



An Integrated IoT Architecture for Smart Dairy Goat Farming and Nutrient Fortification Control

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ABSTRACT

The rapid development of the Internet of Things (IoT) has enabled the transformation of conventional agricultural practices into intelligent and data-driven production systems. However, IoT adoption in dairy goat farming remains limited, particularly in small- and medium-scale operations, and is often restricted to monitoring functions without integration into downstream processing systems. This study proposes and evaluates an integrated IoT architecture for smart dairy goat farming and automated nutrient fortification control within a unified cyber-physical framework. The architecture consists of multi-layer components, including real-time livestock sensing, wireless data transmission, cloud-based monitoring dashboards, microcontroller-driven pasteurization control, and programmable nutrient injection mechanisms. A design science research approach was employed, encompassing system requirement analysis, architecture development, prototype implementation, and real-world validation. Experimental results demonstrate stable data transmission, accurate environmental and physiological monitoring, precise temperature regulation during pasteurization, and consistent nutrient dosing performance. The integration of monitoring and processing layers enhances operational efficiency, reduces manual intervention, and improves milk quality standardization. The proposed framework transforms traditional dairy goat farming into a scalable, data-driven precision production ecosystem aligned with Industry 4.0 principles. This study contributes a comprehensive technological blueprint for end-to-end smart dairy systems and provides a foundation for future integration with artificial intelligence and blockchain-based supply chain transparency.

Keywords: Internet of Things (IoT); Smart Farming; Dairy Goat Farming; Precision Livestock Farming; Automated Pasteurization; Nutrient Fortification Control; Cyber-Physical Systems; Industry 4.0; Smart Agriculture; Microcontroller-Based Control Systems

Fields: Internet of Things (IoT); Smart Agriculture and Precision Livestock Farming; Cyber-Physical Systems; Embedded Systems and Automation; Agricultural Information Systems; Industry 4.0 Applications in Agribusiness

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SDG's: Zero Hunger (2); Industry, Innovation and Infrastructure (9); Responsible Consumption and Production (12);

INTRODUCTION

The rapid advancement of the Internet of Things (IoT) has transformed traditional agricultural practices into data-driven and intelligent production systems (Choudhary et al., 2025). In the context of livestock farming, IoT technologies enable real-time monitoring of animal health, environmental conditions, and production performance, thereby improving efficiency, sustainability, and decision-making accuracy. Smart farming systems have been widely implemented in dairy cattle operations; however, their adoption in dairy goat farming remains relatively limited, particularly in small- and medium-scale farms in developing regions (Suhardjo et al., 2026).

Dairy goat farming plays a crucial role in supporting local food security and providing alternative protein sources, especially in rural economies (Adesogan et al., 2026). Goat milk is known for its high digestibility and nutritional value, making it suitable for children, the elderly, and individuals with lactose sensitivity. Despite its potential, dairy goat production often faces challenges related to inconsistent milk quality, limited health

monitoring, inefficient feeding practices, and lack of standardized processing systems (Jahrizal et al., 2025). Traditional management approaches rely heavily on manual observation and reactive decision-making, which increases the risk of productivity loss, disease spread, and quality degradation.

The integration of IoT-based monitoring systems into dairy goat farming provides an opportunity to shift from conventional practices toward precision livestock management (Bhaskaran et al., 2024). By deploying environmental sensors (temperature and humidity), physiological sensors (heart rate and health indicators), and production tracking systems, farmers can collect real-time data to optimize feed conversion efficiency, reduce mortality rates, and improve milk yield and quality. However, most existing IoT implementations focus primarily on monitoring and data visualization, without extending the architecture into downstream processing and value-added production systems.

Another critical limitation in current dairy farming technologies is the separation between livestock monitoring and post-harvest milk processing (Upton et al., 2025). Nutrient fortification and pasteurization processes are often conducted manually or semi-automatically, resulting in inconsistent nutritional composition and reduced product standardization. The absence of an integrated system connecting farm-level data with automated nutrient control mechanisms restricts the realization of a fully cyber-physical dairy production ecosystem.

To address these gaps, this study proposes an integrated IoT architecture that connects smart dairy goat monitoring with automated nutrient fortification control (KS et al., 2025). The architecture combines real-time livestock sensing, cloud-based data processing, microcontroller-driven pasteurization systems, and precision nutrient injection mechanisms into a unified framework. This integration enables synchronized monitoring of animal productivity and adaptive control of milk processing parameters, thereby enhancing product quality, operational efficiency, and traceability.

Furthermore, the system is designed to support scalable deployment and potential integration with blockchain-based supply chain transparency and AI-driven predictive analytics (Ahmed & MacCarthy, 2023). By bridging upstream livestock management and downstream milk fortification processes, the proposed architecture contributes to the development of an end-to-end smart dairy ecosystem aligned with Industry 4.0 principles.

This research aims to design, implement, and evaluate the proposed IoT architecture in a real-world dairy goat farming environment (Junaedi et al., 2024). The study examines system performance, productivity improvements, and feasibility for commercialization. The findings are expected to provide a technological blueprint for smart dairy goat farming and contribute to the broader field of intelligent agricultural systems and cyber-physical food production networks.

This study introduces a novel end-to-end integrated IoT architecture that connects smart dairy goat monitoring systems with automated milk pasteurization and precision nutrient fortification control within a unified cyber-physical framework (Renaldo et al., 2025). Unlike existing smart livestock research that primarily focuses on environmental sensing and animal health monitoring, the proposed system extends IoT integration beyond farm-level data acquisition into downstream milk processing and value-added production. By linking real-time livestock productivity data with microcontroller-based pasteurization control and programmable nutrient injection mechanisms, this research establishes a synchronized and adaptive production ecosystem rather than isolated technological components.

Another key novelty lies in the integration of monitoring and processing layers, where farm-generated data are not merely visualized on cloud dashboards but utilized to support semi-adaptive fortification strategies. This coupling between IoT-based animal health and productivity metrics and automated nutrient dosing mechanisms represents a significant advancement over conventional dairy processing systems, which typically operate with static formulations and manual quality control. The system thus transforms traditional dairy goat farming into a data-driven precision production model suitable for small- and medium-scale farms.

Furthermore, this study conceptualizes dairy goat farming as a scalable cyber-physical smart dairy ecosystem aligned with Industry 4.0 principles. The architecture is designed to support future integration with artificial intelligence for predictive analytics and blockchain technologies for supply chain transparency, thereby extending its impact beyond technical automation into digital agribusiness transformation. By bridging upstream livestock management and downstream nutrient fortification within a single interoperable IoT architecture, this research contributes a comprehensive technological blueprint that has not been extensively addressed in prior smart farming literature.

LITERATURE REVIEW

IoT in Smart Livestock Farming

The adoption of the Internet of Things (IoT) in agriculture has significantly accelerated the transformation of traditional farming into intelligent and data-driven production systems (Choudhary et al., 2025). In livestock farming, IoT technologies are widely used to monitor environmental parameters, animal health indicators, and production performance in real time. Sensors measuring temperature, humidity, heart rate, rumination activity, and movement patterns are commonly deployed to detect early signs of disease and optimize feeding strategies. Cloud computing platforms and wireless communication protocols enable continuous data transmission and remote farm management.

Previous studies on smart livestock systems have primarily focused on dairy cattle, where IoT-based monitoring has demonstrated improvements in milk yield prediction, feed efficiency, and disease detection accuracy. However, research on IoT implementation in dairy goat farming remains relatively limited. Goat farming typically operates at small- and medium-scale levels, especially in developing regions, where technological adoption faces constraints related to cost, infrastructure, and technical expertise. As a result, many dairy goat farms still rely on manual observation and conventional management practices.

Existing IoT-based livestock frameworks generally emphasize sensing and monitoring functions, providing dashboards and alert systems for farmers. While these approaches enhance situational awareness and decision-making, they rarely extend beyond farm-level monitoring toward integrated production and processing control. This limitation highlights the need for more comprehensive architectures that integrate upstream livestock monitoring with downstream value-added production processes.

Precision Livestock Farming and Data-Driven Decision Systems

Precision Livestock Farming (PLF) represents an emerging paradigm that leverages sensors, automation, and data analytics to optimize animal production systems (Nyamuryekung'e, 2024). PLF systems aim to improve animal welfare, reduce operational costs, and increase production efficiency through continuous monitoring and adaptive management strategies. Data collected from sensors are analyzed to detect anomalies, predict health risks, and adjust feeding regimes.

Recent advancements in machine learning and predictive analytics have further strengthened PLF frameworks by enabling pattern recognition and early disease detection. However, most PLF implementations are designed to support decision-making at the management level rather than directly controlling downstream processing systems. In other words, data-driven insights are often separated from automated actuation mechanisms within the milk processing stage.

In dairy production contexts, maintaining consistent milk quality requires not only accurate monitoring of livestock health but also standardized post-harvest processing systems. The absence of integration between precision livestock data and automated processing control reduces the overall efficiency of smart farming ecosystems. Therefore, bridging monitoring systems with automated control systems remains an important research gap.

Automated Pasteurization and Nutrient Fortification Systems

Milk pasteurization and nutrient fortification processes are essential components of dairy value chains (Dash et al., 2022). Conventional pasteurization systems rely on controlled heating processes (e.g., high-temperature short-time methods) to eliminate pathogens while preserving nutritional quality. In small-scale dairy operations, pasteurization is often conducted using semi-automatic equipment with limited temperature stabilization mechanisms, leading to variability in product quality.

Nutrient fortification, such as the addition of vitamins and minerals, is commonly implemented to enhance the functional value of dairy products. However, fortification processes are frequently performed using fixed formulations without dynamic adjustment based on raw milk quality or production conditions. Microcontroller-based dosing systems have been explored in food processing industries, yet their integration with real-time livestock monitoring data remains underdeveloped.

Most existing research treats pasteurization control and fortification systems as standalone engineering solutions. Limited attention has been given to designing integrated architectures that connect farm-level sensor data with automated nutrient injection mechanisms in a synchronized and adaptive manner.

Cyber-Physical Systems and Industry 4.0 in Agriculture

The concept of Cyber-Physical Systems (CPS) has gained prominence in Industry 4.0, where physical processes are tightly integrated with computational intelligence and networked communication infrastructures. In

agriculture, CPS enables the interaction between sensors, actuators, data analytics platforms, and automated control mechanisms to create smart and autonomous production systems.

Smart agriculture frameworks increasingly incorporate cloud computing, edge computing, artificial intelligence, and blockchain technologies to enhance traceability, transparency, and predictive capabilities. Blockchain-based supply chain systems, for instance, provide immutable transaction records that improve consumer trust and product authenticity verification. Meanwhile, AI-driven analytics support predictive maintenance and production optimization.

Despite these advancements, many agricultural IoT systems remain fragmented, focusing either on monitoring, analytics, or supply chain management independently. The development of an end-to-end cyber-physical dairy ecosystem that integrates sensing, processing control, and digital commercialization remains an emerging research frontier.

Research Gap

Based on the existing literature, several gaps can be identified:

1. Limited implementation of integrated IoT architectures specifically tailored for dairy goat farming.
2. Separation between livestock monitoring systems and automated milk processing mechanisms.
3. Lack of synchronization between real-time productivity data and nutrient fortification control.
4. Minimal integration of cyber-physical production systems with scalable Industry 4.0 frameworks in small- and medium-scale dairy operations.

Addressing these gaps requires a holistic architecture that connects real-time livestock sensing, cloud-based data processing, microcontroller-driven pasteurization, and precision nutrient injection within a unified IoT framework. The present study seeks to contribute to this emerging domain by designing and evaluating an integrated IoT architecture for smart dairy goat farming and nutrient fortification control.

METHODOLOGY

This study adopts a design science research approach to develop and evaluate an integrated IoT architecture for smart dairy goat farming and nutrient fortification control. The research methodology consists of four main stages: system requirement analysis, architecture design, prototype development, and experimental validation (Junaedi et al., 2026). In the initial stage, field observations and interviews were conducted with dairy goat farmers to identify operational challenges related to livestock monitoring, milk quality control, and processing inefficiencies (Hutahuruk et al., 2026). These findings were used to define system specifications, including sensor selection, communication protocols, data processing requirements, and control parameters for pasteurization and nutrient injection mechanisms.

In the architecture design phase, a multi-layer IoT framework was constructed, consisting of a sensing layer, network layer, cloud processing layer, and actuation layer. The sensing layer includes environmental sensors (temperature and humidity) and physiological monitoring sensors to collect real-time livestock data. Data transmission is facilitated through a microcontroller-based gateway connected to a wireless communication module, enabling real-time synchronization with a cloud-based dashboard. The processing layer utilizes cloud computing infrastructure for data storage, visualization, and rule-based decision support. The actuation layer integrates a temperature-controlled pasteurization unit and a programmable nutrient dosing system operated by microcontroller-based control logic to ensure precise thermal regulation and nutrient injection.

Prototype development involved assembling sensor nodes, configuring the microcontroller unit, developing the cloud dashboard interface, and implementing the control algorithms for automated pasteurization and fortification. The pasteurization system was calibrated to maintain stable temperature control (e.g., high-temperature short-time standards), while the nutrient injection mechanism was programmed to deliver predetermined dosages with adjustable parameters. System integration testing was performed to ensure synchronization between monitoring data and processing control components.

Experimental validation was conducted in a real-world dairy goat farming environment over a defined observation period. System performance was evaluated based on data transmission stability, sensor accuracy, temperature control precision, nutrient dosing consistency, and improvements in production indicators such as milk yield and quality stability. Descriptive statistical analysis was applied to compare operational conditions before and after system implementation. Additionally, feasibility assessment was performed by analyzing scalability, operational efficiency, and potential economic viability for small- and medium-scale dairy farms.

Through this structured methodology, the study aims to validate the technical performance and practical applicability of the proposed integrated IoT architecture within a cyber-physical smart dairy production ecosystem.

RESULTS AND DISCUSSION

Result

The implementation of the proposed integrated IoT architecture was successfully conducted in a real-world dairy goat farming environment. The system operated continuously during the observation period, enabling real-time monitoring of livestock conditions and automated control of pasteurization and nutrient fortification processes. The results are presented based on system performance evaluation, processing control accuracy, and production-related improvements.

From a system performance perspective, the IoT sensing layer demonstrated stable data acquisition and transmission throughout the testing period. Environmental sensors consistently captured temperature and humidity data with minimal fluctuation, while physiological monitoring sensors provided continuous livestock health indicators. The microcontroller-based gateway successfully transmitted data to the cloud dashboard with low latency and no significant packet loss during normal network conditions. The cloud interface enabled real-time visualization and remote monitoring, allowing farmers to respond more quickly to abnormal conditions compared to manual observation practices.

In terms of control system performance, the automated pasteurization unit maintained stable temperature regulation within the predefined range for high-temperature short-time processing. Temperature deviation remained within an acceptable tolerance margin, ensuring consistent thermal treatment of the milk. The programmable nutrient injection mechanism delivered precise dosing according to configured parameters, with consistent output across repeated production cycles. Synchronization between monitoring data and control mechanisms was successfully achieved, demonstrating the interoperability of sensing and actuation layers within the integrated architecture.

Operational evaluation indicated improvements in farm management efficiency after system deployment. Real-time monitoring reduced response time to potential livestock health disturbances, minimizing production disruptions. Feed efficiency optimization and environmental control contributed to improved milk yield consistency during the observation period. Additionally, the automation of pasteurization and fortification processes reduced manual intervention and variability in nutritional composition, enhancing product standardization.

From a system integration standpoint, the architecture successfully functioned as a cyber-physical production system, linking upstream livestock monitoring with downstream milk processing control. The modular structure of the framework supports scalability and potential integration with advanced analytics or blockchain-based traceability modules. Preliminary feasibility assessment suggests that the system is technically viable for small- and medium-scale dairy goat farms, with potential for commercialization and replication.

Overall, the results demonstrate that the proposed integrated IoT architecture effectively enhances monitoring accuracy, processing precision, and operational efficiency, supporting the transformation of traditional dairy goat farming into a data-driven smart production ecosystem.

Discussion

The results demonstrate that the proposed integrated IoT architecture successfully bridges the gap between livestock monitoring and automated milk processing, addressing limitations identified in prior smart farming studies. While existing IoT-based livestock systems predominantly focus on real-time sensing and dashboard visualization, this research extends the functionality toward synchronized actuation in the downstream processing layer. This integration confirms that IoT frameworks in agriculture can evolve from passive monitoring tools into active cyber-physical production systems.

From a technical standpoint, the stability of data transmission and the precision of temperature control validate the reliability of the multi-layer IoT architecture. The minimal latency and consistent synchronization between sensing and actuation layers indicate that microcontroller-based gateways combined with cloud processing can effectively support real-time agricultural operations. These findings align with Industry 4.0 principles, where interoperability and system integration are central to smart manufacturing and smart agriculture ecosystems.

The automated pasteurization and nutrient dosing mechanisms represent a significant advancement compared to conventional small-scale dairy operations. In traditional systems, variability in heating temperature and manual fortification often results in inconsistent product quality. The controlled thermal regulation and programmable nutrient injection observed in this study demonstrate that precision control can be achieved without industrial-scale infrastructure. This suggests that small- and medium-scale farms can adopt affordable automation technologies to enhance product standardization and competitiveness.

Moreover, the integration of livestock productivity data with processing control introduces a semi-adaptive production model. Rather than operating monitoring and processing systems independently, the architecture allows farm-level data to inform processing parameters. This interconnected approach enhances operational coherence and reduces inefficiencies caused by fragmented system designs. Such synchronization has been underexplored in prior precision livestock farming literature, where decision support systems are typically not directly linked to automated production mechanisms.

From a managerial perspective, the reduction in response time to livestock health disturbances and the improved consistency in milk quality highlight the practical benefits of real-time data-driven management. The system supports proactive decision-making, minimizing risks associated with delayed interventions. Furthermore, by conceptualizing dairy goat farming as a scalable cyber-physical ecosystem, this study extends the discourse beyond technical automation toward digital agribusiness transformation.

The architecture's modular design also enables future integration with artificial intelligence for predictive analytics and blockchain for supply chain transparency. This forward-compatible design strengthens the long-term sustainability and scalability of the system. However, challenges remain regarding infrastructure readiness, farmer digital literacy, and initial investment costs, particularly in rural contexts. Addressing these challenges will be critical for broader adoption.

Overall, the findings confirm that integrating IoT-based livestock monitoring with automated pasteurization and nutrient fortification control enhances technical precision, operational efficiency, and production standardization. The study contributes to the evolution of smart agriculture by demonstrating that end-to-end system integration is both technically feasible and practically beneficial for small- and medium-scale dairy goat farming operations.

CONCLUSION

Conclusion

This study developed and validated an integrated IoT architecture for smart dairy goat farming and automated nutrient fortification control within a unified cyber-physical framework. The results demonstrate that the proposed system successfully integrates real-time livestock monitoring, cloud-based data processing, microcontroller-driven pasteurization control, and programmable nutrient injection mechanisms into a synchronized production ecosystem. The architecture operated reliably in a real-world environment, maintaining stable data transmission, accurate temperature regulation, and consistent nutrient dosing performance.

By bridging upstream livestock sensing with downstream milk processing automation, the system transforms traditional dairy goat farming into a data-driven precision production model. The findings confirm that small- and medium-scale dairy operations can adopt scalable IoT solutions to enhance productivity, improve product standardization, and increase operational efficiency. Overall, the study contributes to the advancement of smart agriculture by demonstrating the feasibility of end-to-end IoT integration aligned with Industry 4.0 principles.

Implication

This research demonstrates that IoT architectures in agriculture can evolve beyond monitoring functions into integrated cyber-physical production systems. The successful synchronization of sensing, cloud processing, and actuation layers highlights the potential of modular IoT frameworks for scalable smart farming applications. The integration model may serve as a technological reference for other livestock and agri-food production systems.

For farm operators, the system supports proactive decision-making through real-time data visibility and automated control mechanisms. Improved milk quality consistency and reduced manual intervention may enhance competitiveness and market trust. The architecture also opens opportunities for digital traceability and value-added product strategies.

The framework aligns with digital transformation agendas in agriculture and rural development. Policymakers and agritech developers may utilize this model to promote smart farming adoption among small- and medium-scale producers, supporting food security and technological inclusivity.

Limitation

Despite its contributions, this study has several limitations. First, the experimental validation was conducted within a limited operational environment and observation period, which may restrict the generalizability of results across different farm scales and climatic conditions. Second, the nutrient fortification mechanism operates under semi-adaptive logic rather than fully AI-driven optimization, limiting dynamic responsiveness. Third, economic analysis was preliminary and did not include long-term cost–benefit evaluation across multiple production cycles. Additionally, infrastructure dependency, such as stable internet connectivity, may pose challenges in rural settings.

Recommendation

To enhance system robustness and scalability, future implementations should incorporate advanced communication protocols with redundancy mechanisms to ensure reliability under unstable network conditions. Optimization of the nutrient injection algorithm using adaptive control models may further improve precision. Stakeholder training and user-friendly dashboard interfaces are also recommended to increase adoption among farmers with varying levels of digital literacy. Furthermore, comprehensive techno-economic feasibility studies should be conducted to strengthen commercialization pathways.

Future Research

Future research may extend this architecture in several directions. First, integration of artificial intelligence and machine learning algorithms could enable predictive health analytics and dynamic nutrient optimization based on real-time milk composition data. Second, blockchain integration may be explored to enhance supply chain transparency and product traceability from farm to consumer. Third, comparative multi-site studies across different geographic and climatic contexts would strengthen external validity. Finally, the development of fully autonomous closed-loop control systems combining IoT sensing, AI analytics, and automated actuation represents a promising direction toward next-generation smart dairy ecosystems.

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