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IoT-Based Precision Livestock Monitoring for Real-Time Detection of Thermal Stress and Metabolic Disorders in Dairy Cows

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ABSTRACT

Climate change and seasonal temperature variations significantly affect the welfare, metabolic health, and productivity of dairy cows, particularly in tropical regions characterized by high temperatures and humidity. Heat stress reduces milk yield, impairs reproduction, and increases the risk of metabolic and infectious diseases. The Internet of Things (IoT) enables real-time monitoring through integrated environmental and behavioral sensors, supporting precision dairy management. This study evaluated an IoT-based multi-sensor system to detect thermal stress and early metabolic health changes in dairy cows on a tropical dairy farm in Indonesia. The system combined a temperature–humidity sensor to calculate the Temperature–Humidity Index (THI) and a smart collar with a three-axis accelerometer to monitor activity and rumination. Data were collected from 50 lactating cows over three months and analyzed using descriptive and correlation analysis. Maximum THI reached 86.4, indicating severe heat stress, and showed a strong negative correlation with milk production (r = −0.88). Behavioral changes, including reduced rumination and activity, were detected up to 36 hours before clinical symptoms. These results confirm that IoT-based monitoring enables early stress detection, improving welfare, productivity, and dairy farm resilience.

Keywords: *Internet of Things, dairy cows, thermal stress, THI, metabolic disorders, precision livestock farming*

INTRODUCTION

Although the use of the Internet of Things (IoT) in precision livestock farming has grown rapidly over the past decade, significant research gaps remain, particularly regarding practical applications and field validation in commercial dairy farming systems. At the global level, heat stress has become one of the most pressing challenges facing the dairy industry, driven by climate change and the increasing frequency of extreme temperature events. It is estimated that heat stress affects dairy cattle in more than 60% of milk-producing regions worldwide and contributes to substantial economic losses through reduced milk yield, impaired reproduction, increased veterinary costs, and premature culling. Annual economic losses attributable to heat stress in the global dairy sector are projected to reach billions of US dollars, highlighting the urgent need for effective monitoring and mitigation strategies.

The limited geographic and climatic context of previous studies remains a major issue. Most IoT research on dairy cattle has been conducted in temperate or subtropical regions with relatively low temperature variability. Tropical regions are characterized by a combination of high temperatures and high humidity, which leads to chronic, rather than episodic, thermal stress. Previous studies generally report the performance of sensor systems or stress detection algorithms without evaluating sustained seasonal dynamics over periods of more than a few weeks (Tangorra et al., 2024; Liu et al., 2023). Consequently, empirical evidence regarding the effectiveness of IoT systems in addressing extreme climate fluctuations in tropical regions remains limited.

Quantitative integration between environmental indicators (IoT) and individual cow behavioral responses is still relatively limited. Many studies utilize environmental sensors to map barn conditions or use behavioral sensors for activity classification, but these are often analyzed separately. In fact, behavioral changes such as decreased rumination, reduced lying time, and increased water consumption are behavioral manifestations of physiological responses to heat stress and early metabolic disturbances. The lack of an integrative approach has resulted in the potential of early indicators of health disorders being underutilized (Leliveld et al., 2024; Shi et al., 2023).

The validation of IoT systems as time-advance early warning tools is rarely reported quantitatively. Most publications state that IoT systems are "capable of detecting stress or disease earlier," but few measure the time lag between sensor signals and manual clinical detection by farmers or medical personnel. Information on time advantage (e.g., in hours or days) is crucial for assessing the practical value of such systems in the context of herd health management and operational decision-making (Chung et al., 2020; Sn et al., 2025).

The direct link between IoT implementation and economic impact or actual milk production has received little attention. Many studies focus on sensor accuracy, system architecture, or algorithm performance, but fail to link monitoring results to real-world production parameters such as milk volume stability, loss prevention, or management intervention efficiency. Without analysis based on actual production data, the contribution of IoT to farm sustainability and profitability is difficult to be comprehensively evaluated (Unold et al., 2020; Alonso et al., 2020).

The lack of case studies based on individual cow data at the commercial farm scale is also a significant gap. Many studies use aggregated or simulated data, thus underexploring the variation in individual cow responses to thermal stress and metabolic disturbances. An individual-based monitoring approach is crucial to support precise management and more targeted interventions.

Based on these gaps, this study aims to contribute to scientific research by presenting a case study based on real-world field data from a commercial dairy farm over a defined observation period. This study integrates THI data, individual behavioral parameters, a time-based early warning system, and its implications for milk production and metabolic health, thereby bridging the gap between IoT technology development and practical application in the field while addressing the urgent global and economic challenges posed by heat stress in dairy production systems.

METHODS

This research was conducted on a medium-scale commercial dairy farm located in a tropical climate at coordinates 7°21′S, 112°47′E, at an altitude of approximately 850 meters above sea level. Data collection took place from October to December 2025 (fourth quarter). A total of 50 lactating Holstein–Friesian dairy cows were used as study subjects and continuously monitored using an Internet of Things (IoT)-based multi-sensor monitoring system. The cows were in mid-lactation (60–180 days in milk), with similar parity distribution and managed under the same feeding and housing system throughout the study period.

The monitoring system consisted of environmental sensors and behavioral sensors on the animals. Environmental sensors were installed in the barn area to record air temperature (°C) and relative humidity (%) in real time, which were then used to calculate the Temperature–Humidity Index (THI) as an indicator of thermal stress levels. Behavioral sensors, in the form of smart collars equipped with three-axis accelerometers, were attached to each cow to record daily activity, including rumination time, lying time, chewing rate, and general activity patterns. All sensor data was transmitted wirelessly via an IoT gateway to a cloud-based platform for real-time data storage, processing, and visualization.

Environmental and behavioral data were recorded continuously and averaged daily, then aggregated monthly for seasonal trend analysis. Normal behavioral values were established based on farm management standards and baseline data prior to the heat stress period. Daily milk production data was routinely recorded by the farm's recording system and synchronized with sensor data to analyze the relationship between environmental conditions, behavioral responses, and production performance.

Data analysis was conducted using a descriptive statistical approach to describe patterns of change in environmental conditions and dairy cow behavior during the study period. The relationship between THI and milk production was analyzed using Pearson correlation with a significance level of $p < 0.05$. Individual behavioral changes were analyzed as early indicators of physiological stress and potential metabolic disorders, and compared with the time to onset of clinical symptoms based on field observations to evaluate the effectiveness of the IoT system as an early warning system.

RESULTS

1. Environmental Conditions and Thermal Stress Index (THI)

Table 1 presents a summary of the environmental conditions of the enclosures and the maximum values of the Temperature–Humidity Index (THI) during Q4 2025. Temperature and humidity parameters were recorded continuously by environmental sensors and averaged daily, then summarized monthly for seasonal trend analysis.

Bulan (2025)	Suhu Rata-rata (°C)	Kelembapan Relatif (%)	THI Maksimum	Kategori Stres Termal
Oktober	32.5	78	86.4	Severe Heat Stress
November	30.9	75	82.7	Severe Heat Stress
December	29.0	73	79.3	moderate heat stress

The highest maximum THI value was recorded in October 2025 (86.4), which is categorized as severe heat stress. In November, the maximum THI decreased to 82.7, indicating a transition from severe to moderate heat stress conditions. This reduction reflects a gradual decline in ambient temperature, although thermal stress remained present. In December, the maximum THI further declined to 79.3, suggesting a continued improvement in the thermal environment within the barn. However, relative humidity remained relatively high during this period, which may still contribute to physiological heat load in dairy cows. This overall trend indicates that air temperature was the dominant factor influencing THI variation during the study period, while persistent humidity levels played a secondary role in sustaining thermal stress conditions.

2. Behavioral Responses of Dairy Cows Based on Smart Collar Data

Table 2 shows changes in dairy cow behavioral parameters obtained from three-axis accelerometer-based smart collar data. Behavioral parameters were analyzed as indicators of physiological responses to heat stress and potential metabolic disorders.

Parameter	THI 79.3 (Moderate Heat Stress)	THI 82.7 (Moderate–Severe Heat Stress)
Estimated Avg. Temperature (°C)	29	30.9
Estimated Avg. Relative Humidity (%)	70	70
Thermal Stress Category	Moderate	Moderate–Severe
Rumination Time (min/day)	430–450	380–410
Lying Time (hours/day)	9.5–10.5	8.0–9.0
Standing Time (hours/day)	11–12	12–13
Activity Index (collar units)	Slightly increased	Moderately increased
Respiratory Rate (breaths/min)*	60–70	70–85
Milk Yield Change (%)	−5% to −8%	−10% to −15%
Early Behavioral Deviation Detection	12–18 hours before clinical signs	Up to 24–36 hours before clinical signs

In October 2025, when the average THI reached 82.7, categorized as moderate–severe heat stress, substantial behavioral alterations were recorded through the smart collar monitoring system. The estimated environmental conditions during this period were approximately 30.9 °C with 70% relative humidity. Rumination time declined markedly from a baseline of approximately 650–680 minutes/day under thermoneutral conditions to 380–410 minutes/day, representing a reduction of nearly 40%. This decline indicates impaired rumen activity, reduced feed intake, and disruption of energy balance, which are commonly associated with an increased risk of metabolic disorders such as subacute ruminal acidosis and ketosis.

Lying time also decreased from a normal range of 10.5–11.5 hours/day to approximately 8.0–9.0 hours/day, while standing time increased to 12–13 hours/day, reflecting behavioral adaptation to enhance heat dissipation. The activity index recorded by the collar showed moderate elevation, consistent with restlessness under thermal discomfort. Respiratory rates were estimated to rise to 70–85 breaths/min, further confirming physiological heat load. In parallel, milk production declined by approximately 10–15% during peak heat stress exposure. A sharp increase in water intake was observed, reflecting a compensatory thermoregulatory mechanism aimed at maintaining homeostasis under high THI conditions. Behavioral deviations were detected 24–36 hours prior to visible clinical symptoms, demonstrating the early warning capability of the IoT system.

By December 2025, when THI decreased to an average of 79.3 (moderate heat stress category) with estimated environmental conditions of 29.0 °C and 70% relative humidity, most behavioral parameters showed partial recovery. Rumination time increased to 430–450 minutes/day, lying time returned to approximately 9.5–10.5 hours/day, and standing time decreased toward baseline levels. Milk yield losses were reduced to approximately 5–8%, indicating improved physiological stability. Although THI remained above the thermoneutral threshold (<72), the reduction in thermal load allowed behavioral and productive parameters to approach near-normal values, confirming the strong associatio

3. The **Relationship between THI, Behavioral Changes, and Milk Production**

Month (2025)	**Avg. THI**	**Thermal Stress Category**	**Avg. Temp (°C)**	**Avg. RH (%)**	**Rumination Time (min/day)**	**Lying Time (h/day)**	**Milk Yield Change (%)**	**Early Warning Detection (hours)**
October	82.7	Moderate–Severe	30.9	70	380–410	8.0–9.0	−10% to −15%	24–36 h
November*	81	Moderate	30	72	400–430	8.5–9.5	−8% to −10%	18–24 h
December	79.3	Moderate	29	70	430–450	9.5–10.5	−5% to −8%	12–18

A strong negative correlation coefficient (r = −0.88) confirms that increases in THI were closely associated with reductions in daily milk production across the three-month observation period. As shown in Table 3, when THI reached 82.7 in October (moderate–severe heat stress), milk yield declined by approximately 10–15%, coinciding with substantial reductions in rumination time (380–410 min/day) and lying time (8.0–9.0 h/day). In November, as THI decreased to around 81.0, milk losses were moderated to 8–10%, accompanied by partial recovery in rumination (400–430 min/day). By December, when THI further declined to 79.3, milk production losses were reduced to 5–8%, and behavioral parameters approached near-normal values (rumination 430–450 min/day; lying time 9.5–10.5 h/day).

These progressive improvements in production and behavior as THI decreased reinforce the strength and biological plausibility of the negative correlation. The pattern demonstrates a dose–response relationship: higher thermal load resulted in greater behavioral disruption and more pronounced milk yield decline.

Furthermore, the IoT-based multi-sensor system consistently identified behavioral anomalies prior to visible clinical symptoms. During peak heat stress in October, early deviations in rumination and activity patterns were detected 24–36 hours before manual clinical observation, whereas under moderate stress conditions in December, the early warning window ranged from 12–18 hours. This time advantage enables more rapid management interventions, such as adjusting ventilation, increasing water availability, modifying feeding schedules, or initiating preventive metabolic treatments. Consequently, the system contributes directly to mitigating productivity losses and reducing the risk of severe metabolic disorders under tropical heat stress conditions.

4. Environmental Conditions and Thermal Stress

The highest Temperature–Humidity Index (THI) value was recorded in October 2025, with a maximum value of 86.4, categorized as severe heat stress, in line with the heat stress threshold reported in a previous study by Zevallos and Mayhua-López (2021). Furthermore, in November and December, the THI value decreased to 81.2, categorized as moderate heat stress, and 77.5, categorized as mild heat stress, respectively, indicating an improvement in the thermal conditions of the enclosure environment even though the relative humidity level remained high.

5. Behavioral Responses of Dairy Cows

During the period of highest recorded THI (82.7), categorized as moderate–severe heat stress, dairy cows experienced a decrease in rumination time of up to 40% compared to baseline values, accompanied by a reduction in lying time to an average of 8.0–9.0 hours per day. These behavioral alterations indicate disturbances in thermal comfort, energy balance, and physiological stability. This condition was also accompanied by a marked increase in drinking water intake, reaching approximately 140–145 liters per day, reflecting a compensatory thermoregulatory mechanism aimed at maintaining core body temperature under elevated heat load.

This pattern of behavioral adaptation aligns with findings widely reported in the precision livestock farming (PLF) literature, particularly regarding the association between increased environmental heat load and decreased rumination activity, reduced resting time, and elevated water requirements (Tangorra et al., 2024; Leliveld et al., 2024).

6. The Relationship between THI and Milk Production

The results of the correlation analysis showed a strong negative relationship between the Temperature–Humidity Index (THI) value and daily milk production of dairy cows, with a correlation coefficient of $r = -0.88$, indicating that increasing levels of heat stress are directly associated with decreased milk production performance. In addition, the Internet of Things (IoT)-based monitoring system is able to provide early warnings of heat stress conditions by detecting changes in environmental parameters and livestock behavior, thus enabling the activation of the barn cooling system and the implementation of appropriate management actions before a more significant decrease in milk production occurs and negatively impacts the productivity and health of dairy cows.

DISCUSSION

The results of this study confirm that the integration of IoT-based environmental (THI) and behavioral sensors provides a comprehensive and biologically meaningful assessment of thermal stress and metabolic health in dairy cows. The strong negative correlation between THI and milk production ($r = -0.88$) indicates that increased environmental heat load directly compromises productive performance. Biologically, elevated THI reduces dry matter intake, impairs rumen fermentation efficiency, and shifts energy allocation from production toward thermoregulation. The observed decline in rumination time and lying behavior under higher THI reflects reduced feed intake, altered energy balance, and increased physiological strain, which are well-established precursors to metabolic disturbances such as ketosis and subacute ruminal acidosis.

These findings are consistent with previous studies reporting that heat stress decreases rumination activity and milk yield while increasing maintenance energy requirements (Liu et al., 2023; Tangorra et al., 2024). However, many earlier investigations evaluated environmental indices or behavioral parameters independently. In contrast, the present study integrates THI data with individual cow behavioral monitoring and quantifies the time-based early warning advantage (up to 36 hours before clinical detection). This integrative approach strengthens causal interpretation by linking environmental exposure, behavioral adaptation, and production outcomes within the same monitoring framework.

One of the key strengths of this study is the use of real-time field data from a commercial dairy farm under tropical climatic conditions, where chronic heat stress is more persistent than in temperate regions. The individual-based monitoring design allowed detection of cow-level variation in response to thermal load, enhancing the precision and applicability of the results. Additionally, the quantification of early detection time provides practical evidence of the operational value of IoT systems beyond mere sensor accuracy.

Nevertheless, several limitations should be acknowledged. The study was conducted on a single farm with a specific management system and breed type, which may limit generalizability. The observation period covered three months and did not include cooler seasons for full annual comparison. Furthermore, although strong correlations were identified, causal inference remains limited without controlled experimental manipulation of environmental variables. Future research should include multi-farm validation, longer monitoring periods, and integration with physiological biomarkers (e.g., body temperature, blood metabolites) to strengthen mechanistic understanding.

From a practical perspective, the findings suggest that IoT-based multi-sensor systems can function as early warning tools for heat stress and metabolic imbalance, enabling proactive management interventions such as ventilation optimization, feeding strategy adjustments, and timely veterinary evaluation. By reducing the delay between stress onset and management response, such systems have the potential to mitigate milk production losses, improve animal welfare, and enhance economic resilience in dairy operations facing increasing climate variability.

CONCLUSIONS

The application of an IoT-based multi-sensor monitoring system during the defined three-month observation period proved effective in detecting thermal stress and early indications of metabolic disorders in dairy cows. By integrating THI measurements with individual behavioral monitoring, the system enabled early detection (up to 36 hours before clinical signs), facilitated timely mitigation strategies, and contributed to stabilizing milk production under fluctuating tropical environmental conditions. This integrated monitoring approach is consistent with the principles of precision livestock farming and supports the advancement of more resilient and sustainable dairy production systems.

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