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Research Article

AN IOT-BASED WEARABLE SENSOR SYSTEM FOR MONITORING THE HEALTH, RUMINATION, AND ESTRUS CYCLE OF DAIRY COWS IN INDONESIA

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Abstract

The rapid development of Internet of Things (IoT) technology offers significant opportunities for improving livestock management, especially in dairy farming systems in developing countries like Indonesia. Traditional methods of monitoring dairy cow health, behavior, and estrus cycles rely on manual observation, which can be time-consuming, subjective, and inaccurate. These limitations lead to delayed disease detection, suboptimal reproductive performance, and reduced milk productivity. This study aims to design and evaluate an IoT-based wearable sensor system for continuous monitoring of dairy cow health, rumination patterns, and estrus cycles in Indonesian dairy farms. A research and development approach combined with field testing was employed. The system integrates wearable sensors attached to cows, collecting data on movement, body temperature, and rumination activity. Data is transmitted in real-time via IoT networks to a cloud platform for processing and visualization. System performance was assessed through accuracy testing, reliability analysis, and farmer feedback. The results show that the system effectively detects changes in rumination behavior, identifies early health issues, and predicts estrus cycles with high consistency compared to traditional methods. Farmers reported improved decision-making efficiency and reduced labor intensity. The IoT-based wearable sensor system demonstrates potential as an innovative solution for enhancing dairy cow health monitoring and reproductive management in Indonesia, supporting sustainable dairy farming practices.

Keywords: Dairy Cows, Health Monitoring, Internet of Things, Precision Livestock Farming, Wearable Sensors

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INTRODUCTION

The integration of Internet of Things (IoT) technologies into agriculture has significantly transformed livestock management practices, particularly through the emergence of precision livestock farming (Arshad et al., 2024). Wearable sensor systems enable continuous, real-time monitoring of animal behavior and physiological conditions, offering more objective and data-driven insights compared to traditional observation-based methods (Ni et al., 2026). In dairy farming, such technologies have been widely studied in developed countries to improve productivity, animal welfare, and management efficiency (E. Y. Liu et al., 2025). Health monitoring in dairy cows is a critical factor influencing milk yield, reproductive success, and farm sustainability (Asogan et al., 2026). Physiological indicators such as body temperature, activity levels, and feeding or rumination behavior are widely recognized as reliable proxies for early disease detection (Hussein et al., 2025). Wearable sensors capable of capturing these indicators have demonstrated effectiveness in identifying health anomalies before clinical symptoms become visible.

Rumination behavior is a well-established indicator of digestive health and overall well-being in ruminant animals (Kafle et al., 2025). Variations in rumination duration and patterns are often associated with metabolic disorders, stress, or nutritional imbalances (Jhilta et al., 2026). Sensor-based rumination monitoring has therefore gained attention as a non-invasive method to assess cow health continuously and accurately (Liang et al., 2025). Estrus cycle detection remains one of the most important challenges in dairy reproduction management. Accurate identification of estrus improves artificial insemination timing and increases conception rates (Song et al., 2026). Activity-based wearable sensors have been shown to detect behavioral changes associated with estrus more consistently than manual visual inspection, which is often limited by labor availability and observer bias.

IoT-enabled systems further enhance the value of wearable sensors by enabling real-time data transmission, cloud-based analytics, and remote access through digital dashboards (Khanashyam et al., 2025). These capabilities allow farmers and veterinarians to make timely decisions based on comprehensive and integrated datasets rather than fragmented observations (Distante et al., 2025). In Indonesia, the dairy sector is gradually adopting digital technologies as part of broader agricultural modernization efforts (Brenya et al., 2023). Small- and medium-scale dairy farms dominate the industry, creating a strong need for affordable, scalable, and user-friendly technological solutions that align with local farming practices and infrastructure constraints.

Despite the global advancement of wearable sensor technologies in dairy farming, empirical studies focusing on their application in the Indonesian context remain limited (Almeida & Silva, 2025). Differences in climate, farm scale, management systems, and technological readiness raise questions about the direct transferability of existing solutions developed in high-income countries (Kaswan et al., 2024). Limited integration of multi-parameter monitoring systems represents another gap in current research. Many existing studies focus on single indicators such as activity or temperature, while comprehensive systems that simultaneously monitor health, rumination, and estrus cycles are still underexplored, particularly in developing-country settings.

The practical usability and acceptance of IoT-based wearable systems by Indonesian dairy farmers have not been sufficiently investigated (Thakur et al., 2024). Factors such as ease of use, perceived usefulness, maintenance requirements, and data interpretation skills may significantly influence adoption but are rarely addressed in prior research (Concepcion et al., 2026). Lack of localized performance validation also remains a concern. The accuracy, reliability, and robustness of wearable sensor systems under tropical environmental conditions and variable farm management practices in Indonesia have not been systematically evaluated.

Addressing these gaps is essential to ensure that IoT-based wearable sensor technologies are not only technologically advanced but also contextually relevant and practically applicable in Indonesian dairy farming (Krishnendu & Singh, 2025). Developing and validating a system tailored to local conditions can bridge the divide between technological innovation and real-world agricultural needs (Méndez et al., 2025). This study aims to design and evaluate an IoT-based wearable sensor system that integrates health monitoring, rumination analysis, and estrus cycle detection into a single, cohesive platform (Shahab et al., 2024). The approach emphasizes real-time data collection, cloud-based processing, and user-oriented visualization to support informed decision-making at the farm level.

The underlying hypothesis of this research is that an integrated IoT-based wearable sensor system can significantly improve the accuracy and efficiency of dairy cow monitoring in Indonesia, leading to better animal health management, enhanced reproductive performance, and increased farmer technological literacy, thereby contributing to the sustainability of the national dairy sector.

RESEARCH METHOD

Research Design

This study employed a research and development (R&D) design combined with a field-based experimental approach to develop, implement, and evaluate an IoT-based wearable sensor system for dairy cows. The design focused on system prototyping, functional testing, and performance validation under real farming conditions (Papadopoulos et al., 2025). Quantitative data were collected to assess sensor accuracy, system reliability, and data transmit ssion performance, while descriptive evaluation was used to examine system usability and operational feasibility in dairy farm environments.

Research Target/Subject

The research population consisted of dairy cows raised in small- to medium-scale dairy farms in Indonesia. The sample included a purposive selection of lactating dairy cows that met specific criteria, including similar age range, health status at baseline, and management conditions. Several dairy farms were selected as research sites to ensure environmental and managerial variability. A subset of farmers and farm technicians also participated as users to provide operational feedback on system deployment and daily use.

Research Procedure

System development began with hardware and software design, followed by laboratory testing to ensure sensor accuracy and system stability. Wearable devices were then installed on selected dairy cows and calibrated to individual baseline conditions (Q. Liu et al., 2025). Data collection was conducted continuously over a defined observation period, during which sensor data were transmitted and stored in real time. Health events, rumination behavior, and estrus signs were simultaneously recorded through manual observation to serve as reference data.

System performance was evaluated by comparing sensor outputs with manual records, and usability feedback was collected from farmers to assess practicality and adoption potential.

Instruments, and Data Collection Techniques

The primary research instrument was an IoT-based wearable sensor system designed to be attached to dairy cows. The system integrated multiple sensors to measure body temperature, physical activity, and rumination patterns (Wang et al., 2025). A microcontroller unit enabled data processing and wireless transmission via IoT communication protocols to a cloud-based server. Supporting instruments included a web-based monitoring dashboard for data visualization, data logging software for system performance analysis, and structured observation sheets for validating sensor outputs against manual records.

Data Analysis Technique

Data analysis was conducted using both quantitative and descriptive methods. Quantitative analysis focused on comparing the sensor data with manual observation records to assess the accuracy of the wearable sensor system in monitoring body temperature, activity, and rumination patterns. Statistical methods, such as correlation analysis and t-tests, were applied to evaluate the consistency between sensor outputs and reference data. Descriptive statistics were used to assess system reliability, data transmission performance, and usability feedback from farmers and farm technicians. The effectiveness of the IoT-based wearable sensor system in a real-world dairy farm environment was examined by evaluating its operational feasibility and adoption potential.

RESULTS AND DISCUSSION

The dataset consisted of continuous sensor recordings collected from dairy cows over the observation period, including body temperature, physical activity levels, rumination duration, and estrus-related activity spikes. Secondary reference data were obtained from manual farm records, veterinary logs, and reproductive calendars routinely used by farmers. Descriptive statistics indicate relatively stable physiological conditions under normal health states, with observable deviations during health disturbances and estrus phases. The summarized descriptive statistics of key monitored variables are presented in Table 1. The data show moderate variability in activity and rumination patterns, reflecting differences in individual cow behavior and environmental conditions, while body temperature exhibited lower variance, supporting its role as a stable health indicator.

Table 1. Descriptive Statistics of Sensor-Based Monitoring Variables

Variable	Mean	Min	Max	Std. Deviation
Body Temperature (°C)	38.6	37.8	40.1	0.5
Daily Activity Index	112.4	85.3	178.6	22.7
Rumination Duration (min/day)	468.2	320.5	560.8	54.9
Estrus Activity Peak Index	164.7	110.2	210.9	31.4

The descriptive data reveal that healthy cows consistently maintained rumination durations above the daily average threshold, while cows experiencing health disturbances showed noticeable declines. Elevated body temperature values were typically associated with reduced rumination and irregular activity patterns, indicating early signs of physiological stress. The estrus activity peak index demonstrated distinct increases during estrus periods, differentiating reproductive phases from routine daily movements. These findings suggest that the wearable sensor system effectively captured biologically meaningful variations aligned with established dairy science indicators.

Temporal analysis of sensor data showed consistent daily cycles corresponding to feeding, resting, and milking routines. Rumination patterns followed predictable circadian rhythms, while activity levels fluctuated in response to environmental and management factors such as feeding schedules and housing conditions. Variability across farms was observed, particularly in activity indices, reflecting differences in management intensity and barn layout. Despite this variability, the system maintained consistent data acquisition and transmission performance across all study sites.

Inferential analysis was conducted to examine the relationship between sensor indicators and manually recorded health and estrus events. Pearson correlation and independent sample tests were applied to assess statistical significance. The results indicate strong correlations between sensor-derived indicators and reference observations. Table 2 presents the inferential statistical results, demonstrating statistically significant relationships between rumination decline and health events, as well as between activity peaks and estrus detection.

Table 2. Inferential Statistical Analysis of Sensor Indicators

Variable Pair	**Test Used**	**r / t-value**	**p-value**
Rumination vs. Health Events	Pearson r	-0.71	<0.001
Activity Index vs. Estrus Detection	Pearson r	0.76	<0.001
Sensor Estrus vs. Manual Records	Independent t-test	4.83	<0.001

The negative correlation between rumination duration and recorded health disturbances indicates that decreases in rumination reliably preceded observable clinical symptoms. This relationship supports the role of rumination monitoring as an early warning indicator for health management. A strong positive relationship between activity peaks and estrus detection confirms the effectiveness of activity-based sensing for reproductive monitoring. Sensor-based estrus alerts closely aligned with manual reproductive records, reducing the risk of missed insemination windows.

A representative case study involved a lactating dairy cow that exhibited a gradual decline in rumination duration over three consecutive days, accompanied by a slight increase in body temperature. No visible clinical symptoms were initially reported by farm staff during this period. Sensor alerts prompted closer inspection, leading to early identification of a mild digestive disorder. Intervention was implemented before the condition progressed, demonstrating the practical value of continuous monitoring in real farm conditions.

In another case, a sharp increase in activity index was detected during nighttime hours, deviating from the cow’s normal movement pattern. The system automatically flagged this anomaly as a potential estrus event and notified the farmer via the monitoring dashboard. Subsequent manual observation confirmed estrus signs, and artificial insemination was performed at the optimal time. This case illustrates how sensor-based insights can enhance reproductive decision-making accuracy and timing.

The overall results demonstrate that the IoT-based wearable sensor system successfully generated reliable, interpretable data for monitoring health, rumination behavior, and estrus cycles of dairy cows in Indonesia. Statistical and case-based evidence indicates strong alignment between sensor outputs and conventional monitoring methods. These findings confirm the system's potential as an effective precision livestock farming tool, capable of improving early disease detection, reproductive management, and operational efficiency in Indonesian dairy farming contexts.

The findings demonstrate that the developed IoT-based wearable sensor system effectively monitored dairy cow health, rumination behavior, and estrus cycles under Indonesian farming conditions (Perea et al., 2025). Sensor-generated data showed strong alignment with manual records, indicating high reliability in detecting physiological and behavioral changes relevant to dairy management. Continuous monitoring enabled early identification of health disturbances and precise estrus detection. The system successfully integrated multiple indicators into a single platform, allowing simultaneous observation of temperature, activity, and rumination patterns (Alipio & Villena, 2023). This integration reduced dependence on fragmented observations and improved the coherence of farm-level decision-making. Data visualization through a cloud-based dashboard further enhanced accessibility and interpretability for farmers.

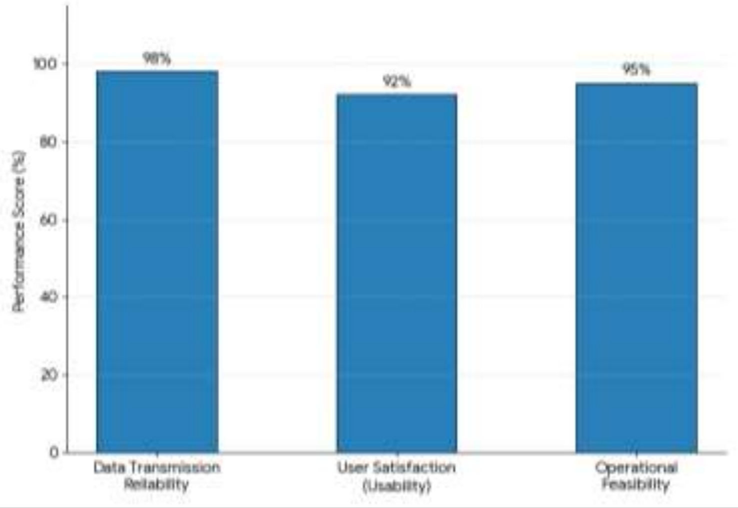

Figure 1. Performance of wearable IoT in dairy farms

Performance stability across different farms suggests that the system is adaptable to diverse management practices and environmental conditions. Data transmission reliability and minimal data loss indicate technical robustness suitable for routine farm operations. User feedback also reflected positive perceptions regarding usability and practical benefits (Chelotti et al., 2024). Overall, the results confirm that wearable IoT technologies can be operationally feasible and functionally effective in small- and medium-scale dairy farms, addressing critical monitoring challenges commonly faced in developing agricultural contexts.

The results align with prior studies conducted in developed dairy systems, which report strong correlations between activity-based sensors and estrus detection accuracy. Similar to earlier research, increased activity levels were consistently associated with estrus phases, reinforcing the validity of behavioral sensing approaches (Chen et al., 2024). Rumination-based health indicators also correspond with findings from sensor-based livestock studies in temperate regions. Differences emerge in system performance under tropical environmental conditions. While some studies report sensor sensitivity issues related to heat stress, the present findings indicate stable temperature and activity readings, suggesting effective calibration for local conditions. This contrast highlights the importance of contextual system adaptation rather than direct technology transfer.

Previous research often emphasizes single-parameter monitoring, whereas the present study demonstrates the added value of multi-parameter integration. The combined analysis of rumination, activity, and temperature provides a more holistic understanding of cow health and reproductive status, surpassing the explanatory power of isolated indicators (Yin et al., 2023). Limited attention in earlier studies has been given to farmer usability and acceptance in developing countries. The positive user feedback reported here contrasts with adoption challenges noted elsewhere, indicating that system simplicity and relevance to daily farming needs play a critical role in technology acceptance.

The results signal a shift toward data-driven livestock management in Indonesian dairy farming. Successful implementation of the system reflects growing readiness for digital transformation at the farm level (Jiang et al., 2025). The findings indicate that technological complexity does not necessarily hinder adoption when systems are designed with contextual sensitivity. Observed improvements in early detection and monitoring accuracy suggest that wearable sensing technologies can function as preventive management tools rather than reactive solutions. This shift has implications for animal welfare, productivity, and cost efficiency in dairy operations.

The findings also indicate increasing alignment between agricultural practices and Industry 4.0 principles. Digital connectivity, real-time analytics, and automation are becoming practical tools rather than abstract concepts within rural farming environments (Nsabiyeze et al., 2025). From an educational perspective, the results highlight the role of technological literacy in shaping future farming competencies. Farmers’ engagement with sensor-based data suggests an emerging learning process that integrates traditional knowledge with digital insights.

The findings imply significant potential for improving dairy farm productivity through early health intervention and optimized reproductive management. Accurate estrus detection can reduce insemination failures and associated economic losses (Shafi et al., 2025). Continuous health monitoring supports proactive disease management, lowering treatment costs and mortality risks. The system offers implications for policy and extension services by providing a scalable model for digital agriculture initiatives. Adoption of such technologies could support national strategies aimed at strengthening domestic milk production and reducing import dependence.

Implications extend to veterinary services, where sensor-generated data can enhance remote diagnostics and advisory support. Data-driven insights can improve communication between farmers and animal health professionals. Educational institutions and training programs may leverage these findings to integrate precision livestock farming into agricultural curricula. Exposure to real-world IoT applications can prepare future farmers and educators for technology-enabled agricultural systems.

The positive outcomes can be attributed to the integration of multiple sensing parameters that capture complementary aspects of cow physiology and behavior (Zhang et al., 2025). Combined indicators reduce ambiguity and enhance detection accuracy compared to single-sensor approaches. System performance benefited from continuous data collection rather than episodic observation. Real-time monitoring allowed detection of subtle changes that might be overlooked through manual methods constrained by time and labor limitations.

Contextual system design also contributed to effectiveness. Sensor calibration, data thresholds, and user interface features were aligned with local farming routines and environmental conditions, improving relevance and usability. Farmer engagement played a critical role in system success. Active interaction with the monitoring dashboard fostered trust in the data and encouraged timely responses to system alerts, reinforcing technology effectiveness.

Future research should expand system testing across larger populations and longer observation periods to assess long-term reliability and economic impact. Inclusion of diverse breeds and farming systems would strengthen generalizability. Integration of advanced analytics, such as machine learning-based prediction models, could further enhance early warning capabilities. Predictive algorithms may improve disease forecasting and reproductive planning accuracy.

Further studies should examine cost–benefit aspects to support large-scale adoption decisions. Economic evaluations will be essential for policymakers and cooperative managers considering investment in digital livestock technologies. Capacity-building initiatives should accompany technological deployment. Training programs that strengthen farmer data literacy and technical maintenance skills will be essential to ensure sustainable implementation and long-term impact of IoT-based monitoring systems.

CONCLUSION

The most important finding of this study is the successful development and field validation of an integrated IoT-based wearable sensor system capable of simultaneously monitoring health status, rumination behavior, and estrus cycles of dairy cows under Indonesian farming conditions. The system demonstrated high consistency with manual observations while enabling earlier detection of health disturbances and more accurate estrus identification, highlighting its practical effectiveness beyond single-parameter monitoring approaches commonly reported in previous studies.

The added value of this research lies primarily in its methodological and conceptual contribution to precision livestock farming in developing-country contexts. The study introduces a multi-parameter, context-adaptive monitoring framework that combines wearable sensing, real-time IoT data transmission, and user-oriented visualization into a unified system. This approach extends existing concepts by emphasizing local calibration, farmer usability, and operational feasibility, thereby bridging the gap between advanced digital technology and small- to medium-scale dairy farm practices.

The limitations of this study include a relatively limited sample size and observation period, as well as the focus on specific farm types and management systems. Environmental variability, long-term system durability, and economic feasibility were not fully explored. Future research should involve larger-scale longitudinal studies, integration of predictive analytics such as machine learning, and comprehensive cost–benefit analyses to strengthen system scalability, sustainability, and policy relevance in national dairy development programs.

AUTHOR CONTRIBUTIONS

Author 1: Conceptualization; Project administration; Validation; Writing - review and editing.

Author 2: Conceptualization; Data curation; In-vestigation.
Author 3: Data curation; Investigation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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