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Analysis of the Dynamics of Sensor Technology Adoption in Decision-Making within Sustainable Livestock Systems

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ABSTRACT

This study aims to analyze the dynamics of sensor technology adoption in decision-making within sustainable livestock systems. The issue is important because livestock farmers are increasingly expected to improve productivity, animal welfare, environmental efficiency, and farm resilience while still facing limited access to digital tools, technical knowledge, and reliable decision-support systems. This research used a qualitative case study design conducted in Lembang District, West Bandung Regency, West Java, Indonesia, from March to May 2026. Data were collected through semi-structured interviews, field observation, and documentation involving 24 participants, consisting of dairy farmers, extension officers, veterinarians, cooperative managers, and technology providers. Thematic analysis identified five main themes: sensor technology as an early warning tool, negotiation between local experience and digital data, trust and uncertainty in sensor-based decisions, social support as a condition for adoption, and sustainability-oriented changes in farm management. The findings show that farmers did not adopt sensor technology only because of its technical function. They accepted it when the data was understandable, reliable, relevant to daily farm problems, and supported by trusted actors. This study contributes to the sociotechnical understanding of precision livestock farming by showing that digital decision-making depends on the interaction between technology, farmer knowledge, institutional support, and local farm culture. The findings imply that effective sensor adoption requires practical training, affordable access, continuous assistance, and policies that strengthen farmer readiness for sustainable digital livestock management.

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1. Introduction

Sustainable livestock systems are increasingly shaped by the need to improve productivity while reducing environmental pressure, disease risk, labor burden, and uncertainty in farm decision-making. Livestock farmers now face more complex management demands because production decisions must consider animal health, feed efficiency, reproductive performance, welfare standards, climate stress, and market expectations. In this context, sensor technology has become an important component of precision livestock farming because it allows continuous monitoring of animal behavior, physiological signals, barn conditions, and production indicators. Tedeschi et al. (2021) explain that sensor technology and decision-support tools can strengthen smart livestock farming by improving data collection, real-time monitoring, and management response.

This development changes the way livestock systems operate because decisions are no longer based only on visual observation or routine experience, but also on digital data generated from animals and their surrounding environment.

At the global level, the adoption of sensor technology reflects a broader transition toward data-driven livestock management. Sensors, artificial intelligence, Internet of Things devices, thermal imaging, wearable systems, and automated identification tools are used to detect early signs of disease, stress, estrus, lameness, feeding changes, and abnormal movement. Neethirajan (2020) argues that sensors, big data, and machine learning have expanded the capacity of modern animal farming to monitor welfare and health more accurately. This technological transition is important because livestock production must respond to sustainability targets while maintaining economic viability for farmers. García et al. (2020) show that machine learning applications in precision livestock farming have grown rapidly, especially in areas related to behavior classification, animal health detection, and productivity prediction. These studies indicate that sensor technology has moved from being a supportive device to becoming part of the decision-making structure in livestock systems.

In Indonesia, the issue is highly relevant because many livestock farms still depend on manual observation, inherited experience, and reactive decisions. Small and medium-scale farmers often identify health problems after visible symptoms appear, such as reduced feed intake, abnormal movement, body temperature changes, or reproductive failure. This condition limits early intervention and may reduce farm efficiency. Karthick et al. (2020) note that Internet of Things-based animal health monitoring can improve real-time observation, but its use depends on infrastructure, affordability, and user readiness. In many local livestock contexts, the problem is not only whether sensor devices are available, but also whether farmers trust the data, understand the system, and feel able to convert sensor outputs into practical actions. Therefore, adoption must be studied as a social and technical process rather than as a simple decision to buy or reject a device.

Field-level adoption of sensor technology often shows uneven patterns. Some farmers may install devices but still rely on traditional observation when making final decisions. Others may use sensor data only when advised by extension workers, veterinarians, cooperative managers, or technology providers. Mahmud et al. (2021) demonstrate that deep learning applications in cattle farming can support accurate monitoring, but the effectiveness of such systems depends on how users interpret and apply the information. In practice, farmers may compare sensor alerts with their own visual judgment, past experience, and advice from trusted actors. This creates a decision-making dynamic in which digital data and local knowledge interact. The adoption process becomes more complex when farmers must deal with device errors, unstable connectivity, maintenance costs, limited training, and uncertainty about economic benefits.

Previous research has shown that precision livestock farming can support animal welfare, productivity, and environmental management. Aquilani et al. (2022) report that precision livestock farming technologies in pasture-based systems can help monitor animal behavior, reduce labor intensity, and support welfare-oriented management. Hossain et al. (2022) also show that machine learning-based cattle identification contributes to traceability, biosecurity, and farm management. However, much of the existing literature still emphasizes technical performance, algorithm accuracy, system design, and device capability. Jiang et al. (2023) found that global research on precision livestock farming has grown substantially, but many studies remain concentrated on sensor development, automation, and data processing. This technical focus leaves limited space for understanding how farmers experience, negotiate, and interpret the adoption of sensor technology in daily decision-making.

The research gap lies in the limited qualitative understanding of how livestock farmers make sense of sensor technology and how digital data affects their decisions. Ohashi et al. (2024) show that smart livestock technology adoption is sequential and iterative, influenced by farmers' digital literacy, implementation support, technology availability, and observable benefits. This finding suggests that adoption is not a single event, but a process shaped by repeated learning and social adjustment. Selvaggi et al. (2024) also found that adoption of precision livestock farming tools is affected by economic expectations, perceived usefulness, and farm-level constraints. These findings support the need for qualitative inquiry that explores the meanings, experiences, doubts, and adaptations that occur when farmers integrate sensor technology into sustainable livestock practices.

Theoretically, this study is grounded in a sociotechnical perspective and technology acceptance theory. The sociotechnical perspective views sensor technology as part of an interaction between people, tools, data, institutions, and farm routines. Niloofar et al. (2023) emphasize that decision-support systems for sustainable livestock farming must consider economic, environmental, social, and governance dimensions. Technology acceptance theory helps explain why perceived usefulness, ease of use, trust, and social support affect the willingness to adopt digital tools. Papakonstantinou et al. (2024) argue that precision livestock farming offers benefits for welfare and climate-related management, but it also raises challenges related to cost, skills, ethics, and farmer adaptation. These theoretical perspectives are useful because the study examines not only technology use, but also the decision-making process that emerges when sensor-based data enters farm management.

Based on this background, this study aims to analyze the dynamics of sensor technology adoption in decision-making within sustainable livestock systems. The study focuses on how farmers understand sensor technology, how they interpret sensor-generated data, how they combine digital information with local experience, and how they respond to barriers in using sensor-based decision tools. Yin et al. (2023) show that non-contact sensing technology can strengthen smart farm monitoring, but its value depends on the practical context in which it is applied. This research contributes theoretically by expanding sociotechnical discussions in precision livestock farming through qualitative evidence from farmer experiences. It also offers practical contributions for government agencies, extension workers, cooperatives, veterinarians, and technology developers in designing adoption strategies that are more accessible, trusted, and relevant to sustainable livestock development.

2. Materials and Methods

This study used a qualitative research approach with a case study design. The design was selected because the study aimed to explore the process, meaning, and experience of sensor technology adoption in farm decision-making. A case study approach was appropriate because the research focused on a specific livestock area where farmers had begun to interact with digital monitoring tools, sensor-based devices, and data-supported management practices. Akinyemi et al. (2023) used qualitative inquiry to explore stakeholder perspectives on precision livestock farming and showed that this approach can reveal practical concerns, perceived benefits, and adoption barriers that are often missed by technical studies. In this study, the case was defined as the adoption of sensor technology among dairy cattle farmers in Lembang District, West Bandung Regency, West Java, Indonesia.

The research was conducted in Lembang District from March to May 2026. This location was selected because the area is known as one of the dairy cattle production centers in West Java and has active farmer groups, cooperative networks, veterinary services, and extension support. The research site also provided access to farmers who had different levels of exposure to sensor technology, including farmers who had used pedometers, digital temperature monitoring devices, livestock identification systems, barn monitoring tools, or mobile-based farm recording applications. Fuentes et al. (2022) explain that the digital transformation of livestock farming depends not only on technological availability, but also on user capacity, system integration, and the practical environment where technology is implemented. Therefore, Lembang was considered suitable for examining how sensor technology enters real farm routines and influences decisions related to feeding, health monitoring, reproduction, and animal welfare.

Participants were selected through purposive sampling. The main participants were dairy cattle farmers who had at least six months of experience using or interacting with sensor-based technology in their farms. The inclusion criteria covered farmers who used sensor data for animal health, feeding, reproduction, movement monitoring, or barn condition assessment. The study also involved supporting informants, including extension officers, cooperative staff, veterinarians, and technology providers. Dell'Unto et al. (2025) show that adoption of precision livestock farming devices in the dairy sector is influenced by economic feasibility and farm-level decision contexts. For this reason, the study included different actors who could explain not only the technical use of devices, but also the institutional, economic, and advisory factors that shaped adoption.

Snowball sampling was used after the initial participants identified other relevant informants. This technique helped the researcher reach individuals who had specific knowledge about training, device installation, data interpretation, maintenance, or farmer support. The study involved 24 participants, consisting of 14 dairy farmers, 3 extension officers, 2 veterinarians, 2 cooperative managers, and 3 technology providers. This number was considered sufficient because the data began to show repeated themes related to perceived usefulness, trust in sensor data, digital literacy, cost, technical support, and changes in decision-making. LaDonna et al. (2021) argue that rigor in qualitative interviews should not depend only on the claim of saturation, but also on the relevance of participants, depth of information, and transparency of analytic decisions. Therefore, recruitment was stopped when the data provided enough depth to answer the research focus.

Data were collected through semi-structured interviews, field observation, and documentation. Semi-structured interviews were used to explore how farmers first learned about sensor technology, why they accepted or rejected it, how they interpreted data, and how sensor outputs influenced farm decisions. Trapanese et al. (2025) indicate that precision livestock farming has developed through a long process of technological change, but adoption still depends on how users connect tools with management needs. Interview questions covered farmers' experiences with device use, perceived benefits, barriers, trust in alerts, support from extension workers, and changes in daily routines. Interviews lasted between 45 and 90 minutes and were conducted in Indonesian to allow participants to explain their experiences naturally. With participant consent, interviews were audio-recorded and later transcribed for analysis.

Field observation was conducted to examine how sensor technology was used in daily farm activities. The researcher observed barn routines, feeding practices, health checks, device placement, mobile application use, data recording, and interactions between farmers and support actors. Bernabucci et al. (2025) note that sensor technologies are widely used to monitor animal behavior, health, and environmental conditions in livestock systems. Observation was important because actual technology use can differ from what participants describe in interviews. Documentation was also collected to support the analysis. Documents included farmer records, application screenshots, device manuals, cooperative reports, health monitoring notes, and training materials. These documents helped the researcher understand how digital data was recorded, interpreted, and used in farm-level decisions.

Data validation was conducted through source triangulation, method triangulation, member checking, and audit trail. Source triangulation was applied by comparing information from farmers, veterinarians, extension officers, cooperative managers, and technology providers. Method triangulation was applied by comparing interview findings with observation notes and documents. Ahmed (2024) explains that trustworthiness in qualitative research can be strengthened through credibility, transferability, dependability, and confirmability. Member checking was conducted by sharing summaries of preliminary findings with selected participants to confirm whether the interpretation reflected their experience. An audit trail was maintained by documenting interview guides, field notes, coding decisions, analytic memos, theme development, and revisions made during analysis. This process helped ensure that the findings were traceable and not based only on the researcher's assumptions.

Data were analyzed using thematic analysis supported by the interactive logic of data condensation, data display, and conclusion drawing. The analysis began with repeated reading of interview transcripts and field notes to understand the context of each participant. Kiger and Varpio (2020) state that thematic analysis is useful for identifying, organizing, and interpreting repeated patterns of meaning in qualitative data. Initial codes were developed from meaningful data segments related to technology awareness, adoption motivation, trust in data, decision changes, technical barriers, economic considerations, and sustainability orientation. The codes were then grouped into broader themes, such as "sensor data as decision support," "negotiation between experience and digital evidence," "trust and uncertainty," "support networks," and "sustainability-oriented farm decisions." Themes were reviewed by comparing data across participants and checking their relevance to the research questions.

Ethical procedures were applied throughout the research process. Each participant received information about the purpose of the study, the type of data collected, voluntary participation, confidentiality, and the right to withdraw. Participants were given codes such as F1 for farmers, E1 for extension officers, V1 for veterinarians, C1 for cooperative staff, and T1 for technology providers. Losacco et al. (2025) emphasize that digital transition in precision livestock farming should be understood in relation to farm management needs and responsible implementation. In line with this concern, the study protected participants' identities and avoided exposing sensitive information related to farm income, business strategy, or technology providers. All recordings, transcripts, and documents were stored securely and used only for academic purposes. These procedures allowed the study to produce a detailed, transparent, and context-sensitive account of sensor technology adoption in sustainable livestock systems.

3. Results and Discussions

The analysis produced five major themes that explain the dynamics of sensor technology adoption in decision-making within sustainable livestock systems. These themes were developed from interviews, field observations, and supporting documents collected from dairy farmers, extension officers, veterinarians, cooperative managers, and technology providers in Lembang District, West Bandung Regency. The five themes were: sensor technology as an early warning tool, negotiation between local experience and digital data, trust and uncertainty in sensor-based decisions, social support as a condition for adoption, and sustainability-oriented changes in farm management. These themes show that the adoption of sensor technology was not only a technical process. It was also shaped by farmer experience, social relations, economic concerns, and the cultural routines of livestock management.

The first theme showed that farmers understood sensor technology mainly as an early warning tool. Most participants did not describe sensors as advanced technology in abstract terms. They understood sensors through practical benefits, such as detecting changes in animal movement, body temperature, feeding behavior, and reproductive signs. Farmers valued the technology when it helped them identify problems before visible symptoms became severe. One farmer stated, "The device helps me know earlier when the cow is not normal. Before this, I usually waited until the cow looked weak or stopped eating." This finding indicates that sensor technology changed the timing of farm decisions. Decisions that were previously taken after direct visual symptoms appeared could now be taken earlier based on digital alerts. Observation in several farms also showed that farmers checked mobile applications in the morning before feeding activities, especially when alerts appeared during the night.

The second theme concerned the negotiation between local experience and digital data. Farmers did not immediately replace their traditional judgment with sensor-based information. Instead, they compared sensor alerts with their own observation, previous experience, and advice from trusted actors. A farmer explained, “I do not directly believe the notification. I check the cow first, then I decide whether the data is correct.” This pattern shows that sensor data became part of a broader decision-making process rather than a single source of authority. Farmers still considered physical signs, such as body posture, appetite, rumination, movement, and interaction with other animals. This finding suggests that adoption occurred through adaptation. Farmers accepted sensor technology when it supported their practical knowledge, but they questioned it when the data did not match their field experience.

The third theme revealed that trust and uncertainty strongly influenced technology use. Farmers trusted sensor technology when alerts were accurate, easy to understand, and followed by visible changes in animal condition. However, trust declined when devices produced false alerts, experienced battery problems, lost connectivity, or generated data that farmers could not interpret. One participant said, “Sometimes the signal is weak, so the data is late. If the data comes late, I still rely on what I see in the barn.” This statement reflects a practical concern. Farmers were willing to use sensor data, but they needed reliable systems and clear interpretation. The issue of trust was also linked to cost. Some farmers hesitated to invest in devices because they were unsure whether the technology would produce direct economic benefits. This was especially clear among small-scale farmers who managed limited herd sizes and had narrow profit margins.

The fourth theme showed that social support played a central role in adoption. Farmers who received regular assistance from extension officers, veterinarians, cooperatives, or technology providers tended to use sensor data more actively. They were also more confident in interpreting alerts and connecting them to farm decisions. One cooperative staff member stated, “Farmers need someone to explain what the numbers mean. Without explanation, the application is only seen as a tool, not as a guide.” This finding indicates that adoption depended on learning networks. Farmers did not adopt technology as isolated individuals. They learned through demonstrations, peer discussion, technical assistance, and repeated interaction with support actors. Snowball data also showed that farmers were more likely to try a device when they saw other farmers in the same area benefit from it. This pattern reflects the importance of social proof in livestock communities.

The fifth theme showed that sensor technology encouraged sustainability-oriented changes in farm management, although these changes remained gradual. Farmers reported that sensor data helped them reduce unnecessary treatment, monitor reproductive timing more carefully, prevent delayed health responses, and manage feed more efficiently. One veterinarian noted, “When farmers respond earlier, the treatment is usually lighter, and the animal recovers faster.” Several farmers also explained that sensor alerts helped reduce labor pressure because they did not need to observe each animal manually throughout the day. However, sustainability outcomes were not automatic. They depended on whether farmers used data consistently and whether they had access to follow-up support. Documentation from farm records showed that farmers who used sensor data regularly had more structured notes on health, reproduction, and feeding changes. This indicates that sensor adoption contributed not only to immediate decisions, but also to better farm record culture.

Overall, the findings show that sensor technology adoption in sustainable livestock systems occurred through a gradual process of learning, testing, comparing, and adjusting. Farmers did not adopt technology simply because it was available. They adopted it when they could see its relevance to daily problems, when the data was understandable, and when the technology aligned with their economic capacity. The findings also show that sensor-based decision-making was strongest when digital data, local knowledge, and expert support worked together. This pattern is important because it challenges the assumption that digital transformation in livestock farming only depends on device installation. In this study, adoption depended more on the ability of farmers and support actors to translate sensor data into meaningful farm actions.

Discussion

The findings support the sociotechnical view that technology adoption in livestock systems involves interaction between human actors, digital tools, institutional support, and local routines. Sensor technology did not function as a neutral device that automatically improved decisions. It became useful when farmers connected sensor outputs with animal behavior, farm experience, veterinary advice, and cooperative support. This finding is consistent with Niloofar et al. (2023), who argue that decision-support systems for sustainable livestock farming must consider social, economic, environmental, and governance dimensions. The present study extends this argument by showing that sustainability-oriented decisions emerge when farmers trust the data and can translate it into practical action.

The finding that farmers used sensors as early warning tools aligns with Tedeschi et al. (2021), who state that sensor technology and intelligent decision-support tools can strengthen real-time monitoring in smart livestock farming. In this study, farmers valued sensors because they helped detect health and reproductive problems earlier. This finding also supports Neethirajan (2020), who highlights the role of sensors, big data, and machine learning in improving animal health and welfare monitoring. However, this study adds a qualitative insight. Farmers did not define the value of sensor technology based on technical sophistication. They defined it based on whether the technology reduced uncertainty in daily farm decisions.

The negotiation between local experience and digital data provides an important contribution to the literature on precision livestock farming. Previous studies often emphasize algorithm accuracy, system performance, and automated monitoring capacity. García et al. (2020) show that machine learning has been widely applied to precision livestock farming for classification, prediction, and detection purposes. Mahmud et al. (2021) also report that deep learning applications support precision cattle farming through image-based and sensor-based analysis. In contrast, the present study shows that farmers did not treat algorithmic outputs as final decisions. They used sensor data as one form of evidence and compared it with embodied knowledge developed through years of livestock care. This finding suggests that successful adoption requires integration between digital intelligence and farmer intelligence.

The issue of trust also confirms previous research on adoption barriers in precision livestock farming. Selvaggi et al. (2024) found that the adoption of precision livestock farming tools is influenced by perceived usefulness, cost, and farm-level constraints. The present study supports this finding by showing that farmers trusted technology when alerts were accurate, timely, and understandable. Trust weakened when devices produced false alerts, lost connectivity, or required interpretation beyond farmers' digital skills. This finding is also consistent with Papakonstantinou et al. (2024), who note that precision livestock farming faces challenges related to skills, cost, data ethics, and user adaptation. The present study adds that trust is not formed only through technical reliability. It also develops through repeated confirmation between sensor data and observable farm reality.

The role of social support in adoption is another key finding. Farmers were more likely to use sensors effectively when extension officers, veterinarians, cooperatives, and technology providers helped them interpret data. This finding aligns with Ohashi et al. (2024), who explain that smart livestock technology adoption is sequential, iterative, and shaped by support systems. In this study, support actors acted as translators between digital data and practical farm decisions. They helped farmers understand what an alert meant, what action should follow, and whether the sensor result matched animal condition. This finding offers a practical implication. Technology providers should not only sell devices. They need to provide training, follow-up assistance, and simple interpretation systems that match farmers' literacy levels.

The findings also show that sensor technology contributed to sustainability-oriented farm management, but the contribution remained dependent on consistent use. Farmers who used sensor data regularly reported earlier health responses, better reproductive timing, more structured records, and reduced labor pressure. This finding supports Aquilani et al. (2022), who found that precision livestock farming technologies can support animal monitoring, welfare, and labor efficiency in pasture-based livestock systems. It also relates to Fuentes et al. (2022), who argue that the digital transformation of livestock farming depends on the integration of artificial intelligence, emerging technologies, and practical farm implementation. The present study adds that sustainability cannot be achieved only by introducing technology. Sustainability requires routines, interpretation, and decision discipline.

The results differ slightly from studies that present sensor technology mainly as an efficiency tool. In this study, farmers did not always prioritize efficiency as the main reason for adoption. Some farmers adopted sensors because they wanted to reduce anxiety over animal health, avoid reproductive losses, or gain confidence in daily decisions. This finding shows that emotional and experiential dimensions also matter in technology adoption. For small-scale farmers, the value of technology was not only calculated through productivity gains. It was also shaped by the feeling of being more informed and less uncertain. This perspective enriches technology acceptance theory because perceived usefulness includes not only economic benefit, but also psychological assurance and decision confidence.

Theoretically, this study strengthens the argument that technology acceptance in livestock systems should be understood through a sociotechnical lens. Perceived usefulness, ease of use, trust, and social influence remain important, but they operate within specific farm cultures and local decision routines. The study shows that farmers accepted technology when it respected their existing knowledge and helped solve concrete problems. They resisted or delayed adoption when technology appeared too costly, too complicated, or disconnected from daily realities. This means that adoption models in sustainable livestock systems should include local knowledge, peer influence, support networks, and interpretive trust as core elements.

Practically, the findings suggest that sensor adoption programs should begin with farmer problems rather than device promotion. Government agencies, cooperatives, and technology providers should identify the most urgent decision areas, such as disease detection, estrus monitoring, feed efficiency, or heat stress management. Training should use simple farm cases, not only technical manuals. Cooperatives can also play a strategic role by providing shared access, group-based training, device maintenance support, and data interpretation assistance. For small-scale farmers, subsidy schemes, rental models, or cooperative-based ownership may reduce the economic barrier to adoption.

Future research should compare sensor adoption across different livestock commodities, such as beef cattle, dairy cattle, goats, poultry, and pigs. Further studies could also examine how gender, age, farm size, education level, and cooperative membership influence digital decision-making in livestock systems. Longitudinal research would be useful to understand how farmer trust changes after repeated use of sensor technology. Quantitative studies may also test the relationship between sensor adoption, farm productivity, animal welfare indicators, and environmental outcomes. These future directions can deepen understanding of how sensor technology contributes to sustainable livestock systems in different social and ecological contexts.

4. Conclusions

This study concludes that the adoption of sensor technology in sustainable livestock systems is not merely a technical process, but a sociotechnical process shaped by farmer experience, trust, local knowledge, institutional support, and economic capacity. The findings show that farmers used sensor technology mainly as an early warning tool for detecting changes in animal health, movement, reproduction, and barn conditions. However, farmers did not rely on sensor data automatically. They compared digital alerts with visual observation, practical experience, and advice from veterinarians, extension officers, cooperatives, and technology providers. This finding contributes to the literature on precision livestock farming by showing that digital decision-making in livestock systems emerges through negotiation between sensor-based evidence and farmer knowledge.

The study has theoretical, practical, and policy implications. Theoretically, it strengthens the sociotechnical perspective by showing that technology acceptance in livestock farming depends on trust, interpretation, and social support, not only perceived usefulness or ease of use. Practically, the findings suggest that sensor adoption programs should focus on farmer training, simple data interpretation, technical assistance, and cooperative-based support models. From a policy perspective, government and livestock institutions need to design inclusive digital livestock programs that reduce cost barriers and improve farmer readiness. Future studies should examine sensor adoption across different livestock commodities, farm scales, and regional contexts. Longitudinal and mixed-method studies are also needed to assess how continued use of sensor technology affects productivity, animal welfare, environmental efficiency, and farmer decision-making over time.

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