

Nanomaterial-Based Environmental Sensors Integrated with PLC Control for Smart Livestock Farming Applications

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Abstract: In the context of agricultural digital transformation, this study proposes a PLC-based smart livestock management system that integrates multi-gas environmental sensing, automated control, and cloud-based monitoring within a unified architecture. The system employs a wireless sensor network to simultaneously monitor temperature, humidity, light intensity, wind speed, and key gases (O₂, CO, CO₂, and NH₃), enabling comprehensive assessment of barn microclimate conditions. Sensor data are processed in real time by a Programmable Logic Controller (PLC) to execute automatic and semi-automatic control of ventilation, cooling, lighting, and roof mechanisms, ensuring stable and safe environments for livestock. The use of nanomaterial-based sensing elements enhances gas sensitivity and response time, improving microclimate regulation accuracy compared with conventional sensors. A cloud-connected platform further enables remote monitoring, data storage, scenario-based operation, and real-time alerts via web and mobile applications. The system was experimentally deployed in a commercial poultry farm in Hung Yen, Vietnam, demonstrating improved environmental stability, reduced labor demand, and increased poultry survival rates. These results confirm the novelty, feasibility, and scalability of the proposed nanomaterial-PLC integrated approach.

Keywords: nanomaterial-based sensors; sensing performance; microclimate stability; Programmable Logic Controller; Smart control

1. Introduction

The rapid shift of agriculture toward automation and digitalization has driven the development of smart livestock farming systems, where maintaining a stable barn microclimate is crucial for animal health, productivity, and survival. Recent advances in sensing technologies and industrial automation enable effective real-time monitoring and control of environmental parameters, helping reduce costs, mitigate disease risks, and improve production efficiency. Advanced approaches based on artificial intelligence, computer vision, and data analytics have been explored for disease detection, behavior analysis, and productivity optimization [1–4]. Despite their analytical potential, such solutions often involve high computational complexity and significant investment costs. Meanwhile, livestock farming continues to face challenges related to labor shortages and the need for continuous, high-precision environmental management. Manual monitoring of temperature, humidity, light, and air quality is time-consuming and unreliable, leading to inefficient control of ventilation, cooling, and roofing systems. To address these issues, PLC-based automation has emerged as a reliable and practical solution [5]. Owing to their stability, flexibility, and ease of programming, PLCs are widely applied in industrial and agricultural automation [6–8]. However, most existing PLC-based systems focus on production processes and lack integrated environmental sensing for comprehensive microclimate control. To bridge this gap, this study develops a PLC-based livestock management system integrating wireless communication and cloud computing [8,9]. Unlike AI-intensive or cloud-centric solutions, the proposed architecture emphasizes robustness, cost-effectiveness, and long-term operation under real farm conditions. Furthermore, recent advances in nanomaterial-based sensors significantly enhance sensitivity and response speed, enabling accurate detection of microclimate variations and gas concentrations critical to livestock health and productivity.

2. Design

The PLC functions as the core controller of the system, collecting real-time data from distributed environmental sensors, processing control algorithms locally, and directly actuating farm equipment such as ventilation fans, cooling systems, lighting, and roof mechanisms. In this system, the PLC was chosen over conventional embedded controllers due to its ability to handle multiple industrial sensors and actuators with high immunity to environmental interference. The PLC supports modular input/output expansion, robust communication with Human–Machine Interface (HMI) devices, and seamless integration with cloud platforms, while maintaining autonomous local control in the event of network disruptions. This industrial-grade architecture ensures deterministic real-time control, which is essential for maintaining stable microclimate conditions in livestock environments.

2.1. System model

The livestock farm management system model is designed according to a layered architecture, integrating Internet of Things (IoT) technology and cloud computing to optimize monitoring and control [10], [11]. Recent studies highlight both the current applications and challenges of IoT in agriculture [12] as well as the critical aspects of security and privacy in industrial IoT (IIoT) environments, which must be considered when deploying such smart livestock systems [13]. The system includes three main layers: the sensor and actuator layer, the local control layer, and the cloud layer (Cloud) [14]. From a materials engineering perspective, the sensing layer of the proposed system benefits from recent advances in nanomaterial-based sensors. Compared to conventional sensors, nanostructured materials offer higher sensitivity, faster response, and improved stability under harsh livestock conditions. These characteristics enable more accurate detection of microclimate variations and toxic gases, thereby enhancing the effectiveness of PLC-

based automatic control. Some large-scale farm application models have also shown significant reductions in operating costs, mainly due to reduced labor and energy savings, with savings of 30–50% depending on farm conditions [18]. In addition, cloud-based IoT systems have demonstrated the ability to flexibly scale up to tens of thousands of livestock without compromising data stability and response speed [10], [12]. Research on precision livestock farming also confirms that automated models when deployed on a large scale maintain higher control accuracy than semi-automated models, especially in temperature and toxic gas management [4]. These results create a clear scientific foundation for the application of PLC combined with IoT in livestock farming in Vietnam. From a materials engineering perspective, several environmental sensors used in the proposed system employ nanostructured sensing layers, particularly in gas detection (NH_3 , CO_2 , and CO). Metal-oxide semiconductor and nanomaterial-based sensing elements provide higher sensitivity, faster response time, and improved stability under high humidity and dust conditions typically found in livestock barns. These material advantages enhance the accuracy and reliability of microclimate monitoring, enabling the PLC to execute timely and precise control actions. The integration of nanomaterial-based sensors therefore plays a critical role in improving the overall performance and practical applicability of the proposed smart livestock system.

2.2. The system layers

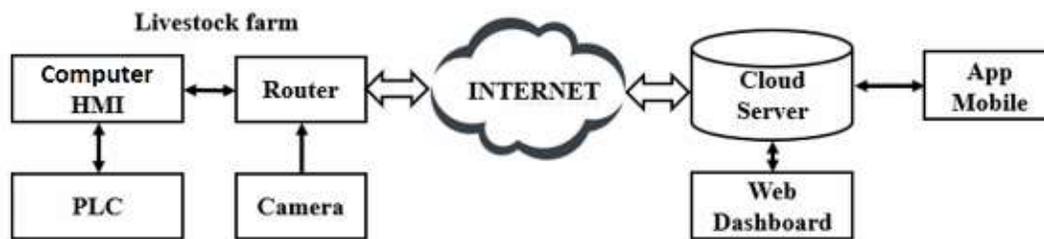


Figure 1. PLC data transmission system model

Sensor and actuator layer: This is the physical layer, directly collecting data and executing control commands. Smart sensors are placed throughout the barn to collect microclimate parameters such as temperature, humidity, light, wind speed, along with concentrations of toxic gases such as O_2 , CO , CO_2 and NH_3 [15]. The actuators include ventilation fans, sprinklers, lighting, and roof cooling systems, which are automatically activated based on sensor data analysis.

Local control layer Programmable Logic Controller (PLC): In addition, the use of a modular PLC-based design allows flexible expansion or replacement of sensors and actuators without requiring major changes to the overall system architecture. This design characteristic is particularly advantageous for livestock farms, where operational conditions and production scale may change over time. Consequently, the proposed PLC-centered system supports gradual technological upgrading while maintaining system reliability and minimizing maintenance complexity [16]. The PLC performs automatic control tasks based on pre-programmed algorithms and set threshold values. The PLC functions as the central on-site control unit, performing real-time data processing and deterministic control of actuators. Its industrial-grade robustness allows continuous operation in harsh livestock environments, while autonomous local control ensures system stability even during temporary network disruptions. The PLC also has the task of communicating with the Human Machine Interface (HMI) screen to display the status and allow the user to manually control on-site.

Cloud layer: This layer receives data from the PLC through network devices and transmits it to the cloud server

[17]. The data is then stored and analyzed to provide overview information, data history, and in-depth reports [18]. The user interface on the web dashboard and mobile application is connected to the cloud server, allowing the farm manager to conveniently monitor and control the system remotely. In the Figure 1, the cloud layer also integrates advanced functions such as real-time alerts via Short Message Service (SMS) or email, and big data management to support trend analysis and forecasting. The programmable logic controller (PLC) serves as a microprocessor that executes commands stored in its program memory. It receives input data, processes the program logic, generates the corresponding output, and transmits control signals directly to actuators to perform the desired actions. This workflow ensures seamless processing from input to output within the automated system. PLC has a functional block diagram as shown in Figure 2.

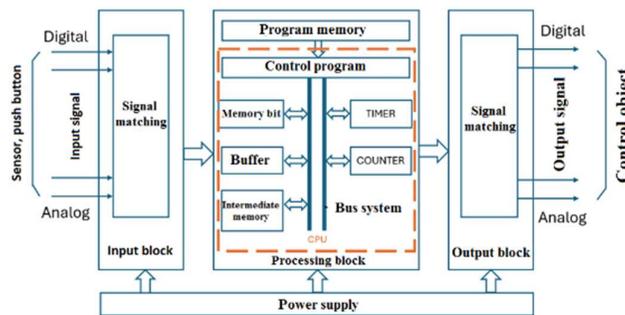


Figure 2. Functional block diagram of PLC

2.3. System design block diagram at the farm

This diagram describes a closed automatic control system, in which the PLC plays a central role in collecting data, processing and controlling devices based on measurement parameters from sensors and pre-programmed programs (Figure 3). This system can be monitored and controlled remotely via the Internet, helping to increase the efficiency and reliability of the production or operation process. Environmental parameter signals at the barn are collected by smart sensors and transmitted to the PLC. The PLC processes the information displayed on the HMI screen and transmits it to the router to transmit to the server via the internet. Information from the server network on the internet is transmitted to the PLC to control electrical devices such as fans, water pumps, humidifiers, etc. through contactors.

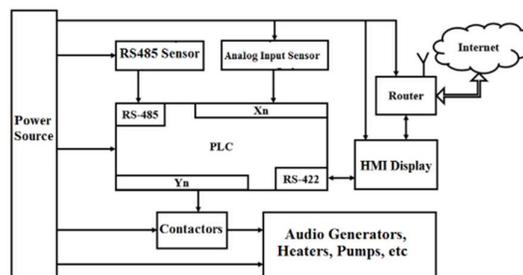


Figure 3. Monitoring and control system at the farm

2.4. Diagram of automatic monitoring and control system for chicken farms

Figure 4 is a diagram of the automatic monitoring and control system including hardware and software. The hardware is the system that collects data and controls devices including: Global System for Mobile Communications (GSM) positioning sensor, O₂, CO, CO₂, NH₃ gas sensor. The system controls the

surveillance camera, ventilation fan, warning siren system, heating device, humidifier, water pump to cool the roof of the barn, motor to pull the canopy, lower the canopy when needed. The control software operates in two modes, manual mode and automatic mode (Figure 5).

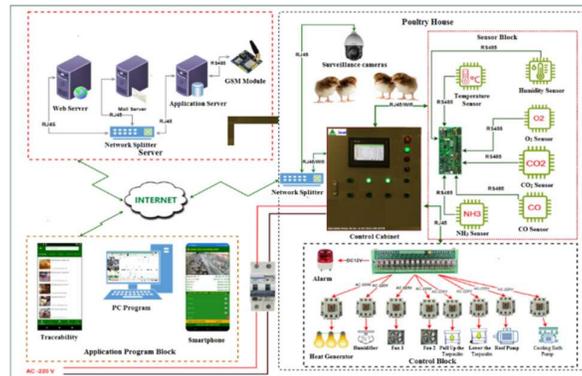


Figure 4. Diagram of the automatic monitoring and control system of the chicken farm

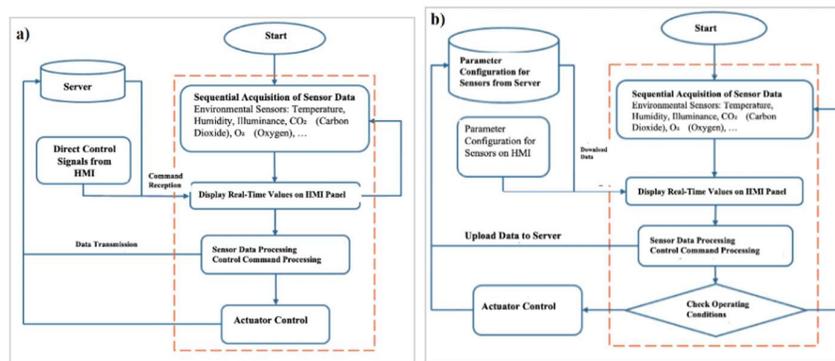


Figure 5. Algorithm diagram for the controller

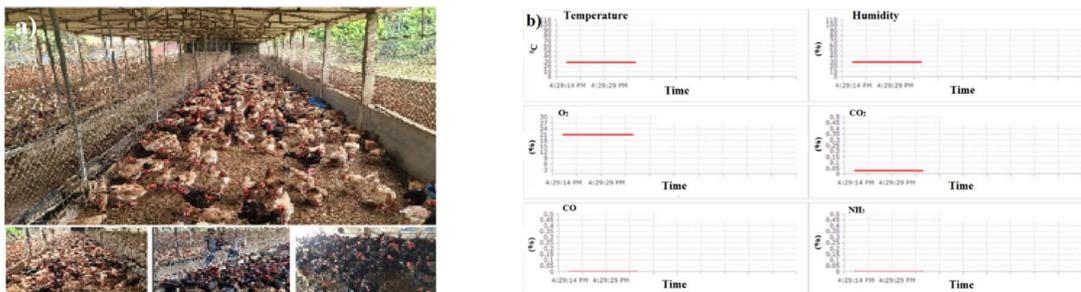


Figure 6. Main screen of the software on the computer

With manual control mode, you can operate directly on the HMI screen or on the Web Dashboard and Mobile App. As for automatic mode, depending on the scenario of each different livestock farm, the appropriate sensor parameters will be set. According to the above algorithm diagram, if the current sensor value is equal to or reaches the allowable threshold compared to the set parameter value, this case is correct and the program ends. Conversely, if the current measured sensor values do not satisfy the conditions with the set parameters, the program executes the control commands of the actuator to change the environmental conditions back to the state according to the set scenario. The server-side software uses the communication between the controller and the sensors protocol to communicate with other functional blocks in the system, which is responsible for managing devices and processing data from sensors, providing a user interface for farm managers, performing automatic functions based on sensor data

analysis, and promptly issuing real-time alerts (Figure 6). Support block: Includes functions on system introduction; user manual; software copyright; online support. The software on the phone has an interface as shown in Figure 7. The user can monitor and control the list of barns of the registered farm. At the barn monitoring and control interface, the user can control ON/OFF of peripheral devices (humidification, heating, turning on/off the fan, pulling/lowering the roof, etc). Or switch to automatic monitoring mode, controlling according to the scenario.

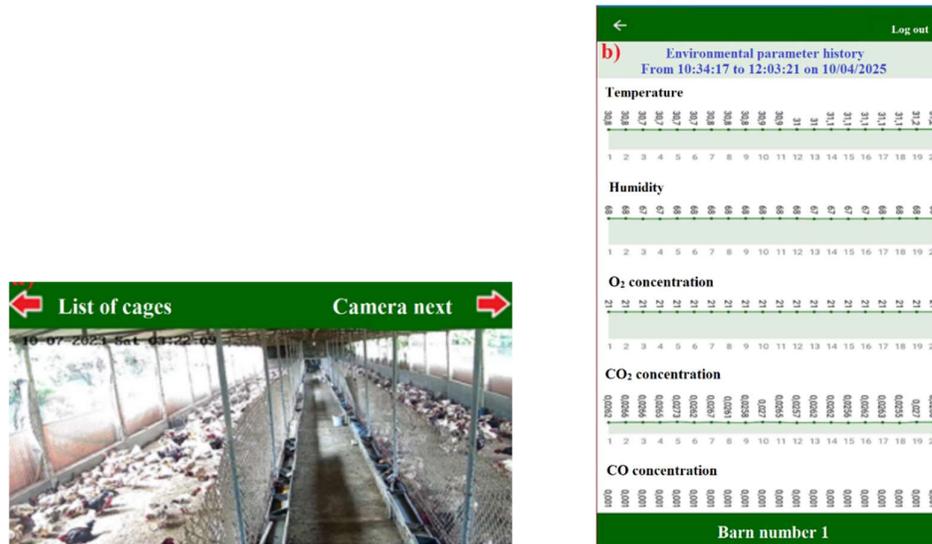


Figure 7. Main screen of the software on the phone

Experimental deployment and sensor calibration: The system was operated continuously over a complete poultry production cycle, allowing evaluation of system stability, robustness, and control effectiveness under real farming conditions. This long-term deployment ensured that the reported performance indicators reflect practical operation rather than short-term laboratory testing. The proposed PLC-based control system was deployed in a commercial poultry farm located in Kim Dong district, Hung Yen province, Vietnam. The experimental setup consisted of one closed-type poultry house with a capacity of approximately 10,000 broiler chickens. Prior to deployment, all environmental sensors (temperature, humidity, O₂, CO, CO₂, and NH₃) were calibrated using manufacturer-recommended procedures and cross-checked with reference measuring devices to ensure acceptable accuracy. The calibration process was conducted before the start of the experiment and periodically verified during operation to minimize measurement drift. The experimental design emphasizes applied validation rather than laboratory-scale testing, ensuring that the reported results reflect realistic operational constraints and long-term system behavior.

2.5. Nanomaterial-Based Environmental Sensors

The environmental monitoring system employs nanomaterial-based sensors for temperature, humidity, and gas detection. Compared to conventional sensing elements, nanomaterial-based sensors offer enhanced sensitivity due to their high surface area and improved adsorption–desorption dynamics. Metal oxide nanostructures and carbon-based nanomaterials are particularly effective in detecting low-concentration gases and microclimate variations, which are critical parameters in livestock environments. The sensing units employed in this study are based on nanomaterial-enhanced sensing layers, which play a critical role in improving detection sensitivity and response stability under harsh livestock farming

conditions. At the nanoscale, the large specific surface area and high density of active sites facilitate effective adsorption–desorption processes between target gases and the sensor surface, leading to measurable changes in electrical conductivity. Compared to conventional bulk-material sensors, nanomaterial-based sensors exhibit faster response and recovery times, as well as improved signal stability under continuous operation. These characteristics are particularly advantageous for long-term environmental monitoring in large-scale poultry houses, where temperature, humidity, and gas concentrations fluctuate dynamically. The integration of nanomaterial-based sensors with PLC-controlled data acquisition ensures reliable real-time monitoring while preserving the intrinsic sensing advantages provided by nanostructured materials.

3. Results and Discussion

This high-tech livestock management system is designed to not only automate processes but also ensure the highest level of continuity, safety and efficiency of operations.

3.1. Continuous Operation and Data Security

The first highlight of the system is the ability to operate in real time, ensuring that all reactions to the barn environment are instantaneous, without delay. The ability to automatically reconnect is an important layer of protection. When a temporary loss of connection occurs with the communication between the controller and the sensors server or software, the system will automatically restore, ensuring the continuity of the control process. This helps prevent potential problems such as water shortages or sudden temperature changes, which can cause stress or disease in livestock. This is a key factor to protect information transmitted between devices and servers, preventing the risk of leakage or theft of important farm data, such as production data or livestock information. This level of security creates absolute trust for users, especially in the context of data becoming a valuable asset of businesses

3.2. In-depth Data Analysis and Decision Support

The system not only collects but also turns data into useful information. With the integration of a Database or backend system, all environmental parameters are systematically stored and analyzed. The management software supports the creation of in-depth reports and graphs, giving managers an overview of the development of the farm over time. These data analyses allow managers to identify trends, evaluate the effectiveness of care processes, and make data-driven decisions instead of traditional experience. For example, analyzing historical temperature and humidity can help optimize the on/off time of fans or cooling pumps, saving energy while still ensuring ideal living conditions for livestock.

3.3. Multi-layered Warning and Control System

The performance indicators presented in Table 1 were obtained by comparing the experimental production cycle using the proposed PLC-based system with historical data from the same farm operating under conventional manual control. This comparison approach minimizes the influence of external factors such as farm layout, climate, and management practices, thereby enhancing the reliability of the reported improvements. The system is equipped with multiple layers of warning and automation to ensure absolute safety. The software will immediately alert managers when there is an emergency such as temperature exceeding the threshold, power failure, or lack of water. At the same time, the system will automatically perform corrective actions, such as activating pumps or fans to maintain a stable living environment. Specialized modules help the system operate precisely according to pre-set scenarios, including: Temperature and humidity control: The system automatically maintains temperature from 15°C to 35°C and humidity from 60% to 70% based on the age of the poultry. Improve air quality: Automatically control

ventilation fans to remove toxic gases when CO, CO₂, NH₃ concentrations exceed the allowable level, while maintaining O₂ concentrations at the ideal level. In addition, the surveillance camera system not only supports monitoring development and security but also has the ability to take photos, create a database to trace the origin of food, meeting increasingly high market standards. With the ability to support care for farms with about 10,000 poultry, this system is truly a comprehensive solution, bringing livestock farming to a new level of efficiency and sustainability. Some of the efficiencies of the Programmable Logic Controller (PLC) based automatic system are shown in Table 1.

Table 1. Efficiency table when using automation

Indicators	Traditional Model	PLC	Improvement (%)
Chicken survival rate	87.4%	98.3%	+12.5%
Labor cost/month	12.000.000 VNĐ	6.200.000 VNĐ	48,3%
Leftover feed	8.1%	5.2%	2,9%
Variable temperature	±4°C	±1.5°C	More stable
Variable humidity	±10% RH	±3% RH	More stable

In addition, the high sensitivity of nanomaterial-based sensors enables early detection of microclimate deviations, allowing timely corrective actions. The observed improvements in poultry survival rate, labor cost reduction, and microclimate stability can be directly explained by the deterministic control behavior of the PLC-based system. Unlike manual operation, which depends heavily on human response time and experience, the PLC continuously processes sensor data and executes control actions with consistent timing and accuracy.



Figure 8. Image of ventilation fan system, lighting, surveillance camera, environmental sensors

This mechanism significantly reduces temperature and humidity fluctuations, thereby creating a more stable living environment for poultry. In addition, automated control minimizes unnecessary operation of ventilation and cooling equipment, contributing to reduced energy consumption and labor requirements. These results confirm that the performance gains reported in Table 1 are not incidental but are closely linked to the engineering characteristics of the PLC-based control architecture. The performance improvements reported in Table 1 are primarily attributed to the deterministic and real-time control characteristics of the PLC-based system. Continuous sensor-driven regulation minimizes fluctuations in temperature and humidity, resulting in a more stable microclimate and reduced labor intervention compared to conventional manual operation. Some images of the deployed system are shown in Figure 8 and Table 2. The comparison in Table 2 emphasizes the importance of nanomaterial-based sensors in smart livestock systems. Higher sensitivity and faster response enable early detection of microclimate changes and toxic gas accumulation, allowing the PLC to execute timely and precise control actions. This integration

between advanced sensing materials and industrial-grade control significantly improves system reliability and practical performance under real farming conditions.

Table 2. Comparison between conventional sensors and nanomaterial-based sensors in smart livestock applications

Criteria	Conventional sensors	Nanomaterial-based sensors
Sensitivity	Medium	High
Response time	Slow–moderate	Fast
Detection of low gas concentration	Limited	Excellent
Stability in harsh environments	Medium	High
Suitability for smart livestock systems	Moderate	High

3.4. Comparison with International Studies: System Performance, Cost-effectiveness and Scalability

Compared with previous international studies on PLC and IoT based livestock management systems, the proposed system demonstrates competitive and, in some aspects, superior performance in terms of environmental control accuracy, operational efficiency, and economic benefits. Previous studies have reported improvements of 10–25% in operational efficiency and reductions in labor and energy costs ranging from 30–50%, depending on farm size and system complexity [9,10,14,18]. The results obtained in this study are consistent with these findings, as evidenced by the 12.5% increase in poultry survival rate, nearly 50% reduction in labor costs, and improved microclimate stability compared to traditional manual control models. In terms of system performance, the achieved temperature fluctuation range ($\pm 1.5^\circ\text{C}$) and humidity variation ($\pm 3\%$ RH) are comparable or better than those reported in precision livestock farming systems deployed in large-scale farms in Europe and Asia [4,14]. This indicates that PLC-based control, when combined with real-time sensor networks, can provide high reliability and robustness even under variable environmental conditions. Regarding cost-effectiveness, the use of PLC technology offers a significant advantage over fully cloud-dependent or AI-centric systems reported in recent literature. While advanced AI-based solutions may achieve high analytical accuracy, they often require substantial computational resources and investment costs [3,11]. In contrast, the proposed PLC–IoT architecture balances performance and cost, making it particularly suitable for small- and medium-scale farms in developing countries, while still remaining adaptable to larger industrial farms. Scalability is another important aspect where the proposed system aligns well with international trends. Cloud-based data management and modular PLC design allow the system to be extended from a single barn to multiple barns or farms without major structural changes. Previous studies have demonstrated that IoT-enabled livestock platforms can scale to tens of thousands of animals while maintaining data stability and response speed [10,12]. The architecture presented in this study follows similar principles, suggesting strong potential for deployment across different livestock types (poultry, pigs, dairy cattle) and farm sizes with minimal customization. Overall, this comparative analysis confirms that the proposed system is not only technically feasible but also economically and operationally competitive with existing international solutions. The results support its potential as a scalable and cost-effective model for smart livestock farming, particularly in regions where investment constraints and labor shortages remain critical challenges. It should be emphasized that the objective of the proposed system is not to replace advanced artificial intelligence-based livestock management platforms, but rather to provide a robust and economically viable solution for practical farm deployment. Compared to AI-intensive approaches that require high computational resources and complex system integration, the PLC-based solution prioritizes operational reliability, ease

of implementation, and long-term stability. This design philosophy makes the system particularly suitable for small- and medium-scale farms, where practical feasibility often outweighs algorithmic sophistication. This comparative analysis confirms that the proposed system is not only application-oriented but also scientifically competitive with internationally reported smart livestock solutions.

3.5. Comparison of PLC-Based Control with Alternative Technologies

Table 3. Comparison of control technologies for smart livestock farming

Criteria	PLC-based system	Microcontroller-based system	PC-based system	Cloud-centric IoT system
Real-time determinism	High	Medium	Medium	Low
Environmental robustness	High (industrial grade)	Low–Medium	Medium	Medium
Dependence on internet	Low	Medium	Medium	High
Scalability	High	Medium	Medium–High	High
Initial cost	Medium	Low	High	Medium
Maintenance complexity	Low	Medium–High	High	Medium
Suitability for livestock farms	High	Medium	Medium	Medium

The selection of a control platform significantly affects system reliability, responsiveness, scalability, and overall cost in smart livestock farming. Table 3 compares the proposed PLC-based system with other commonly used control solutions, including microcontroller-based platforms, PC-based control systems, and cloud-centric IoT architectures. PLC-based controllers provide deterministic real-time performance, high immunity to electrical noise, and long-term operational stability, which are essential in harsh livestock environments characterized by dust, humidity, and continuous operation. These advantages are reflected in the stable environmental control achieved in this study, particularly the reduced temperature and humidity fluctuations reported in Table 1. In contrast, microcontroller-based systems offer lower initial costs and greater flexibility for prototyping but often lack industrial robustness and require additional hardware and software layers to achieve comparable reliability. PC-based systems enable advanced data processing but involve higher energy consumption, maintenance complexity, and vulnerability to system crashes. Cloud-only IoT solutions excel in large-scale data analytics and remote access but depend heavily on network stability, which can compromise real-time control in rural farming environments. The experimental results demonstrate that the PLC-based architecture offers an effective balance between performance, reliability, and cost. The observed improvements in poultry survival rate, labor cost reduction, and microclimate stability confirm that the advantages of PLC-based control outweigh its limitations for medium- to large-scale smart livestock farming applications. While cloud-centric systems offer advantages in large-scale data analytics, their dependence on stable network connectivity limits their suitability for real-time environmental control in rural farming environments. The proposed PLC-based architecture effectively addresses this limitation by ensuring continuous and autonomous operation at the farm level.

3.6. Validation and Accuracy of the Experimental Results

The obtained results were validated through sensor calibration, long-term operational monitoring, and comparison with historical farm data and previously reported studies. Prior to deployment, all environmental sensors were calibrated against reference instruments to ensure measurement accuracy within manufacturer-specified tolerance ranges. During operation, sensor readings were continuously

logged and cross-checked to detect abnormal deviations or drift. The performance indicators reported in Table 1 were evaluated by comparing the experimental production cycle with historical records from the same farm under conventional manual control. This approach minimizes the influence of external factors such as farm layout, climate, and management practices, thereby improving the reliability of the comparison. In terms of accuracy, the achieved temperature stability ($\pm 1.5^{\circ}\text{C}$) and humidity variation ($\pm 3\%$ RH) are consistent with or slightly better than those reported in international PLC- and IoT-based livestock control studies, where typical fluctuations range from $\pm 2\text{--}3^{\circ}\text{C}$ and $\pm 5\%$ RH. The observed improvements in environmental stability and system performance are attributed not only to PLC control logic but also to the high-quality sensing data provided by nanomaterial-based sensors. Their enhanced accuracy and rapid response enable more precise and timely control actions. The observed increase in poultry survival rate is also consistent with previously reported improvements of approximately 8–15% following automated environmental control. Overall, the agreement between experimental results, historical farm data, and literature confirms the robustness and practical validity of the proposed system.

4. Conclusion

This study confirms the strong potential of Programmable Logic Controller (PLC)-based systems in transforming traditional livestock farming into a high-technology, automation-oriented model. By integrating IoT solutions and remote monitoring interfaces, the proposed system enables reliable real-time monitoring and control of environmental parameters while improving operational efficiency and economic performance. The user-friendly design allows convenient operation via computers and smartphones, reducing the requirement for specialized technical expertise and supporting wider adoption of automation in livestock farming. The optimized system demonstrates clear benefits in resource efficiency, including reductions in labor demand, energy consumption, and feed and water usage, thereby enhancing productivity and lowering production costs. Importantly, the results show that stable environmental control and operational efficiency can be achieved without relying on complex algorithms or high-cost infrastructure. This application-oriented approach highlights the practical feasibility of deploying industrial automation solutions under real farming conditions. From an engineering perspective, the study provides a reference architecture for PLC-based smart livestock systems that emphasizes robustness, affordability, and scalability. Furthermore, the integration of nanomaterial-based environmental sensors with a PLC-centered control framework significantly improves monitoring accuracy and response reliability. This synergy demonstrates a practical pathway for translating advances in nanomaterials into scalable, reliable, and application-oriented smart livestock farming systems, supporting the gradual digital transformation toward sustainability.

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