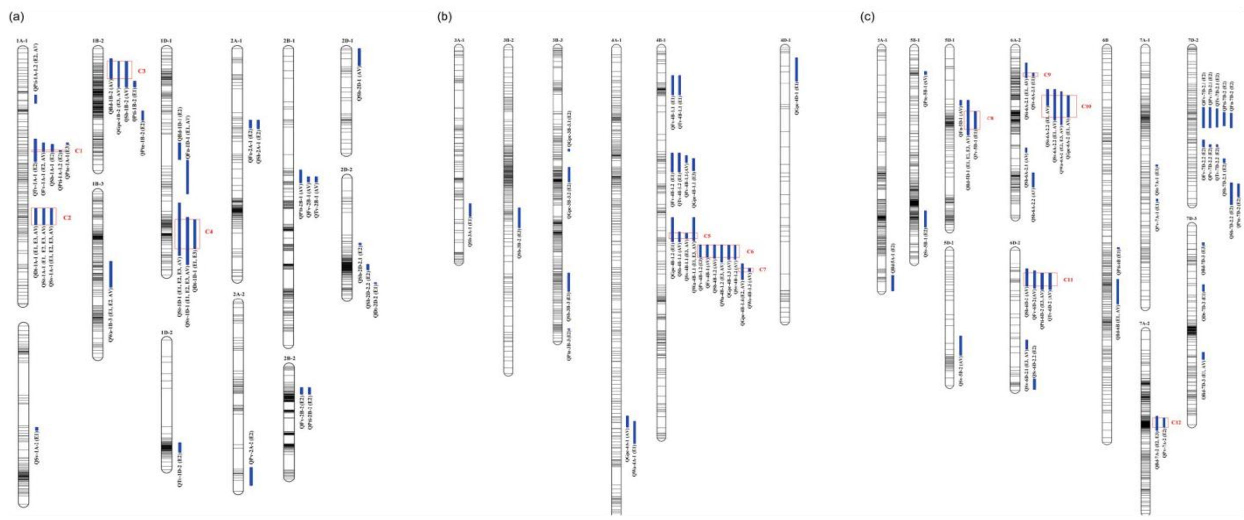

Figure 3 Locations of QTLs for 13 quality traits based on RILs derived from TN18×LM6 (Adopted from Guo et al., 2020)

Image capton: The figure shows the positions of QTLs (quantitative trait loci) detected for 13 wheat quality traits in recombinant inbred lines (RILs) derived from a cross between 'Tainong 18' and 'Linmai 6'. The LOD (logarithm of odds) values for the QTL intervals are all greater than 3.0, as determined by a threshold set through 1000 permutation tests. The blue sections in the figure represent QTLs related to quality traits. This figure indicates that QTLs are widely distributed across 21 chromosomes, explaining 5.32% to 35.09% of the phenotypic variation (Adapted from Guo et al., 2020)

6 Future Directions and Innovations

6.1 Emerging technologies in PLF

The future of Precision Livestock Farming (PLF) is closely tied to the development and integration of emerging technologies. The advent of Industry 4.0 and the Internet of Things (IoT) has significantly propelled the advancement of PLF, enabling real-time monitoring and management of livestock through sophisticated sensors and data analytics (Morrone et al., 2022). Wearable IoT (W-IoT) devices are particularly promising, offering precise perception of animal health and behavior, although their adaptation for farm animals is still in its nascent stages (Vranken and Berckmans, 2017). Additionally, the use of cameras, microphones, and various sensors (e.g., accelerometers, RFID) in pig farming has shown potential for fully automated continuous monitoring, which can enhance animal welfare and feed efficiency (Tzanidakis et al., 2021).

6.2 Potential for integration with other agricultural technologies

The integration of PLF with other agricultural technologies holds significant promise for enhancing farm productivity and sustainability. For instance, PLF technologies can be combined with environmental control systems, disease early warning systems, and remote diagnostic tools to create a more holistic approach to livestock management. In dairy sheep farming, technologies such as electronic identification systems, on-animal sensors, and stationary management systems can be integrated to improve productivity and economic sustainability, particularly in extensive farming systems. Moreover, the combination of PLF with advanced data analytics and machine learning can help in converting vast amounts of data into actionable insights, thereby improving decision-making processes on farms (Banhazi et al., 2012).

6.3 Long-term outlook for PLF

The long-term outlook for PLF is highly optimistic, with the potential to revolutionize livestock farming by improving animal welfare, reducing greenhouse gas emissions, and enhancing the economic stability of rural areas. However, the successful commercialization and widespread adoption of PLF technologies remain challenges that need to be addressed. Efforts should focus on establishing a new service industry, verifying and publicizing the benefits of PLF, and encouraging collaboration between industry and academic organizations. Additionally, future research should aim to quantify the environmental, economic, and social sustainability benefits of PLF to provide a comprehensive understanding of its impact. As PLF technologies continue to evolve, their integration into smart farming systems will be crucial for meeting the growing global demand for sustainably sourced animal-derived food (Lovarelli et al., 2020). By addressing these future directions and innovations, PLF can play a pivotal role in transforming livestock farming into a more efficient, sustainable, and welfare-oriented industry.

7 Concluding Remarks

Precision livestock farming (PLF) has emerged as a transformative approach in modern agriculture, integrating advanced technologies to enhance the management and welfare of livestock. This systematic review has highlighted several key advancements and applications of PLF across various animal production systems. The integration of Industry 4.0 and the Internet of Things (IoT) has significantly propelled the development of PLF, enabling real-time monitoring and management of individual animals, which is crucial for improving productivity, health, and welfare. The adoption of PLF technologies, such as electronic identification systems, on-animal sensors, and automated management systems, has shown promising results in both intensive and extensive farming systems, including dairy cattle, sheep, and pigs.

The implications of these advancements for the future of livestock farming are profound. PLF technologies offer the potential to optimize resource use, reduce environmental impact, and enhance the economic sustainability of farms. By providing detailed and continuous data on animal health and behavior, these technologies can help farmers make informed decisions, ultimately leading to better animal welfare and more efficient production systems. Moreover, the ability to monitor individual animals closely can bridge the gap between farmers and their livestock, fostering a more sustainable and humane approach to animal husbandry.

However, several challenges remain that need to be addressed to fully realize the benefits of PLF. Future research should focus on developing more cost-effective and user-friendly technologies to facilitate wider adoption, especially among small and medium-scale farmers who may face financial and technological barriers. Additionally, there is a need for comprehensive studies to quantify the environmental, economic, and social impacts of PLF to validate its benefits and guide policy-making. Collaboration among researchers, technology developers, and farmers is essential to ensure that PLF systems are practical, reliable, and tailored to the specific needs of different farming systems. In conclusion, while PLF holds great promise for revolutionizing livestock farming, its successful implementation will depend on continued innovation, supportive policies, and effective knowledge transfer to farmers. By addressing these challenges, PLF can contribute significantly to the sustainability and resilience of the livestock sector, meeting the growing global demand for animal-derived food in an ethical and efficient manner.

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Conflict of Interest Disclosure

Author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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