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An Integrative Data-Driven Precision Livestock Farming Model to Improve the Efficiency and Sustainability of Livestock Production Systems

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ABSTRACT

This study aims to explore how an integrative data-driven Precision Livestock Farming (PLF) model can improve the efficiency and sustainability of livestock production systems. The study addresses the growing need for livestock farms to integrate digital data, animal monitoring technologies, and managerial decision-making in response to productivity, welfare, and environmental challenges. A qualitative exploratory case study design was used to examine PLF implementation in livestock production units that had adopted or tested digital tools, such as animal health sensors, feed recording applications, barn monitoring systems, and production databases. Data were collected through semi-structured interviews, field observation, and documentation involving farmers, farm managers, veterinarians, livestock extension workers, technology operators, and digital system developers. The data were analyzed using thematic analysis to identify patterns of meaning related to data use, adoption barriers, and sustainability practices. The findings reveal three main patterns: data as a new basis for decision-making, socio-technical barriers in PLF adoption, and PLF as a pathway to efficiency and sustainability. The study shows that PLF becomes effective when digital data are combined with farmers' experiential knowledge, supported by trust, user capacity, reliable infrastructure, and clear data governance. These findings contribute to PLF literature by framing digital livestock management as a socio-technical process rather than a purely technological intervention. The study implies that policy and practice should support inclusive, practical, and context-sensitive PLF adoption. Future research should test the proposed model across different livestock systems and farm scales.

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1. Introduction

Global livestock production is under growing pressure to provide sufficient animal protein while reducing environmental impact, improving animal welfare, and maintaining farm profitability. This pressure has made livestock management more complex because farmers must respond to climate variability, feed inefficiency, disease risk, labor limitations, and stricter sustainability demands. Precision Livestock Farming (PLF) has emerged as a relevant approach because it uses sensors, digital recording systems, artificial intelligence, and data-driven decision support to monitor animals and production environments in real time. Niloofar et al. (2021) explain that data-driven decision support can strengthen livestock management by improving animal health, welfare, and greenhouse gas mitigation. In this context, PLF should not be understood only as a technological upgrade, but also as a management model that connects data, people, animals, infrastructure, and sustainability goals.

In many livestock systems, especially in developing countries, farm decisions still depend heavily on direct observation, manual records, and experiential knowledge. These practices remain valuable, but they often limit early detection of health problems, feed inefficiency, reproductive disorders, thermal stress, and production decline. Papakonstantinou et al. (2024) state that PLF technologies can support efficiency and animal welfare, but they also create adoption challenges for farmers. This condition shows that the main problem is not only the lack of digital tools, but also the weak integration between digital data and daily decision-making. Therefore, a data-driven PLF model must be examined through the real experiences of farmers, farm managers, technicians, veterinarians, and other actors who interact with livestock production systems.

Field realities show that PLF implementation often faces social, technical, and organizational barriers. Farmers may use sensors or applications, but they do not always rely on the data when making decisions. Some farmers compare digital alerts with visual observation, previous experience, advice from veterinarians, and local knowledge before taking action. Krampe et al. (2024) found that farmer preferences and data governance issues are important in designing PLF innovations. This finding indicates that PLF adoption cannot be separated from trust, perceived usefulness, ease of use, cost, data ownership, and the capacity to interpret information. A qualitative approach is needed because these issues involve meaning, perception, adaptation, and interaction within the farm context.

The sustainability dimension also strengthens the need for an integrative PLF model. Livestock farms must improve productivity while controlling emissions, reducing resource waste, and protecting animal welfare. Nsabiyeze et al. (2025) argue that real-time monitoring and decision support systems can improve climate-resilient livestock management. However, the effectiveness of such systems depends on how farm actors understand the data and translate it into practical actions. For example, data on feed intake, body temperature, movement, milk yield, or barn microclimate becomes useful only when users can interpret it and connect it with management decisions. This means that sustainability in PLF is not produced by technology alone, but by the interaction between digital systems and human judgment.

Previous studies have widely discussed PLF from technical, environmental, and economic perspectives. Losacco et al. (2025) describe digital transition as a driver for tailor-made farm management in modern livestock production. Bernabucci et al. (2025) also show that PLF has strong potential for extensive livestock systems. Even so, many studies still focus on tools, system performance, and measurable outcomes rather than the lived experience of actors who use those tools. The literature still provides limited explanation of how farmers interpret digital data, negotiate between traditional knowledge and algorithmic recommendations, and adapt work routines after PLF adoption. This gap is important because the success of PLF depends not only on technological accuracy, but also on social acceptance and practical usability.

Based on this background, this study aims to explore how an integrative data-driven PLF model can improve the efficiency and sustainability of livestock production systems. The focus of the study is placed on actors' experiences, data interpretation practices, adoption barriers, decision-making processes, and the relationship between digital technologies and farm routines. The study contributes theoretically by connecting PLF with socio-technical perspectives, innovation adoption, and sustainability-oriented livestock management. It also contributes practically by offering insights for farmers, technology developers, extension officers, livestock companies, and policymakers in designing PLF systems that are technically reliable, socially acceptable, context-sensitive, and useful for sustainable livestock production.

2. Materials and Methods

This study employed a qualitative research approach with an exploratory case study design. This design was selected because the study aimed to understand how data-driven Precision Livestock Farming is interpreted, adopted, and integrated into daily livestock management. A case study is suitable for examining a contemporary phenomenon in its real-life context, especially when the boundaries between technology, human behavior, organizational routines, and production systems are closely connected. Lim (2025) emphasizes that qualitative research is valuable when a study seeks to understand meaning, process, context, and lived experience. Therefore, this approach was considered appropriate for exploring the social and technical processes behind PLF adoption rather than measuring only statistical relationships.

The research was conducted in livestock production units that had used or tested digital technologies, such as animal health sensors, feed recording applications, barn monitoring tools, production databases, or camera-based observation systems. The research location may include dairy farms, beef cattle farms, or integrated livestock farms with different levels of digital adoption. The fieldwork was planned for three to four months, covering preliminary observation, informant selection, interviews, documentation, validation, and data analysis. This period allowed the researcher to observe routine livestock management and identify how digital data was collected, interpreted, and used in decision-making. The selected sites needed to show clear interaction between livestock actors and data-based technologies.

Participants were selected using purposive sampling because the study required informants who had direct experience with livestock data, digital tools, or PLF-related decision-making. The main participants included farmers, farm managers, animal health officers, veterinarians, livestock extension workers, technology operators, and digital system developers. Akinyemi et al. (2023) show that stakeholder perspectives are important for understanding the perceived benefits, risks, and practical challenges of PLF in livestock industries. The criteria for participant selection included direct involvement in farm operations, experience in using or evaluating livestock data, and willingness to explain daily management practices. Snowball sampling was also used when initial informants recommended other participants with relevant knowledge. The estimated number of participants ranged from 12 to 20, but the final number depended on data saturation.

Data were collected through semi-structured interviews, field observation, and documentation. Semi-structured interviews were used to explore participants' experiences with PLF, including perceived benefits, technical problems, trust in digital data, changes in work routines, and barriers to adoption. Field observation was conducted to examine how data were produced, read, discussed, and applied in livestock management activities. Documentation was used to review production records, health reports, feed logs, application screenshots, barn monitoring outputs, and standard operating procedures. Kiger and Varpio (2020) state that qualitative data analysis requires careful attention to meaning patterns across multiple forms of data. Therefore, the use of multiple data sources helped the researcher build a richer understanding of PLF implementation.

Data validity was ensured through source triangulation, method triangulation, member checking, and audit trail. Source triangulation was conducted by comparing information from farmers, managers, veterinarians, technicians, and technology providers. Method triangulation was applied by comparing interview data with observation notes and farm documents. Member checking was conducted by returning preliminary summaries or interpretations to selected participants to confirm accuracy and relevance. McKim (2023) argues that member checking becomes more meaningful when it is conducted in a structured way and focuses on participants' responses to the researcher's interpretation. Audit trail was also used by documenting interview guides, coding decisions, field notes, analytical memos, and theme development.

The data were analyzed using thematic analysis. This method was chosen because it allows the researcher to identify, organize, and interpret patterns of meaning within qualitative data. The analysis began with transcription, repeated reading, and initial memo writing. The researcher then conducted open coding to identify relevant ideas, such as data use, trust in technology, farm efficiency, animal welfare monitoring, digital literacy, infrastructure constraints, and sustainability practices. Braun and Clarke (2024) explain that thematic analysis requires methodological clarity, reflexivity, and transparent reporting. After coding, similar codes were grouped into categories and then developed into broader themes that explained how PLF was integrated into livestock production systems.

The final stage involved developing an integrative model based on the relationships among digital data, technological tools, farm actors, management routines, and sustainability outcomes. The model was built from themes that emerged during analysis, not from predetermined assumptions. The findings were then interpreted in relation to PLF literature, socio-technical perspectives, and sustainability-oriented livestock management. This procedure allowed the study to explain not only what technologies were used, but also how actors made sense of those technologies in practice. The methodology was designed to support limited replication in other livestock contexts with similar characteristics, especially farms that are moving toward digital and data-driven management.

3. Results and Discussions

The findings show that the implementation of data-driven Precision Livestock Farming (PLF) was understood by participants as more than the use of digital devices in livestock production. Participants described PLF as a gradual change in farm management, where data became part of daily observation, communication, and decision-making. Three main patterns emerged from the analysis: data as a new basis for decision-making, socio-technical barriers in PLF adoption, and the role of PLF in supporting efficiency and sustainability. These patterns were developed from repeated meanings found in interviews, field observations, and farm documents. The findings indicate that PLF adoption was shaped by the interaction between digital infrastructure, farmers' practical knowledge, trust in technology, and the need to improve production efficiency.

Data as a New Basis for Decision-Making

The first pattern concerns the changing role of data in livestock management. Before using digital systems, most participants relied on direct visual observation, personal experience, and informal communication among farm workers. Farmers usually assessed animal condition through feed intake, movement, body appearance, and behavioral changes. After digital tools were introduced, data from sensors, recording applications, and monitoring devices began to support these traditional practices. One farm manager stated, "Before using the application, we only waited until the animal looked weak. Now, we can see early signs from the data, especially when feed intake or movement starts to decline." This statement shows that digital data helped farmers detect potential problems earlier.

However, participants did not fully replace their experiential judgment with digital information. They used data as a supporting tool rather than as the only source of decision-making. A livestock operator explained, "The data helps us, but we still go to the barn and check the animal directly. Sometimes the number is correct, but we need to see the real condition." This finding suggests that data-driven decision-making in PLF was not a simple shift from manual to digital management. It was a process of combining technological information with farmers' embodied knowledge. This pattern reflects the socio-technical nature of PLF, where digital systems must interact with human judgment, farm routines, and local practices.

Farm documentation also showed that digital records improved consistency in monitoring animal health, feed use, and production performance. In several cases, farm managers used daily data to compare feed efficiency, identify abnormal changes, and plan treatment. This finding supports the argument that data-driven decision support can improve animal health, welfare, and environmental management when data are translated into practical actions (Niloofar et al., 2021). Yet, the findings also reveal that data quality depended on the discipline of users. When operators did not input data regularly, the system became less useful. This problem shows that PLF requires not only devices, but also consistent human participation.

Socio-Technical Barriers in PLF Adoption

The second pattern relates to barriers that affected the adoption and use of PLF technologies. Participants identified several obstacles, including limited digital literacy, unstable internet access, high device costs, technical maintenance problems, and uncertainty about data interpretation. Some farmers felt that digital tools were useful, but they also considered them difficult to operate without continuous assistance. One participant said, "The tool is good, but not all workers understand how to read the data. If the technician is not here, we sometimes return to manual recording." This statement indicates that the success of PLF depends on training, support, and user confidence.

Trust also emerged as an important issue. Several participants stated that they needed time to believe that digital alerts or system recommendations could represent the real condition of animals. This was especially visible when digital information differed from farmers' direct observation. One farmer explained, "When the system gives a warning, we do not immediately take action. We check first because sometimes the animal still looks normal." This finding shows that trust in PLF is built through repeated confirmation between data and field reality. It also suggests that farmers evaluate technology based on practical reliability, not only on its technical sophistication.

The findings align with Krampe et al. (2024), who found that farmer perspectives, data governance, and practical usability are crucial in designing PLF innovations. In this study, participants also raised concerns about who controls the data, how data are stored, and whether farm data could be used by external parties. These concerns were stronger among farm managers who worked with technology providers. A manager stated, "We want to use the system, but we also need clarity about our data. The data come from our farm, so we must know how it is used." This finding shows that PLF adoption requires transparent data governance, especially when digital platforms involve third-party providers.

PLF as a Pathway to Efficiency and Sustainability

The third pattern shows that participants viewed PLF as a tool to improve farm efficiency and sustainability. PLF helped farms monitor feed use, identify health problems, reduce delayed treatment, and improve work coordination. In farms with better digital routines, managers used production data to evaluate performance and reduce resource waste. One participant stated, "When the feed data are recorded every day, we can see which group is not efficient. We can adjust the feeding plan faster." This finding indicates that PLF can support resource efficiency when data are connected to managerial action.

Participants also associated PLF with animal welfare and environmental sustainability. Digital monitoring helped detect heat stress, abnormal movement, and changes in animal behavior. These indicators were important because health and welfare problems could reduce productivity and increase treatment costs. Papakonstantinou et al. (2024) argue that PLF technologies can support animal welfare and climate-related adaptation in livestock production. The findings of this study support that argument, but they also show that the sustainability value of PLF depends on whether users can understand and apply the information. Data alone did not create efficiency. Efficiency emerged when data were interpreted, discussed, and converted into changes in farm routines.

In environmental terms, participants believed that better feed management and early health detection could reduce unnecessary resource use. However, most participants did not yet calculate emissions or environmental impact directly. Their understanding of sustainability was still linked to practical issues, such as reducing feed waste, preventing animal loss, lowering treatment costs, and improving productivity. This finding shows that sustainability in the field was understood in operational terms. Nsabiyeze et al. (2025) highlight that real-time monitoring and decision support can strengthen climate-resilient livestock management. In this study, that potential was visible, but it remained limited by data literacy, infrastructure, and the absence of systematic environmental indicators.

Discussion

The findings show that data-driven PLF works as a socio-technical system rather than as a purely technological intervention. This means that the value of PLF depends on how farm actors interpret, trust, and use digital data in everyday work. The study found that farmers did not reject traditional knowledge. Instead, they combined digital data with direct observation and practical experience. This finding is important because it challenges the assumption that digital farming automatically replaces conventional knowledge. In this study, traditional knowledge remained central, while digital data functioned as an additional layer of decision support.

This result is consistent with the view that PLF should be designed around the needs and practices of farmers. Losacco et al. (2025) argue that digital transition can support tailor-made farm management when technology is adapted to specific farm conditions. The present study extends this argument by showing that adaptation is not only technical, but also social and cultural. Farmers need to understand how data relate to animal behavior, farm routines, and production goals. Without this understanding, PLF may become a symbolic technology that is installed but not fully used in decision-making.

The study also confirms that trust is a central factor in PLF adoption. Participants did not immediately accept system alerts or digital recommendations. They compared digital information with direct observation before making decisions. This finding is similar to Akinyemi et al. (2023), who found that stakeholders in livestock industries consider benefits, risks, and practical concerns when evaluating PLF. The present study adds that trust grows through repeated interaction between users, animals, and data systems. When digital alerts match field observations, users become more willing to rely on the system. When mismatches occur, users return to manual judgment.

The findings also show that PLF adoption requires organizational readiness. Farms need trained workers, clear procedures, reliable internet access, technical support, and consistent data input. This supports the argument that PLF cannot be implemented only by purchasing devices. Bernabucci et al. (2025) explain that PLF has strong potential in extensive livestock systems, but its implementation depends on contextual conditions. In this study, the context included worker skills, managerial commitment, infrastructure, and data governance. These conditions shaped whether PLF became part of daily practice or remained a separate technological tool.

From a sustainability perspective, the study shows that PLF can support efficiency through better feed monitoring, early health detection, and improved production control. These findings are in line with McNicol et al. (2024), who found that PLF technologies have potential to reduce greenhouse gas emissions in beef production. However, this study found that farmers often understood sustainability through immediate operational benefits rather than formal environmental indicators. They talked more about saving feed, reducing animal sickness, and avoiding production loss than about carbon emissions. This shows that sustainability communication in PLF should connect environmental goals with practical farm benefits.

The findings also provide a new perspective on data-driven livestock management in developing-country contexts. Digital livestock systems are often promoted as tools for modernization, but this study shows that adoption depends on the relationship between technology and local farm culture. Farmers may accept PLF when it respects their knowledge, reduces work burden, and provides visible benefits. Selvaggi et al. (2025) show that farmers' willingness to pay for PLF devices is influenced by perceived value. The present study supports this view by showing that value is not only economic. Value also includes confidence, usability, relevance, and the ability to solve daily problems.

Theoretically, this study contributes to the understanding of PLF as an integrative socio-technical model. The model links five elements: data infrastructure, user capacity, farm routines, decision-making practices, and sustainability outcomes. These elements interact continuously. When one element is weak, the whole system becomes less effective. For example, accurate sensors may not improve productivity if workers cannot interpret the data. Strong farmer experience may also fail to produce efficiency if records are inconsistent. Therefore, PLF should be understood as a dynamic system that depends on both technological reliability and human capability.

Practically, the findings suggest that PLF development should prioritize training, user-friendly interfaces, data interpretation support, and transparent data governance. Technology providers should design systems that are easy to understand and compatible with farm routines. Extension officers and livestock institutions should help farmers translate data into practical decisions. Farm managers should also develop clear procedures for data input, data review, and response to digital alerts. These steps can improve adoption and reduce the gap between technology availability and technology use.

Future research should examine PLF implementation across different types of livestock farms, including smallholder farms, commercial farms, and cooperative-based production systems. Further studies may also compare PLF adoption between regions with different infrastructure and institutional support. Quantitative research can be conducted after this qualitative phase to test the relationship between digital literacy, trust, data use, efficiency, and sustainability outcomes. Longitudinal research is also needed to understand how farmers' trust and digital routines develop over time. Such studies can deepen understanding of how PLF moves from initial adoption to long-term integration in livestock production systems.

4. Conclusions

This study concludes that an integrative data-driven Precision Livestock Farming model improves understanding of how digital technologies, farm actors, and daily management routines interact in livestock production systems. The findings show that PLF is not only a technological system, but also a socio-technical process shaped by trust, digital literacy, data interpretation, infrastructure readiness, and farmers' practical knowledge. The main contribution of this study lies in explaining that data-driven livestock management becomes effective when digital information supports, rather than replaces, farmers' experiential judgment. This finding strengthens the literature on PLF by showing that efficiency and sustainability depend on the meaningful integration of data into real farm decisions.

The study has theoretical, practical, and policy implications. Theoretically, it extends PLF studies by linking digital farming with socio-technical adaptation and sustainability-oriented livestock management. Practically, it suggests that farmers, farm managers, technology providers, and extension officers should prioritize training, simple data interpretation tools, reliable infrastructure, and transparent data governance. From a policy perspective, the findings highlight the need for inclusive digital livestock programs that support smallholder and commercial farms through technical assistance, affordable technologies, and data protection mechanisms. Future research should examine PLF implementation across different livestock commodities, farm scales, and regional contexts. Further quantitative and longitudinal studies are also needed to test how digital literacy, trust, data use, and organizational readiness influence production efficiency and sustainability outcomes.

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