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Exploring the Potential of Precision Livestock Farming Technologies for Enhancing Animal Welfare and Public Health

Danyal Khan[1], Haider Zaman[2*], Aimen Sultan[3], Muhammad Talha Ahmad[4], Rafia Bibi[5], Hifza Athar[6], Saba Bibi[7], Umair Ahmed[8], Ushbah Yasin[9], Muhammad Shahbaz[10]

[1]Livestock of Management, Breeding and Genetics, The University of Agriculture, Peshawar, KPK, Pakistan
[2]Department of Poultry Science, Muhammad Nawaz Sharif University of Agriculture, Multan, Punjab, Pakistan
[3]Department of Food Science and Technology, GC Women University, Faisalabad, Punjab, Pakistan
[4]Department of Human Nutrition and Dietetics, The University of Agriculture, Peshawar, KPK, Pakistan
[5]Faculty of Veterinary and Animal Sciences (FV&AS), PMAS Arid Agriculture University, Rawalpindi, Punjab, Pakistan
[6]Faculty of Animal Husbandry, Department of Dairy Science, University of Agriculture, Faisalabad, Punjab Pakistan
[7]Department of Zoology, Hazara University, Mansehra, KPK, Pakistan
[8]Department of Veterinary Surgery and Medicine, University of Veterinary and Animal Sciences, Lahore, Punjab, Pakistan
[9]Faculty of Veterinary Sciences, University of Veterinary and Animal Sciences, Lahore, Punjab, Pakistan
[10]Faculty of Veterinary and Animal Sciences (FV&AS), PMAS Arid Agriculture University, Rawalpindi, Punjab, Pakistan

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***Corresponding author:** Haider Zaman
Department of Poultry Science, Muhammad Nawaz Sharif University of Agriculture, Multan, Punjab, Pakistan

Abstract **Review Article**

This review explores the potential of Precision Livestock Farming (PLF) technology to enhance animal welfare and improve public health outcomes in contemporary livestock management. As global food demands increase and the necessity for sustainable agricultural methods escalates, Precision Livestock Farming (PLF) technologies—encompassing sensors, automation systems, and big data analytics—present substantial potential in optimizing animal welfare, mitigating disease outbreaks, and improving production. The main aim of this review is to consolidate the existing literature, pinpoint knowledge deficiencies, and assess the function of PLF in tackling critical issues such as antibiotic resistance, disease control, and environmental sustainability in cattle agriculture. This review, through a thorough analysis of existing studies, underscores significant trends, such as the increasing adoption of data-driven methodologies for monitoring animal health, diminished dependence on antibiotics via early disease identification, and incorporation of Precision Livestock Farming systems into wider public health initiatives. Notwithstanding significant progress, substantial deficiencies persist in the scalability of these technologies for small-scale farms, cost-effectiveness of PLF systems in developing areas, and enduring effects on animal behavior and well-being. This review recommends future research initiatives aimed at addressing these obstacles, especially with the enhancement of PLF technologies to ensure their accessibility and efficacy across various agricultural systems. By addressing these deficiencies, this study facilitates the advancement and implementation of PLF technology, thereby promoting more ethical, sustainable, and productive livestock farming practices.

Keywords: Precision Livestock Farming, animal welfare, public health, disease prevention, sustainability, antimicrobial resistance, big data analytics.

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1. INTRODUCTION

In international animal husbandry, the use of Precision Livestock Farming (PLF) technologies can be regarded as a paradigm shift about animal welfare and public health management (Morrone *et al.*, 2022). PLF involves the use of modern technologies, including sensors, automated systems, and big data analytics, for improved animal monitoring and management. Such technologies offer immediate information on animal health, behavior, and environmental conditions, allowing for early disease detection, more resource management, and thus, improved overall welfare (Tao *et al.*, 2023). As there are over 30 billion livestock globally, the need to optimize livestock farming practices is evident. The importance of the role of PLF in the future of animal agriculture is hard to overestimate, considering the increasing demand for food security, sustainability, and ethical values regarding livestock production (Khan &

Babar, 2024). Although countries such as the United States, UK, and some parts of Europe have made significant progress in the deployment of PLF systems, many developing regions still struggle to implement PRS technologies because of economic, technological, and regulatory barriers (Tzanidakis *et al.,* 2023).

While the advantages of PLF technologies in contributing to livestock health and welfare are widely known, a few important gaps exist in how PLF technologies can be capitalized for wider public health gains. Much interest has been generated in the role PLF may play in reducing total antibiotic use, owing to its potential to enable proactive disease management and improved biosecurity (Hu & Cowling, 2020). Nevertheless, many questions remain unanswered and relate directly to the ability of PLF systems to be scalable for smallholder farmers across the developing world, gaining a return on investment for these funds spent, and whether animals will adapt to being managed and housed in this way long-term with minimal detrimental effects on animal behavior and welfare (Dawkins, 2021). Additionally, although the role of PLF in enhancing food safety and disease prevention is gradually being appreciated, issues related to the integration of this technology into international health surveillance systems are yet to be fully explored (Nastasijević *et al.,* 2019). These alternatives should be reviewed systematically: synthesizing existing research, tracking trends over time, and identifying gaps for additional investigation were all highlighted as clear needs in the literature. This review systematically synthesizes the existing literature regarding the contributions of PLF technologies to both animal welfare and public health, aiming to cover these critical knowledge gaps (Silva *et al.,* 2023).

The main aim of this review is to methodically summarize the promethean capacity of PLF technologies in both animal welfare and public health domains. This study seeks to address these gaps and provide insights into the future of PLFs in livestock management through a narrative review of the development of PLF systems, along with their opportunities and challenges (Papakonstantinou *et al.,* 2024). This review will therefore focus on aspects of scalability for PLF technologies, the way they may reduce antimicrobial usage, and their role in zoonotic disease prevention. The review also intends to discuss emerging applications, including advances in combining precision molecular approaches with PLF, to formulate innovative and environmentally considerate farming practices (Himu & Raihan, 2024). A comprehensive review of the status of PLF and a discussion of barriers will enhance our understanding of the implications of PLF for animal welfare and public health. As such, this review serves not only to inform further research, but also to inform policies that will promote global deployment of PLF technologies (Papakonstantinou *et al.,* 2024).

2. Overview of Precision Livestock Farming (PLF) Technologies

Precision Livestock Farming (PLF) is described as the employment of technologies to measure, monitor, and control the health, welfare, and productivity of livestock **(Figure 1)** (Kopler *et al.,* 2023). This refers to high-tech solutions designed to optimize farming with low human effort through real-time data collected from single animals. They combine sensors, automation, big data analytics, and artificial intelligence (AI) technologies to increase farm efficiency and enhance animal welfare (Abi *et al.,* 2024).

The concept of PLF started in response to the greater demand for more sustainable and ethical farming. In the past few decades, the agricultural industry has embraced the use of technology to improve productivity and decrease costs (Guntoro *et al.,* 2019). All these developments have come together to serve one purpose: precision livestock farming (PLF), in which technology helps farmers make more accurate decisions using data collected from their animals. If you are looking for animal diversity, PLF has been confirmed in several of them, dairy, poultry, and swine farming systems, with an increasing body of scientific evidence (Palma-Molina *et al.,* 2023).

The most prominent benefit of PLF is the possibility of monitoring the behavior, health, and environment of each individual animal. Such accuracy enables farmers to detect health issues early, improve feed utilization, and maximize productivity (Carillo & Abeni, 2020). The main technologies used in PLF systems are remote-sensing devices (accelerometers, temperature sensors, etc.) that can monitor the activity, body temperature, and heart rate of the animal. The data collected through these sensors are analyzed through complex algorithms yielding impactful intel, allowing farmers to make informed decisions that enhance the health of the livestock (Bhavana *et al.,* 2024).

The adoption of PLF has been somewhat uneven across global agricultural sectors, with developed nations being the primary adopters. While some countries, particularly in Europe and North America, have implemented PLF at large scales, its application in developing regions remains limited. However, as technology becomes more affordable and accessible, the adoption of PLF is expected to expand, providing more farmers with tools to improve livestock management (Abi *et al.,* 2024).

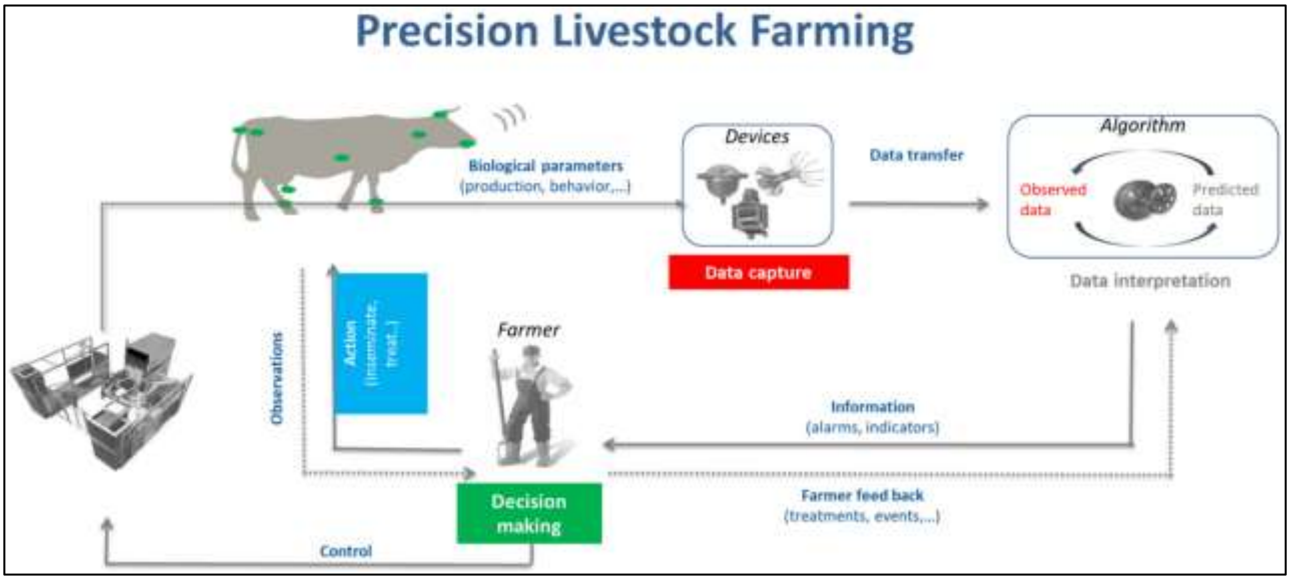

Figure 1: The diagram shows the process involved in Precision Livestock Farming (PLF) which uses sensors fitted to livestock to track biological traits of livestock, such as production and behavior. Data are taken with these sensors and are later transmitted to devices for computing. Constituting observed and predicted data, based on algorithms that the data is analyzed. These data are then interpreted to decide for the farmer to act, such as insemination or treatment, using the knowledge gained from this data. This feedback loop is expected to improve farm management and control, in addition to animal welfare and farm efficiency

3. Impact of PLF on Animal Welfare

One of the main objectives of PLF technology is animal welfare. Animal welfare is defined as the state of an animal as it attempts to cope with its environment, and it is important in providing for the biological needs of livestock. Numerous studies have demonstrated the significant positive impacts of PLF technologies on animal welfare, including monitoring and management of animal health, management of stress associated with environmental conditions, and overall improved living conditions (Papakonstantinou *et al.*, 2024). One of the primary benefits of PLF is that it provides a continuous, dynamic recording of animal health. Farm staff often need to intervene with traditional illness or injury detection methods since it can take time for symptoms to become apparent, often by the time they do it has progressed. This problem is solved by PLF, as it allows farmers to detect health problems as early as possible. For example, sensors may track vital signs, including temperature, heart rate, and movement patterns to look for changes in behavior that might indicate an illness might be on the way (Schillings *et al.*, 2021).

Thermal imaging and biometric sensors have been in use for some time to identify respiratory diseases in poultry before they are clinically visible. Real-time movement and feeding behavior detected with sensors attached to cows in dairy farming can alert farmers early on of lameness, metabolic disorders, or digestive problems. In the dairy sector, for instance, diseases such as mastitis that affect the udder can incur huge losses if not detected early. The early detection systems among this population may decrease CS incidence, leading to improved herd health (Tedeschi & Mendes, 2023).

Another factor regarding the continuous monitoring of animal behavior related to animal welfare is that it can also minimize stress and pain. Stress in livestock can also cause stress from bad housing, livestock overcrowding, and human handling. PLF systems automate many of the tasks traditionally performed by farm workers, and by achieving a decrease in human-animal contact, they greatly reduce the stress associated with handling and transport. Automated feeding systems will provide you with food after certain intervals of time, thereby removing the uncertainty associated with feeding and the anxiety it triggers among pets. Likewise, systems that monitor environmental parameters, such as temperature and humidity, provide livestock with the best conditions, minimizing the stressors associated with physical discomfort. automatic feeding system decreases cow stress levels at dairy farms which is positively correlated with increased milk production. PLF technologies can also lessen pain by automating procedures that would be otherwise invasive. In many advanced livestock systems, common practices such as castration, dehorning, and tail docking are carried out automatically with both great precision and comfort for the animals. As a prime example, it is entirely possible to develop automated solutions to tail docking in pigs, as opposed to traditional human-led tail docking methods that cause acute pain (Schillings *et al.*, 2021).

PLF technologies play a key role in improving livestock housing conditions. Air quality, temperature, and humidity in livestock barns can also be monitored, ensuring that animals are kept in a healthy and comfortable environment (Tedeschi & Mendes, 2023).

Strategically manipulating environmental parameters can result in major reductions in stress and respiratory disease, both of which are highly prevalent in poorly ventilated barns. Furthermore, innovations in waste management within PLF systems are designed to reduce the adverse effects of animal waste on both animals and their environment. Systems for Automatic Waste Removal guarantee that creatures are not presented with unsafe levels of ammonia and other toxic materials that can have negative consequences for their welfare. Automated ventilation and waste management systems used in poultry farms have been shown to improve air quality and animal welfare (Kleen & Guatteo, 2023).

4. Enhancement of Public Health Through PLF

Public health concerns related to livestock farming include the spread of zoonotic diseases, food safety issues, and the overuse of antibiotics as shown in **Figure 2** (Kibooga *et al.*, 2024). PLF technologies play a critical role in addressing these issues by enabling more precise monitoring and management of animal health, improving disease prevention, and reducing the need for antibiotics (Neculai-Valeanu *et al.*, 2024).

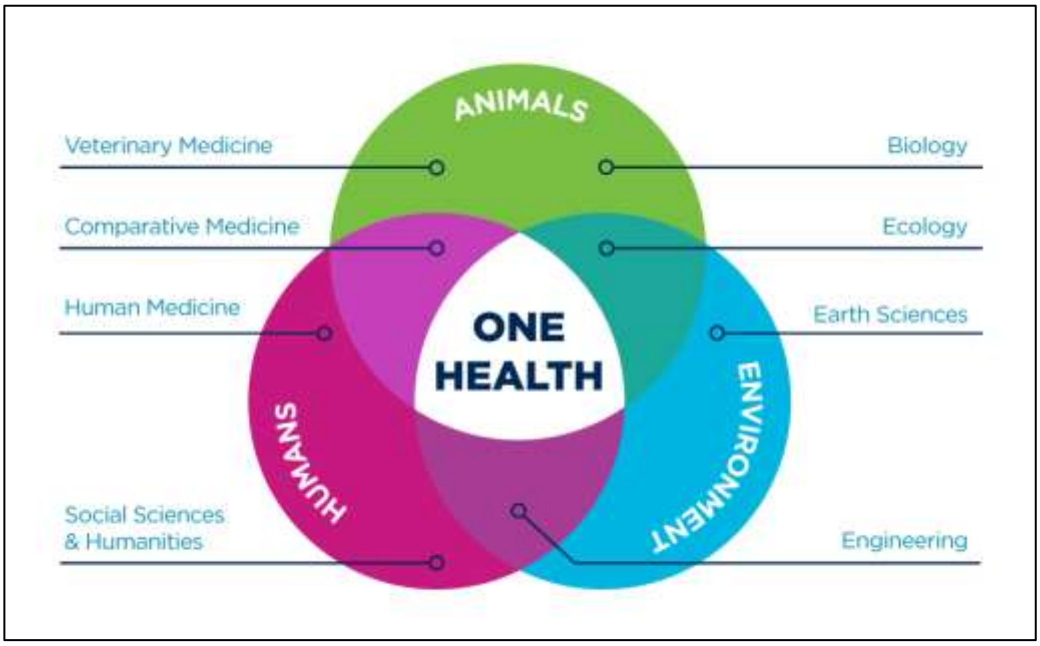

Figure 2: It shows the concept of One Health, which refers to the interconnectedness of human, animal, and environmental health. This can be visualized using a Venn diagram highlighting the intersection of these three domains—Humans, Animals, and Environment. Specific disciplines within those domains are shown for animals and humans (Veterinary Medicine, Comparative Medicine, and Human Medicine) and for the environmental sciences (Biology, Ecology, and Earth Sciences). Social Sciences & Humanities and Engineering are also associated with the larger One Health concept, which exemplifies the transdisciplinary field of this field. This diagram clearly illustrates the requirement for cross-sector engagement to solve global health problems

Zoonoses or diseases that can spread from animals to humans are a significant public health issue. Disease outbreaks in livestock farms — animals susceptible to pet birds causing avian influenza; infections through dirt, water, and soil in infected eggs of poultry to people through farms; Salmonella affecting people through poultry outbursts; and tuberculosis causing surgical patients to be infected both animals and humans discarding each other in those tuberculous bedridden days of men — all these pathetic diseases link livestock farming with human health. PLF systems offer benefits to public health by identifying the early stages of infection to stop the spread of these diseases. One example is where PLF technologies have been deployed to monitor the spread of avian influenza in poultry by tracking temperature changes, movement patterns, and sickness behavior. Similarly, PLF technologies are used to monitor diseases in human-carrying swine and cattle. The health challenges faced by animals, such as tuberculosis and brucellosis, can be controlled and prevented by constant monitoring of animal health, stronger quarantine, and treatment (Neculai-Valeanu *et al.*, 2024).

Additionally, PLF technologies contribute to food safety on the consumer side by minimizing potential contaminating conditions for animals. PLF systems, for instance, can monitor feed and water quality so that animals consume food that is safe and has the right nutrients. Some PLF systems also monitor drug usage, ensuring that no antibiotics or other chemicals are given to animals that could enter the food supply (Kupczyński *et al.*, 2024). The use of PLF systems in the food industry has substantial advantages, one of which is traceability in terms of food safety. Using PLF technologies, farmers trace the entire supply chain of individual animals from birth to slaughter. Such traceability is especially useful in foodborne pathogen outbreaks, where the origin of contamination can be traced, and steps can be taken to reduce further transmission (Nyokabi *et al.,* 2024).

The excessive use of antibiotics in livestock farming has led to antimicrobial resistance (AMR) in humans, which is a major public health problem (Kibooga *et al.,* 2024). PLF technologies assist farmers in tracking animal well-being, consequently lowering their dependency on antibiotics. For instance, data generated by PLF systems can enable farmers to detect infections at a very early stage, which can lead to targeted antibiotics being administered to infected animals instead of broad-spectrum antibiotics. In addition, PLF technologies will encourage precision feeding and enhance nutrition for animals and the immune system. PLF systems help to reduce the incidence of antibiotic treatment diseases by improving nutrition and health management (Neculai-Valeanu *et al.,* 2024).

5. Technological Advancements and Innovations in PLF

Although PLF technologies are continuously evolving, recent innovations have the potential to make these systems even more effective and versatile in their applications. Among the emerging technologies, AI, Big Data, and the integration of wearable devices that are driving new on-farm approaches to animal health and welfare have great potential (Liu *et al.,* 2023).

Big Data and machine learning have made it possible for farmers to handle tremendous amounts of data and draw conclusions that were once unachievable, all thanks to big data — and machine learning is another ingredient added to the Ploughing Machine (Marinello *et al.,* 2023). By using sensors and systems that provide real-time data on animal behavior, health, and environment, farmers can now make more informed decisions. Machine learning (ML) algorithms are also being used to forecast diseases, determine the optimum supply of feed, and screen animal activity. Research on monitoring feeding behavior, movement, and temperature of cows through sensors stimulates the use of machine learning to predict metabolic disorders in dairy cows (Khan & Babar, 2024).

Collars, tags, and harnesses, as types of wearable livestock technologies, are becoming more commonly used for continuous health monitoring without the requirement for humans to interact directly with animals. These can monitor many physiological parameters, including heart rate, body temperature, exertion, and activity, and therefore can indicate the health status of an animal (Lamanna *et al.,* 2025). Such wearable sensors have been especially successful in detecting lameness in dairy cows, which can lead to large losses in productivity and welfare problems. This provides the opportunity to treat early and avoid the need for more dramatic actions, such as culling or euthanasia (Papakonstantinou *et al.,* 2024).

One aspect of livestock management where automation is used extensively is to enhance the efficiency and accuracy of management. Automation in agriculture – Robot technology is now being used for many tasks, including feeding, milking, and health checks (Taer & Taer, 2025). Systems such as these are coming on to the market, reducing stress in cows, and improving productivity. automated milking systems which enable cows to be milked on their own accord. Automated feeding systems, likewise, provide the proper amount of nutrition for their animals, ensuring better health and welfare status for the animals. Through real-time health data, robotic systems will also be able to deliver vaccines and medications. Thus, providing real-time treatment to animals with less human intervention (Chapagaee *et al.,* 2024).

6. Challenges and Barriers in Implementing PLF

As depicted in **Figure 3**, although these characteristics of PLF technologies are beneficial, their widespread adoption is challenged by several factors. This is due to multiple factors, such as economic restrictions, lack of technology, and ethical issues around animal welfare (Papakonstantinou *et al.,* 2024). However, the high costs of PLF technologies, especially for small-scale farmers, remain a major adoption barrier. Although the setup of sensors, automation systems, and data analytics platforms comes with a hefty price tag, the long-term benefits often outweigh the costs. However, in developing regions, with their limited resources, it may be unaffordable (Chapagaee *et al.,* 2024).

This brings us to the second challenge related to the ethical implications of using technology in the livestock sector. Others have criticized the use of technology as it reduces human interaction with animals; this disconnection from animals, they argue, results in feelings of less empathy and compassion for welfare. There have also been ethical issues, including the weakening of traditional farming practices and the danger of exploiting animals for financial profit, surrounding the implementation of PLF in livestock farming (Papakonstantinou *et al.,* 2024). There are no standard regulations for the use of PLF technologies. Farmers need certainty, and without some sort of direction, investments in these technologies would likely be less fruitful, and regulation of their use by governments will face great challenges (Mgendi, 2024). Additionally, the adoption of PLF technologies involves multiple factors, including technology providers, farmers, and policymakers, making it a complex and time-consuming process (Greig *et al.,* 2023).

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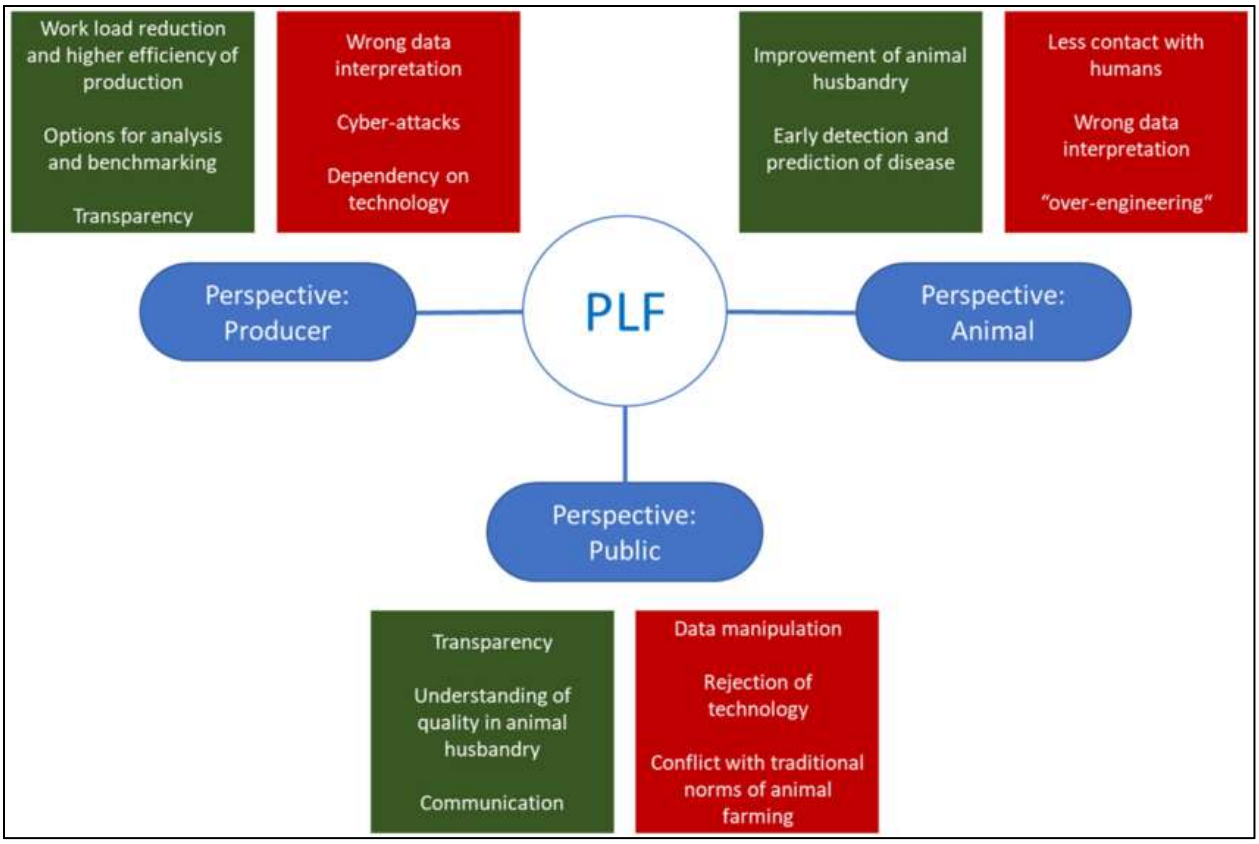

Figure 3: The diagram provides a well-rounded perspective of the perceived major benefits and challenges of PLF from three viewpoints: Producer, Animal and Public. It emphasizes that the benefits include less work, better animal husbandry, earlier disease detection, transparency, and better communication. On the other hand, it lists possible disadvantages, including incorrect data interpretation, cyber-attacks, technology dependence, and public opposition to over-engineering and rejection of technology in conventional agriculture. The resulting pictograph visually conveys the bifurcation of PLF, as it elucidates both the merits and challenges that must be overcome from these two perspectives

7. Future Directions and Emerging Trends in PLF

Precision Livestock Farming (PLF) has a bright future that will probably be influenced by the components of several technologies and ideas, including artificial intelligence (AI), machine learning, sensor technologies, and robotics (Singh *et al.,* 2024). Such innovations will make monitoring systems more precise and predictive of outbreaks, behaviors, and health problems, which will strengthen more proactive management strategies (Han, 2023).

Gene tagging for Precision Medicine would enable the tailoring of health management and use of PLF technologies in conjunction with genetic data to refine breeding and disease control approaches. This could result in less use of antibiotics with healthier livestock populations and more sustainable farming practices (Neglia *et al.*, 2023). Another aspect which ere PLF can create is sustainability. PLF technologies will contribute to explaining the environmental impact of livestock farming, especially greenhouse gas emissions and water use, by improving the information explaining feed efficiency, waste, and other parameters that use resources (Chintakunta *et al.*, 2023).

Improvements in sensor accuracy, sensor costs, and durability of wearable devices for animals. Further progress in AI and machine learning algorithms will allow for more precision management, recognizing patterns, and forecasting health problems through large datasets derived from sensors (Lamanna *et al.,* 2025). Finally, achieving Global Adoption will rely heavily on the affordability and accessibility of PLF technologies for deployment at small-scale zero-sum/closed-loop farms in developing parts of the world. This could entail mobile-based projects and global partnerships to provide farmers around the world with aid, education, and tools (Singh *et al.,* 2024).

8. CONCLUSION

This review has brought together information from the current literature on PLF technologies, examining their considerable prospects for enhancing animal welfare and public health. The results highlight the capability of PLF systems to monitor animal health status to mitigate disease outbreaks, reduce antibiotic usage, and ultimately enhance productivity and sustainability in farming. Such advancements present exciting benefits for agricultural practices on a global scale, including positive implications on ethics and food supply. Nonetheless, there are useful gaps, especially in relation to the scalability of PLF technologies to smallholder farmers in developing regions and whether these systems are cost-effective and influence animal behavior in the long-term. Future research should also benefit from identifying these gaps and work towards innovative, affordable, and accessible PLF solutions, as well as investigating the complementarity between PLF and precision medicine for more relevant implementation of personalized livestock health management. Importantly, research on the governance, ethical, and societal aspects of the PLF is also needed to inform and facilitate its governance and uptake. Although this review is extensive in its coverage of PLF technologies, regional-limited studies and the fast-moving current state of technology suggest the need for regular updates of this review. In conclusion, this review goes a long way in demonstrating the potential of PLF and emphasizes the importance of a continuous flow of innovation and robust research agenda areas for animal welfare, public health, and new sustainable farming practices to all benefit from the ear-marked benefits of PLF.

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