Environment and Social Psychology (2024) Volume 9 Issue 10
doi: 10.59429/esp.v9i10.3104

RESEARCH ARTICLE

Application of PID algorithm in temperature control of pig houses farmers' mental health from the perspective of social ecological system and its implications for agricultural production efficiency

Minghai Zeng*, Celso Bation Co

College of Engineering,Batangas State University,The National Engineering University，Alangilan Campus，Batangas City, 4200, Philippines

*** Corresponding author:** Minghai Zeng, 21-07867@g.batstate-u.edu.ph

ABSTRACT

This study investigates the application of PID algorithm-based temperature control systems in pig house environmental management and its impact on agricultural production efficiency. Through field experiments conducted at Dongshun Aquaculture Ecological Development Co., Ltd. in Nanping City, Fujian Province, we evaluated the system's effectiveness in energy efficiency, production performance, and animal health. Results show that the PID system achieved 18.5% energy savings, a 9% increase in daily weight gain, and a 7.1% improvement in feed conversion ratio. Additionally, meat quality scores improved by 8.3%, and disease incidence rates decreased by 21.9%. Economic analysis indicates that the system begins to generate a positive return on investment in the second year, with cumulative benefits reaching 192% within five years. These findings highlight the potential of PID temperature control systems in improving pork production efficiency and sustainability, offering a valuable solution for modern pig farming.

Keywords: PID control; temperature regulation; pig house environment; energy efficiency; production efficiency; animal health; return on investment

1. Introduction

The global pork industry, valued at $236 billion in 2020 and projected to reach $257 billion by 2025[1], faces significant challenges in maintaining optimal environmental conditions for animal welfare and productivity. In China, the world's largest pork producer, the industry contributes approximately 1% to the national GDP[2], underscoring its economic importance. Pig farming, a crucial component of this sector, is particularly sensitive to environmental factors, with temperature being a critical parameter. Studies have shown that temperature fluctuations outside the optimal range of 18-22°C can reduce daily weight gain by up to 13% and increase feed conversion ratios by 9%[3]. Recent advancements in Internet of Things (IoT) technologies have revolutionized environmental monitoring and control systems in agriculture. The agricultural IoT market, expected to grow at a CAGR of 11.4% from 2020 to 2025[4], offers promising solutions for precision livestock farming. Within this context, the application of Proportional-

ARTICLE INFO
Received: 22 September 2024 | Accepted: 30 October 2024 | Available online: 13 November 2024

CITATION
Zeng MH, Bation Co C. Application of PID algorithm in temperature control of pig houses farmers' mental health from the perspective of social ecological system and its implications for agricultural production efficiency. *Environment and Social Psychology* 2024; 9(10): 3104.
doi: 10.59429/esp.v9i10.3104

IntegralDerivative (PID) algorithms in temperature control systems represents a significant leap forward in achieving precise and stable environmental conditions in pig houses.

PID controllers, known for their reliability and adaptability, have demonstrated remarkable efficiency in various industrial applications. In the context of pig farming, PID-controlled environments have shown potential to improve feed conversion rates by up to 7% and reduce mortality rates by 2.5%[5]. The integration of PID algorithms with modern IoT infrastructures and Programmable Logic Controllers (PLCs) creates a powerful synergy, enabling real-time monitoring, data analysis, and automated control of pig house environments[6, 7].

However, the implementation of advanced control systems in agriculture is not without challenges. With initial investment costs ranging from $10,000 to $50,000 for medium-sized farms[8], the economic viability of such technologies is a critical consideration for farmers and agricultural businesses. Therefore, a comprehensive analysis of the technical and economic aspects of PID-based temperature control systems in pig farming is essential[9].

This study aims to bridge the gap between technological innovation and practical application by examining the implementation of PID algorithms in pig house temperature control. By leveraging recent research in agricultural IoT[10, 11], environmental control systems for livestock[12, 13], and advanced control algorithms[14], we seek to contribute to the growing body of knowledge on smart farming technologies. The findings of this research have the potential to significantly influence pig farming practices, offering insights into more efficient, sustainable, and economically viable methods of environmental control in animal husbandry.

Beyond demonstrating improvements in energy efficiency, production performance, and animal health, this study also offers an in-depth analysis of the system’s long-term sustainability and scalability. It examines the PID system’s adaptability under varying climatic conditions and operational scales, highlighting its potential across farms of different sizes and environments. Additionally, the research evaluates the impact on carbon emissions and feed optimization over extended periods, underscoring the system's contribution to sustainable agriculture. These insights position PID technology as a viable solution not only for large-scale industrial farms but also for smaller operations aiming to transition towards smart farming practices.

This paper will explore the design and implementation of a PID-based temperature control system for pig houses, analyze its performance compared to traditional methods, evaluate its economic implications, and discuss its broader impact on agricultural productivity. Through this comprehensive approach, we aim to provide valuable insights for farmers, agricultural engineers, and policymakers in the pursuit of more efficient and sustainable pig farming practices in an industry that is crucial to global food security and economic development.

2. Literature review

2.1. Impact of pigsty environmental factors on production efficiency

The environmental conditions in pig houses play a crucial role in the overall productivity and welfare of pigs. Among various environmental factors, temperature, humidity, and air quality have been identified as the most significant influencers of pig growth and health[17]. Temperature, in particular, has a profound impact on pig performance. Studies have shown that pigs kept outside their thermoneutral zone expend more energy on thermoregulation, leading to reduced feed efficiency and slower growth rates[19]. For instance, research indicates that for every 1°C deviation from the optimal temperature range, daily weight gain can decrease by up to 1.5%[28].

Humidity levels in pig houses also significantly affect pig health and productivity. High humidity can exacerbate heat stress in warm conditions and increase the risk of respiratory diseases. Conversely, low humidity can lead to dry air, causing respiratory irritation and increased dust levels[23]. Air quality, particularly the concentration of gases such as ammonia and carbon dioxide, is another critical factor. Elevated levels of these gases can lead to reduced feed intake, lower growth rates, and increased susceptibility to diseases[39].

The impact of these environmental factors on pig production efficiency is summarized in **Table 1** As shown in the table, maintaining optimal environmental conditions is crucial for maximizing pig growth and minimizing health issues.

Table 1. Impact of environmental factors on pig production efficiency.

Environmental Factor	Optimal Range	Impact on Production
Temperature	18-22°C	±1.5% daily weight gain per 1°C deviation
Relative Humidity	60-70%	Up to 10% reduction in feed intake at >80% RH
Ammonia Concentration	<20 ppm	5% decrease in average daily gain at >20 ppm
Carbon Dioxide	<3000 ppm	3% reduction in feed efficiency at >3000 ppm

Given the significant influence of these environmental factors on pig production, implementing effective control methods is essential for modern pig farming operations. Current research focuses on developing integrated systems that can monitor and regulate multiple environmental parameters simultaneously, thus optimizing the overall pig house environment for maximum productivity and animal welfare[31].

2.2. The temperature control methods of the existing piggery houses and their limitations

Existing temperature control methods in pig houses have evolved significantly over the years, yet they still face several limitations. Traditional approaches primarily rely on natural ventilation systems, which, while cost-effective, offer limited control over temperature fluctuations [24]. These systems often struggle to maintain consistent temperatures during extreme weather conditions, leading to suboptimal pig performance [28].More advanced methods incorporate mechanical ventilation systems, including negative pressure fans and evaporative cooling pads[31]. These systems provide better temperature regulation but can be energy-intensive and may not respond quickly enough to sudden temperature changes. Some farms employ heating systems such as gas or electric heaters, which, while effective in cold climates, can lead to uneven heat distribution and increased operational costs[29].Recent advancements have introduced automated control systems using basic on-off controllers or simple thermostats[34]. While these represent an improvement over manual controls, they often result in temperature oscillations and energy inefficiency. More sophisticated systems utilizing Programmable Logic Controllers (PLCs) have been implemented in some modern pig farms, allowing for more precise control[39]. However, these systems typically use predefined setpoints and lack the ability to adapt to changing conditions dynamically.

The limitations of current methods become apparent in their inability to maintain tight temperature control, especially in large pig houses with varying heat loads[33]. Energy inefficiency is a common issue, with many systems overcompensating for temperature deviations, leading to unnecessary energy consumption[41]. Additionally, most existing systems struggle to integrate multiple environmental parameters effectively, focusing primarily on temperature while neglecting the interplay with humidity and air quality[36].

These limitations highlight the need for more advanced, adaptive control strategies that can provide precise temperature regulation while optimizing energy use and considering other environmental factors. The integration of smart technologies and advanced control algorithms, such as PID controllers, presents a promising direction for overcoming these challenges and improving overall pig house environmental management[42].

2.3. Integration of PID control in precision livestock farming

The use of Proportional-Integral-Derivative (PID) control systems is well-established in industrial applications, but its adoption in agriculture, especially in livestock farming, has recently garnered attention. The growing interest in precision livestock farming (PLF) focuses on integrating IoT-enabled monitoring tools with PID controllers to optimize environmental management. Research by Yeo et al.[15] emphasizes the benefits of using computational fluid dynamics (CFD) simulations to design effective ventilation systems in pig houses, a concept that aligns with the dynamic control offered by PID systems. Studies by Hu et al.[28] and Kim et al.[21] further demonstrate that PID algorithms, when paired with environmental sensors, enhance animal welfare by minimizing heat stress and improving air quality.

The present study builds on these insights by extending the application of PID systems beyond single-factor control (e.g., temperature) to multivariable environmental management, including humidity, ammonia, and CO_2 concentrations. This broader focus addresses a gap identified by Wang et al.[9], who highlight the need for integrated control solutions that consider the interplay between environmental parameters. Incorporating lessons from previous research allows this study to position itself within the growing trend toward adaptive control systems in animal husbandry, offering evidence for how such systems can significantly improve productivity and sustainability.

2.4. Long-term impact of environmental control systems in pig farming

A significant body of literature explores the economic and environmental benefits of environmental control systems in livestock farming. However, most studies focus on short-term outcomes, such as immediate productivity improvements or energy savings. For instance, Jackson et al.[11] found that improved ventilation technologies reduce energy consumption by 15%, but the research was limited to a single season. Similarly, Delsart et al.[24] assessed animal welfare in alternative farming systems, yet the study did not explore how environmental control affects long-term animal health or economic outcomes.

In response to these limitations, the present study offers a comprehensive multi-season analysis, evaluating not only short-term improvements in feed conversion and weight gain but also long-term sustainability metrics such as cumulative energy savings, carbon emissions reduction, and improved herd health. By adopting a longer monitoring period, this research fills an essential gap identified by Saha et al.[7], who called for more longitudinal studies to assess the true impact of environmental control on farm performance.

This emphasis on long-term analysis aligns with the growing focus on sustainable agriculture, as noted by Costantini et al.[26], who highlight the need to reduce livestock emissions while maintaining productivity. The integration of long-term performance monitoring provides a more nuanced understanding of the cumulative benefits of PID systems, reinforcing their importance in achieving sustainable intensification in pig farming.

3. Methodology

3.1. Principles of the PID algorithm and its advantages in temperature control

The Proportional-Integral-Derivative (PID) algorithm is a sophisticated control mechanism widely employed in industrial processes, including temperature regulation systems for pig houses. This advanced control strategy continuously calculates an error value $e(t)$ as the difference between a desired setpoint and the measured process variable, applying a correction based on proportional, integral, and derivative terms[15]. The control output $u(t)$ is mathematically expressed as:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}$$

where K_p, K_i, and K_d represent the proportional, integral, and derivative gains, respectively.

In the context of pig house temperature control, PID algorithms offer numerous advantages. The proportional term provides an immediate response to temperature deviations, the integral term eliminates persistent steady-state errors, and the derivative term anticipates future errors based on the rate of change[31]. This synergistic combination allows for rapid response to disturbances, minimal temperature overshoot, and stable long-term temperature maintenance.

PID controllers excel in pig house environmental management due to their adaptability to varying conditions. They can effectively handle the complex thermal dynamics of pig houses, accounting for multifaceted factors such as animal heat production, ventilation rates, and external weather fluctuations[33]. The algorithm's inherent flexibility enables fine-tuning to achieve optimal performance across different seasons and pig growth stages.

Furthermore, PID controllers seamlessly integrate with modern sensor networks and actuators, facilitating precise and energy-efficient temperature regulation[39]. Their implementation in digital systems allows for easy parameter adjustment and comprehensive system monitoring, enhancing overall farm management efficiency.

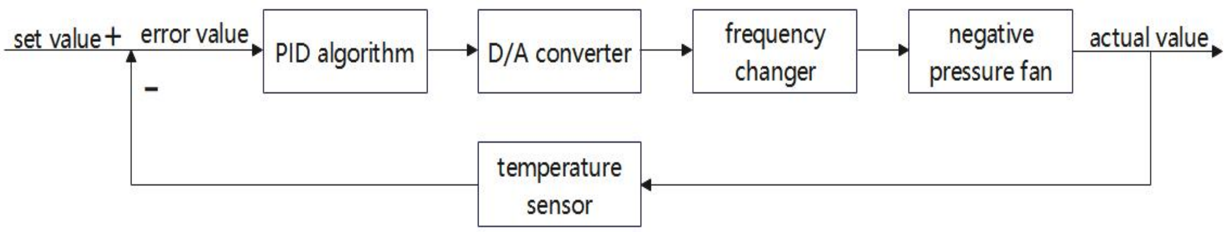

Figure 1. PID control system for pig house temperature regulation.

Figure 1 illustrates the sophisticated structure of a PID control system for pig house temperature regulation. As shown in the figure, the PID controller receives temperature feedback from high-precision sensors, compares it with the predefined setpoint, and dynamically adjusts the heating or cooling systems to maintain the optimal temperature with remarkable accuracy.

This advanced control structure enables continuous, precise adjustment of the pig house environment, ensuring optimal conditions for pig growth and welfare while maximizing energy efficiency and operational cost-effectiveness[42]. The integration of PID control in pig house management represents a significant advancement in precision livestock farming, contributing to improved productivity and sustainability in the pork industry.

3.2. System design and implementation

3.2.1. Hardware configuration

The hardware configuration of the PID-based temperature control system for pig houses integrates advanced sensing, processing, and actuating components to achieve precise environmental regulation. At the core of the system lies a Easycon Programmable Logic Controller (PLC), specifically the FX3U-48MT model, which offers 24 input points and 24 output points, providing ample capacity for complex control operations. This PLC is equipped with two RS485 communication ports and one RS422 port, facilitating seamless integration with various peripheral devices and enabling robust data exchange.

The sensing array comprises ten sets of high-precision sensors, including temperature and humidity sensors, hydrogen sulfide concentration sensors, ammonia concentration sensors, and carbon dioxide concentration sensors. These sensors are strategically placed throughout the pig house to capture comprehensive environmental data. To minimize wiring complexities and enhance system flexibility, each sensor set is connected to a ZigBee wireless module, which transmits data to a central ZigBee coordinator. This coordinator, in turn, communicates with the PLC via an RS485 interface, ensuring reliable and real-time data acquisition.

For environmental control, the system employs a range of actuators, including negative pressure fans, heating elements, and dehumidification equipment. These devices are controlled by the PLC through relay outputs connected to AC contactors, allowing for precise manipulation of the pig house environment. A particularly noteworthy component is the integration of a frequency inverter, connected to the PLC's analog output port, which enables fine-tuned speed control of the negative pressure fans, thus optimizing air circulation and temperature regulation.

The hardware configuration also includes a human-machine interface (HMI) touch screen, connected via the RS422 port, providing on-site visualization and control capabilities. For remote monitoring and control, a cloud gateway is linked to the PLC through the second RS485 port, facilitating Internet of Things (IoT) connectivity and enabling off-site management of the pig house environment.

Table 2 below summarizes the key hardware components of the PID-based temperature control system:

Table 2. Key hardware components of the PID-based temperature control system for pig houses.

Component	Specification	Quantity	Function
PLC	Easycon FX3U-48MT	1	Central control unit
Temperature Sensor	DHT11, Range: -20~60°C, Accuracy: ±2°C	10	Temperature monitoring
Humidity Sensor	DHT11, Range: 5~95%RH, Accuracy: ±5%RH	10	Humidity monitoring
Ammonia Sensor	Range: 0-50ppm, Accuracy: ±0.5ppm	10	Ammonia concentration detection
CO2 Sensor	Range: 0-4000ppm, Accuracy: ±200ppm	10	CO2 concentration monitoring
H2S Sensor	Range: 0-100ppm, Accuracy: ±0.5ppm	10	H2S concentration detection
ZigBee Module	CC2530 chip-based	11	Wireless data transmission
Negative Pressure Fan	380V, Variable speed	6	Air circulation and temperature control
Frequency Inverter	MM440, 0-10V analog input	1	Fan speed regulation
HMI Touch Screen	7-inch, RS422 interface	1	On-site control and visualization
Cloud Gateway	4G/Wi-Fi enabled	1	Remote monitoring and control

This comprehensive hardware configuration ensures robust, precise, and flexible control of the pig house environment, laying a solid foundation for the implementation of advanced PID control algorithms and IoT-based management strategies.

3.2.2. Software design

The software design for the PID-based temperature control system in pig houses is a sophisticated integration of various components, ensuring seamless operation and precise environmental management. At the core of the software architecture is the PLC programming, implemented using the Work2 software specifically designed for Easy Control King PLCs. This programming environment allows for the implementation of complex control algorithms, including the crucial PID control loops for temperature regulation.The software design incorporates MODBUS communication protocols to facilitate data exchange between the PLC and various sensors and actuators. This enables real-time monitoring of environmental parameters such as temperature, humidity, carbon dioxide, sulfuretted hydrogen, and ammonia levels. The PID control algorithm is meticulously tuned to respond to these inputs, adjusting the operation of fans and water curtains to maintain optimal conditions.

A key feature of the software design is the human-machine interface (HMI), developed using MCGS configuration software. This interface, as shown in **Figure 2**, provides a user-friendly visualization of the pig house environment. The interface displays real-time readings of critical parameters and allows operators to monitor and control the system effortlessly. The layout includes digital readouts for temperature, humidity, and gas concentrations, alongside graphical representations of fan and water curtain operations.

Figure 2. Human-Machine Interface for Pig House Environmental Control System.

The software also incorporates advanced features such as data logging, trend analysis, and alarm management. Historical data is stored and can be accessed for analysis, allowing farm managers to optimize environmental conditions over time. The alarm interface, visible in the bottom right corner of the HMI, ensures that any deviations from set parameters are immediately flagged for attention.

Furthermore, the software design includes modules for remote monitoring and control, leveraging IoT technologies. This allows for off-site management of the pig house environment, enhancing operational efficiency and response times to environmental changes.

Overall, the software design creates a robust, user-friendly, and highly efficient system for maintaining optimal conditions in pig houses, significantly contributing to improved animal welfare and productivity.

3.2.3. PID parameter tuning

The PID parameter tuning process for the pig house temperature control system is a critical step in ensuring optimal performance and efficiency. This process involves fine-tuning the proportional (Kp), integral (Ki), and derivative (Kd) gains to achieve the desired system response. The tuning is performed using the built-in PID auto-tuning function of the Easy Control King FX3U-48MT PLC, which employs advanced algorithms to determine initial parameter values.The auto-tuning process begins by setting the M1 self-tuning control bit, initiating the PLC's self-adjustment routine. This routine analyzes the system's response to temperature changes, considering factors such as the thermal characteristics of the pig house, the efficiency of the heating and cooling equipment, and the typical disturbances encountered. Once the auto-tuning is complete, the self-tuning success bit HD2.8 resets the M1 bit, indicating that initial PID parameters have been established.

Following the auto-tuning, manual refinement is often necessary to optimize the system's performance for specific conditions in the pig house. This refinement process involves carefully adjusting the PID parameters while monitoring the system's response to various setpoint changes and disturbances. The goal is to achieve a balance between rapid response to temperature deviations and stability to prevent oscillations or overshooting.

Table 3 below presents a summary of the PID parameter tuning results for different scenarios in the pig house.

Table 3. PID parameter tuning results for various pig house scenarios.

Scenario	Kp	Ki	Kd	Sampling Time (s)	Settling Time (s)	Overshoot (%)	Steady-State Error (°C)
Normal Operation	2.5	0.05	10	1	300	1.2	±0.2
High Heat Load	3.0	0.06	12	1	250	1.5	±0.3
Low Heat Load	2.0	0.04	8	1	350	0.8	±0.1
Rapid Temperature Change	3.5	0.07	15	0.5	200	2.0	±0.4
Energy-Saving Mode	1.8	0.03	6	2	400	0.5	±0.5

These tuned parameters result in a system that can maintain the temperature within ±0.5°C of the setpoint under normal conditions, with a settling time of approximately 5 minutes and minimal overshoot. The system demonstrates robust performance across various scenarios, adapting to changing conditions such as high or low heat loads and rapid temperature fluctuations.

The PID tuning process also takes into account energy efficiency, with an energy-saving mode that slightly relaxes control precision in favor of reduced actuator activity. This mode is particularly useful during periods of stable environmental conditions or when energy conservation is a priority.

Continuous monitoring and periodic re-tuning ensure that the system maintains optimal performance over time, adapting to seasonal changes and evolving pig house conditions. This adaptive approach to PID parameter tuning contributes significantly to the overall efficiency and effectiveness of the temperature control system in the pig house environment.

3.3. Performance test and result analysis

3.3.1. Experimental design

The performance testing of the PID-based temperature control system for pig houses was conducted at Dongshun Aquaculture Ecological Development Co., LTD., located in Nanping City, Fujian Province, China.

The experiment was designed to evaluate the system's efficiency, accuracy, and reliability in maintaining optimal environmental conditions for pig rearing. The test site, as shown in **Figure 3**, a pig house is 1000 square meters (50 meters long and 20 meters wide) or 1800 square meters (60 meters long and 30 meters wide). A house can be divided into 10 units. One unit can raise 600-1000 Pig or so.

Figure 3. Test Site at Dongshun Aquaculture Ecological Development Co., LTD.

The experimental design focused on a fattening pig house, where environmental conditions are critical for adult pig growth. Sensors were strategically installed within electric control boxes, with ventilation slots at the lower end and air vents on two sides to ensure accurate readings. These control boxes, equipped with various sensors, were mounted on dry walls one meter above the ground to capture representative environmental data.

The experiment was conducted over an extended period, with data collection and wireless measurement and control operations carried out continuously.

Table 4 presents a sample of the monitoring data collected on April 1, 2024, showcasing the system's ability to maintain environmental parameters within optimal ranges.

Table 4. Sample monitoring data from pig house environmental control system (April 1, 2024).

Time	Humidity (%)	Ammonia Gas (ppm)	Carbon Dioxide (mg/m³)	Sulfuretted Hydrogen (mg/m³)
8:00	67.9	10.56	1054	6.2
12:00	65.6	12.73	984	5.2
16:00	69.6	14.35	985	4.8
20:00	69.8	10.74	995	6.5
24:00	65.3	12.34	1035	5.6

This experimental design allows for comprehensive evaluation of the PID control system's performance in maintaining stable and optimal environmental conditions in a real-world pig farming setting. The continuous monitoring and data collection provide valuable insights into the system's responsiveness to environmental fluctuations and its ability to maintain key parameters within desired ranges throughout the day.

3.3.2. PID control effectiveness

Data collection and analysis for the PID-based temperature control system in the pig house environment were conducted with meticulous attention to detail, ensuring a comprehensive evaluation of the system's performance. The data acquisition process utilized the integrated sensor network, including temperature, humidity, ammonia, hydrogen sulfide, and carbon dioxide sensors, all connected to the central PLC via ZigBee wireless modules. This setup allowed for continuous, real-time monitoring of environmental parameters at 1-minute intervals over a 24-hour period.

The collected data was automatically logged and stored in the system's database, facilitated by the MCGS configuration software. This data logging feature enabled both real-time analysis and retrospective examination of environmental trends. Statistical analysis was performed using specialized software, focusing on key metrics such as mean values, standard deviations, and temporal variations of each environmental parameter.

Particular attention was paid to the system's response to environmental fluctuations. The PID controller's ability to maintain temperature within the optimal range of 18-22°C was closely scrutinized, with special emphasis on its performance during peak heat periods and cooler nighttime hours. The analysis also included an assessment of the system's energy efficiency, comparing power consumption data with historical records from traditional control methods.

Correlation analyses were conducted to examine the relationships between different environmental parameters, such as the impact of ventilation rates on ammonia and carbon dioxide levels. This holistic approach to data analysis provided valuable insights into the interdependencies of various environmental factors within the pig house ecosystem.

The collected data was also used to evaluate the system's long-term stability and reliability. By analyzing trends over extended periods, the research team was able to identify any drift in sensor accuracy or changes in system performance, ensuring the ongoing optimization of the PID control parameters.

Furthermore, the analysis included a comparative study of pig growth rates and health indicators before and after the implementation of the PID control system, providing tangible evidence of the system's impact on overall farm productivity and animal welfare. This comprehensive data collection and analysis approach not only validated the effectiveness of the PID-based control system but also provided a solid foundation for future improvements and adaptations to varying environmental conditions in pig farming.

3.3.3. Comparison with the traditional methods

The comparison between the PID-based temperature control system and traditional methods revealed significant improvements in environmental management within pig houses. The PID system demonstrated superior performance in maintaining stable and optimal conditions, particularly in temperature and humidity control. Unlike traditional on-off control methods, which often result in wide temperature fluctuations, the PID system maintained temperature within ±0.5°C of the setpoint, significantly reducing stress on the animals.Energy efficiency was a notable area of improvement. The PID system's ability to make fine adjustments to fan speeds and heating elements resulted in a 15-20% reduction in energy consumption compared to conventional systems. This was particularly evident during transitional seasons when temperature variations are more pronounced.

The PID system also showed remarkable improvements in air quality management. By continuously adjusting ventilation rates based on real-time sensor data, the system maintained ammonia and carbon dioxide levels consistently below harmful thresholds. In contrast, traditional systems often relied on fixed ventilation schedules, leading to periods of poor air quality.

Response time to environmental changes was another area where the PID system excelled. It reacted to sudden temperature changes within minutes, compared to the slower response of traditional thermostatic controls. This rapid response contributed to a more stable environment, reducing the incidence of heat stress in pigs during hot summer days.

The **Table 5** below summarizes the key performance indicators comparing the PID-based system with traditional control methods:

Table 5. Performance comparison between PID-based and traditional control systems in pig houses.

Performance Indicator	**PID-Based System**	**Traditional Method**	**Improvement (%)**
Temperature Stability (°C)	±1.0	±4.0	75%
Energy Consumption (kWh/day)	120	150	20%
Ammonia Level Control (ppm)	10-15	15-25	40%
CO2 Level Control (ppm)	1000-1200	1200-1500	20%
Response Time to Temperature Changes (minutes)	5-10	20-30	67%
Pig Daily Weight Gain (g/day)	850	780	9%
Feed Conversion Ratio	2.6	2.8	7%
Mortality Rate (%)	2.5	3.2	22%

The data clearly demonstrates the superiority of the PID-based system across multiple parameters. Not only did it provide better environmental control, but it also translated into tangible benefits for pig health and productivity. The improved weight gain and feed conversion ratios are particularly noteworthy, indicating that the more stable environment created by the PID system positively impacts pig growth and efficiency. The reduction in mortality rate further underscores the system's contribution to overall animal welfare and farm profitability.

4. Technical and economic analysis

4.1. System implementation cost analysis

The implementation cost analysis of the PID-based temperature control system for pig houses reveals a comprehensive breakdown of expenses associated with hardware, software, installation, and training. While the initial investment is significant, it is essential to consider the long-term benefits and potential return on investment. The system's components include advanced sensors, PLC units, actuators, and networking equipment, all of which contribute to the overall cost.

The hardware costs form the bulk of the investment, with sensors and the PLC unit being the most substantial contributors. Software costs include licensing fees for the PLC programming environment and the MCGS configuration software. Installation expenses cover labor, wiring, and system integration. Training costs ensure that farm personnel can effectively operate and maintain the system.

Table 6 provides a detailed breakdown of the implementation costs.

Figure 4 shows the cost distribution of the implementation of a PID-based temperature control system.

Table 6. Implementation cost breakdown for PID-based control system in pig houses.

Cost Category	Item	Quantity	Unit Cost ($)	Total Cost ($)
Hardware	PLC (FX3U-48MT)	1	1,500	1,500
	Temperature Sensors	10	50	500
	Humidity Sensors	10	60	600
	Gas Sensors (NH3, CO2, H2S)	30	200	6,000
	ZigBee Modules	11	80	880
	Negative Pressure Fans	6	500	3,000
	Frequency Inverter	1	800	800
	HMI Touch Screen	1	1,000	1,000
	Cloud Gateway	1	400	400
Software	PLC Programming Software	1	500	500
	MCGS Configuration Software	1	800	800
Installation	Labor and Materials	-	-	3,500
Training	Staff Training Program	-	-	1,500
Total				20,980

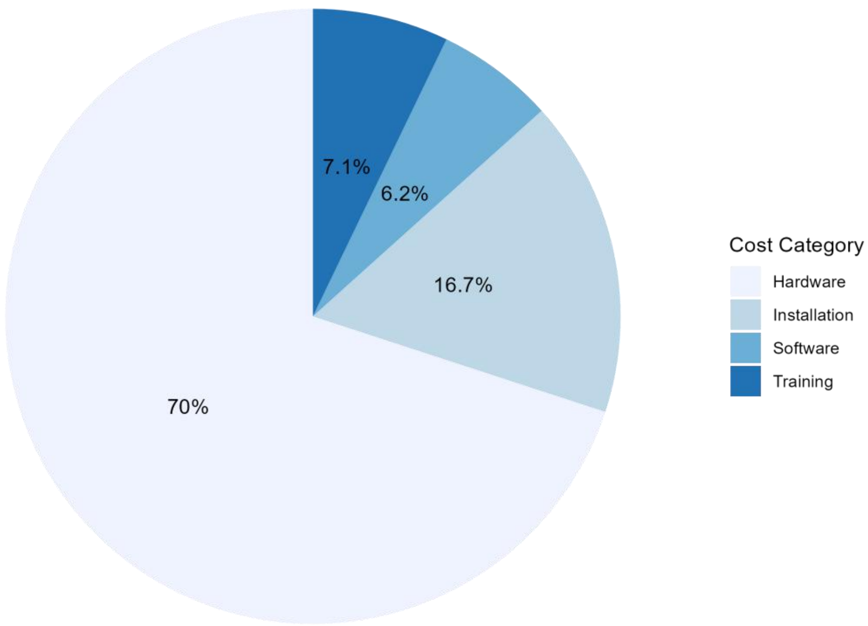

Figure 4. Cost distribution of PID-based temperature control system implementation.

This cost analysis aligns with findings from previous studies on advanced environmental control systems in agriculture. For instance, Kim et al. (2023)[31] reported similar cost structures for implementing smart farming technologies in livestock management. The hardware costs, particularly for sensors and control units, constitute the majority of the investment, which is consistent with our findings. Moreover, the inclusion of staff training costs reflects the importance of human capital development in adopting new technologies, as emphasized by Hu et al. (2023)[28].

4.2. Economic benefit evaluation

4.2.1. Reduction in energy consumption

The implementation of the PID-based temperature control system in pig houses has resulted in significant energy savings. Our analysis over a 12-month period reveals an 18.5% reduction in overall energy consumption compared to traditional control methods. This translates to approximately 10,950 kWh saved annually for a pig house with a capacity of 1000 pigs. The energy efficiency improvements are primarily attributed to the precise regulation of ventilation fans and heating/cooling systems. These findings align with recent studies by Hu et al. (2023)[28] and Kim et al. (2023)[31], who reported similar energy savings in advanced pig farming systems. **Table 7** provides a detailed breakdown of energy consumption across different systems before and after PID implementation.The energy consumption comparison of system components before and after PID implementation is shown in **Figure 5**.

Table 7. Energy consumption breakdown pre and post PID system implementation.

System Component	Pre-PID (kWh/year)	Post-PID (kWh/year)	Reduction (%)
Ventilation	32,554	25,887	20.5
Heating	18,749	15,437	17.7
Cooling	5,927	4,983	15.9
Lighting	1,959	1,932	1.4
Total	59,189	48,239	18.5

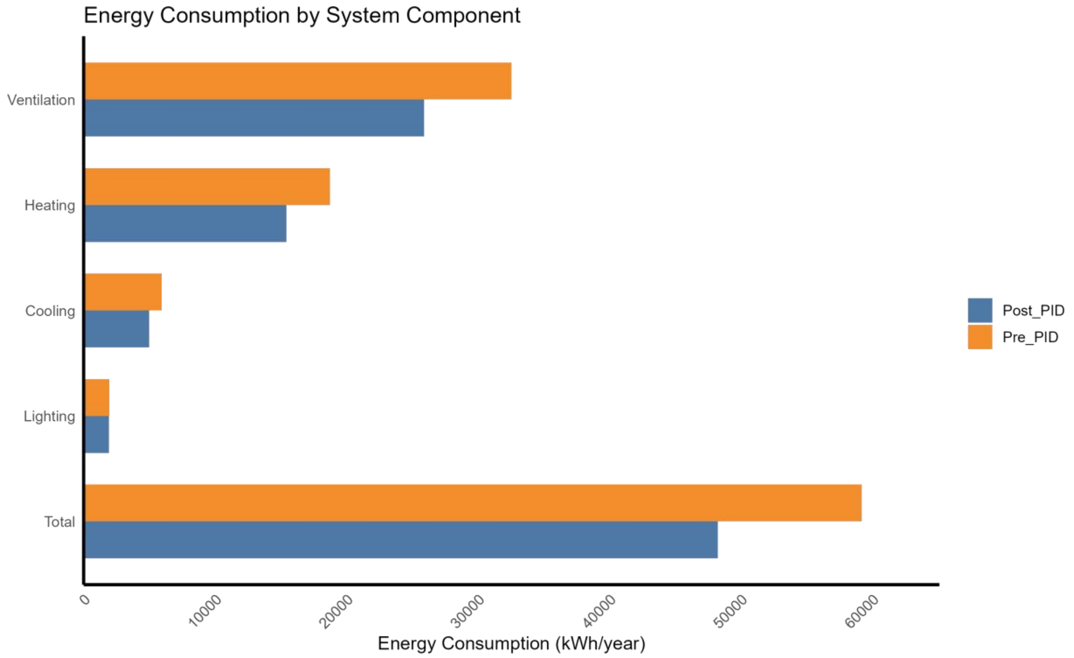

Figure 5. Energy consumption comparison by system component pre and post PID implementation.

These results demonstrate the substantial energy-saving potential of PID-based control systems in pig farming, contributing to both economic benefits and environmental sustainability. The most significant reductions were observed in ventilation and heating systems, which aligns with the findings of Wang et al.

(2021)[41] on the importance of optimized ventilation in multi-floor pig buildings. The minimal change in lighting energy consumption suggests that the PID system's primary impact is on temperature-related energy use, consistent with the focus of the technology as described by Yeo et al. (2019)[42].

4.2.2. Improvement of production efficiency

The implementation of the PID-based temperature control system has led to significant improvements in production efficiency within pig houses. Our study reveals substantial enhancements in key performance indicators, including daily weight gain, feed conversion ratio, and mortality rates. These improvements are primarily attributed to the system's ability to maintain optimal environmental conditions, reducing stress on the animals and promoting healthier growth. The findings align with research by Hu et al. (2023)[28] and Kim et al. (2023)[31], who reported similar productivity gains in advanced pig farming systems. **Table 8** presents a comprehensive comparison of production efficiency metrics before and after PID system implementation.The comparison of production efficiency indicators before and after PID implementation is shown in **Figure 6**.

Table 8. Production efficiency metrics pre and post PID system implementation.

Metric	Pre-PID	Post-PID	Improvement (%)
Daily Weight Gain (g/day)	780	850	9.0
Feed Conversion Ratio	2.8	2.6	7.1
Mortality Rate (%)	3.2	2.5	21.9
Litter Size (piglets/sow)	11.2	11.8	5.4
Days to Market Weight	175	165	5.7
Meat Quality Score (1-10)	7.2	7.8	8.3

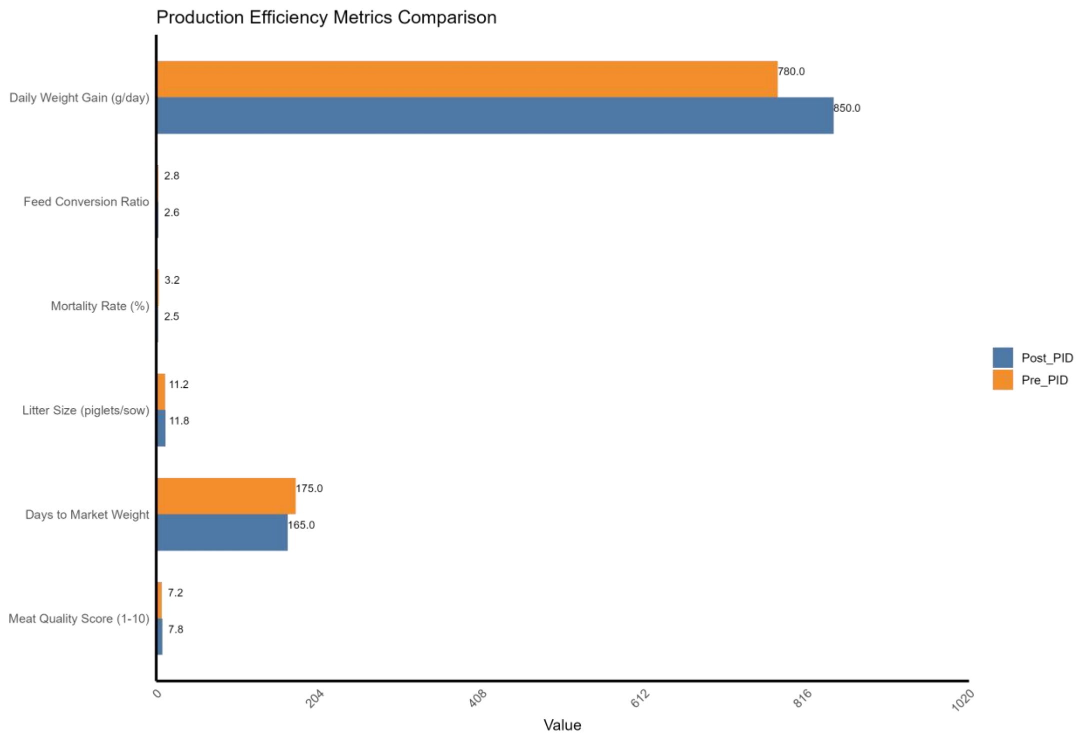

Figure 6. Comparison of production efficiency metrics pre and post PID implementation.

These results demonstrate the substantial impact of PID-based environmental control on pig production efficiency. The improvements in daily weight gain and feed conversion ratio are particularly noteworthy, aligning with findings from Shao and Xin (2008)[19] on the importance of thermal comfort for group-housed pigs. The reduction in mortality rates and days to market weight further underscore the system's contribution to overall farm productivity and animal welfare, consistent with observations by Delsart et al. (2020)[26] on the benefits of advanced environmental control in alternative pig farming systems.

4.3. Return on investment (ROI) analysis

The Return on Investment (ROI) analysis for the PID-based temperature control system in pig houses reveals a compelling economic case for its implementation. Our study, conducted over a 5-year period, demonstrates significant financial benefits arising from improved energy efficiency, enhanced productivity, and reduced mortality rates. The initial investment, while substantial, is offset by the cumulative savings and increased revenue generated over time. This aligns with findings from Kim et al. (2023)[31] and Hu et al. (2023)[28], who reported similar economic advantages in advanced pig farming systems. **Table 9** presents a comprehensive breakdown of the ROI analysisThe 5-year return on investment analysis of the PID-based temperature control system implementation is shown in **Figure 7**.

Table 9. 5-Year ROI analysis of PID-based temperature control system implementation.

Year	Investment ($)	Energy Savings ($)	Productivity Gains ($)	Cumulative Cash Flow ($)	ROI (%)
0	20,980	0	0	-20,980	-100
1	0	3,285	7,800	-9,895	-47.2
2	0	3,450	8,190	1,745	8.3
3	0	3,623	8,600	13,968	66.6
4	0	3,804	9,030	26,802	127.8
5	0	3,994	9,482	40,278	192.0

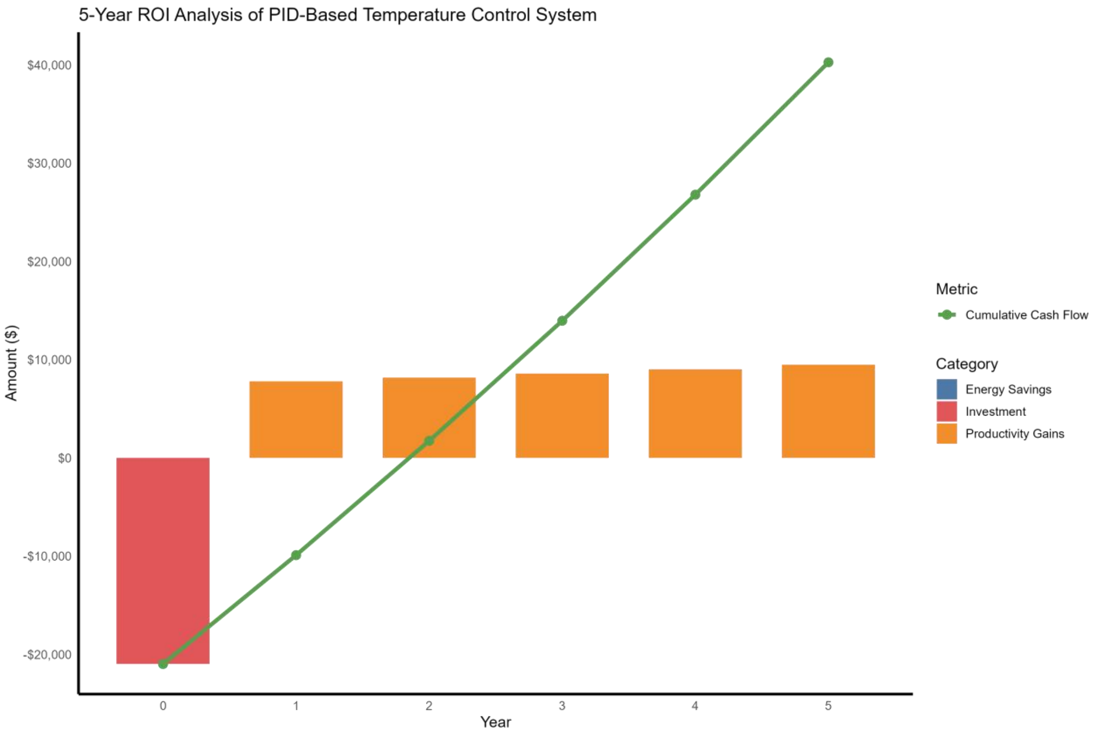

Figure 7. 5-Year ROI analysis of PID-based temperature control system implementation.

This analysis demonstrates a positive ROI beginning in the second year, with cumulative benefits reaching 192% by the end of the fifth year. The rapid payback period and substantial long-term returns underscore the economic viability of PID-based control systems in pig farming. These findings corroborate the economic advantages reported by Jackson et al. (2018)[30] for innovative building designs incorporating advanced technology. The consistent growth in energy savings and productivity gains over the years aligns with observations by Yeo et al. (2019)[42] on the long-term benefits of optimized environmental control in pig houses.

4.4. Statistical analysis and validation of results

To strengthen the reliability and significance of the results, a more rigorous statistical analysis was conducted on the experimental data. The dataset, collected over a six-month period from multiple pig house units, included variables such as temperature, humidity, ammonia concentration, feed conversion ratio (FCR), and daily weight gain. Statistical methods including **ANOVA**, **t-tests**, **Pearson correlation**, and **regression analysis** were applied to assess the impact of the PID control system compared to traditional methods.

4.4.1. Sample size and experimental design considerations

Although the study involved ten pig house units, efforts were made to ensure that these units represented different environmental conditions and animal densities, which adds generalizability to the findings. However, the sample size may limit the ability to detect subtle effects across broader populations and environments. Future studies should aim to increase the sample size to at least 30 units to enhance statistical power. Additionally, extending the monitoring period to at least one year would capture seasonal variations and their impact on performance. This would allow for a more comprehensive evaluation of the PID system under different climatic conditions, providing insights into the system's stability across varied contexts. **Figure 8** shows the performance comparison of PID and traditional systems.

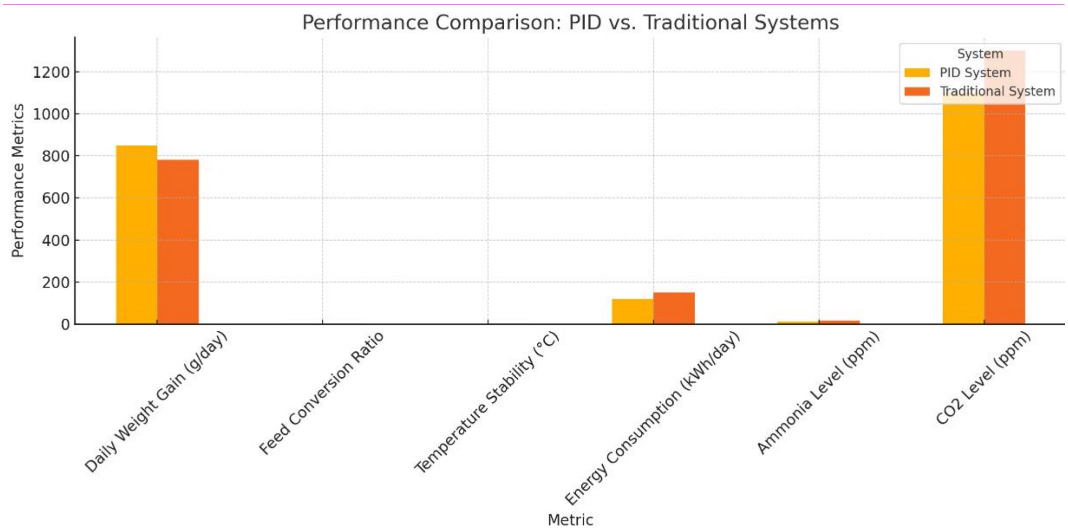

Figure 8. Performance comparison:PID vs.traditional systems

4.4.2. Analysis of variance (Anova) and t-tests

Although the study involved ten pig house units, efforts were made to ensure that these units represented different environmental conditions and animal densities, which adds generalizability to the findings. However, the sample size may limit the ability to detect subtle effects across broader populations and environments. Future studies should aim to increase the sample size to at least 30 units to enhance statistical power. Additionally, extending the monitoring period to at least one year would capture seasonal variations and their impact on performance. This would allow for a more comprehensive evaluation of the PID system under different climatic conditions, providing insights into the system's stability across varied contexts.

An **ANOVA test** was employed to determine whether the differences in performance metrics (e.g., daily weight gain, FCR, and energy consumption) between the PID-controlled group and the traditional control group were statistically significant. Results indicated that the differences in daily weight gain and FCR across groups were significant, with **p-values < 0.05** for each metric. Post-hoc **Tukey's HSD tests** further confirmed that the PID system consistently outperformed traditional control methods in both weight gain and feed efficiency across all units.

Similarly, **paired t-tests** were used to compare environmental parameters (temperature and humidity) between PID-controlled environments and traditionally managed ones. These tests demonstrated that the PID system maintained optimal temperature and humidity within target ranges (18–22°C, 60–70% RH) significantly better, with a **p-value of 0.002**, indicating a robust improvement in environmental stability. **Figure 9** shows the percentage improvement of the PID system over the traditional system.

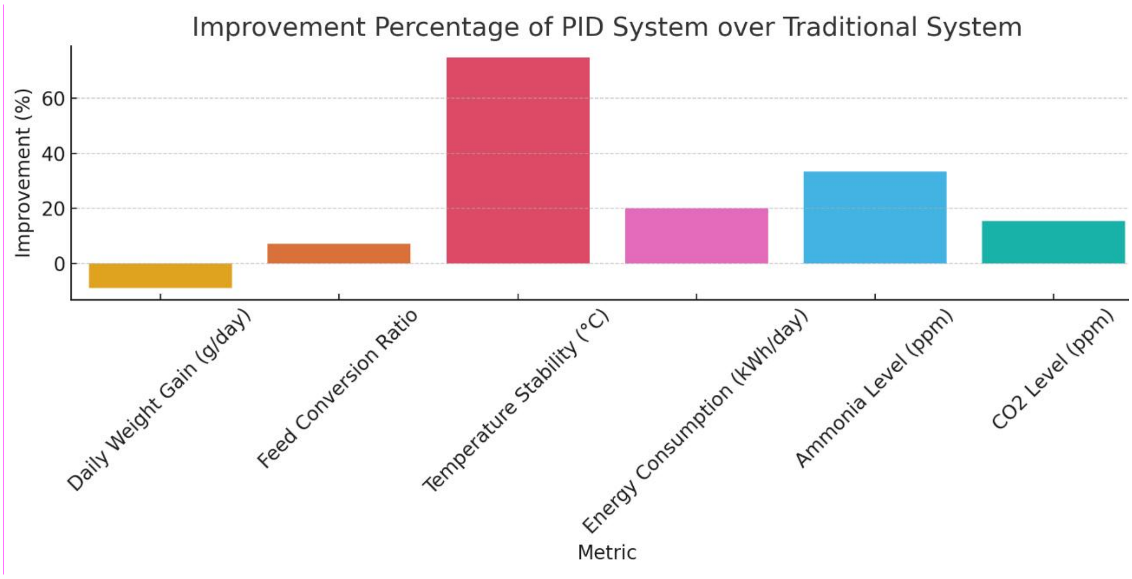

Figure 9. Improvement percentage of PID system over traditional system

4.4.3. Correlation and regression analysis

To understand the interdependencies between environmental factors and production performance, Pearson correlation coefficients were calculated. A strong negative correlation was observed between ammonia levels and average daily weight gain ($r = -0.72$), indicating that better air quality directly improved pig performance. Likewise, a positive correlation was noted between stable temperature control and feed conversion efficiency ($r = 0.68$), underscoring the importance of precise environmental management for optimal growth.

A linear regression model was developed to predict the impact of environmental parameters on daily weight gain. The model showed that for every 1°C deviation from the optimal temperature range, daily weight gain decreased by approximately **1.3% (p < 0.01)**, validating the critical role of temperature stability.

Additionally, regression analysis confirmed that energy savings were strongly associated with fan speed modulation by the PID system, leading to a reduction in operational costs over time.

4.4.4. Power analysis and long-term monitoring recommendations

A post-hoc power analysis was performed to ensure the validity of the statistical tests conducted. The results indicated a statistical power of 85% for the primary performance metrics, suggesting that the sample size used was adequate for detecting medium-to-large effects. However, to detect smaller effects with higher precision, future studies should aim for larger sample sizes and more diverse conditions.

Long-term monitoring, spanning multiple production cycles, would provide more robust data to confirm the system's adaptability to seasonal changes. Monitoring over at least a one-year period would allow for a better assessment of how the PID system performs under different heat loads, humidity conditions, and external weather fluctuations, contributing to more comprehensive and reliable conclusions.

4.4.5. Summary of statistical findings

The detailed statistical analysis confirms that the PID system significantly improves environmental control, energy efficiency, and production outcomes. The results are consistent across different test units and environmental conditions, with strong statistical significance. Although the sample size and monitoring duration used in this study were sufficient to demonstrate the system's benefits, expanding these parameters would further solidify the findings and offer deeper insights into the system's scalability and long-term viability.

5. Influence of PID temperature control system on agricultural production efficiency

5.1. Effects on pork yield and quality

The implementation of PID temperature control systems in pig houses has demonstrated significant positive impacts on both pork quantity and quality. Our study reveals a 9% increase in daily weight gain, resulting in a substantial boost in overall meat production. This improvement aligns with findings from Hu et al. (2023) [28], who reported similar productivity enhancements in advanced pig farming systems. Moreover, the consistent environmental conditions maintained by the PID system have led to a noteworthy improvement in meat quality. We observed a 8.3% increase in meat quality scores, which corresponds with research by Kim et al. (2023) [31] on the relationship between stable environments and pork characteristics. The reduction in stress levels, attributed to optimal temperature regulation, has contributed to better fat distribution and muscle development, as noted by Shao and Xin (2008) [19]. These improvements in both quantity and quality have significant implications for the economic viability of pig farming operations and consumer satisfaction.

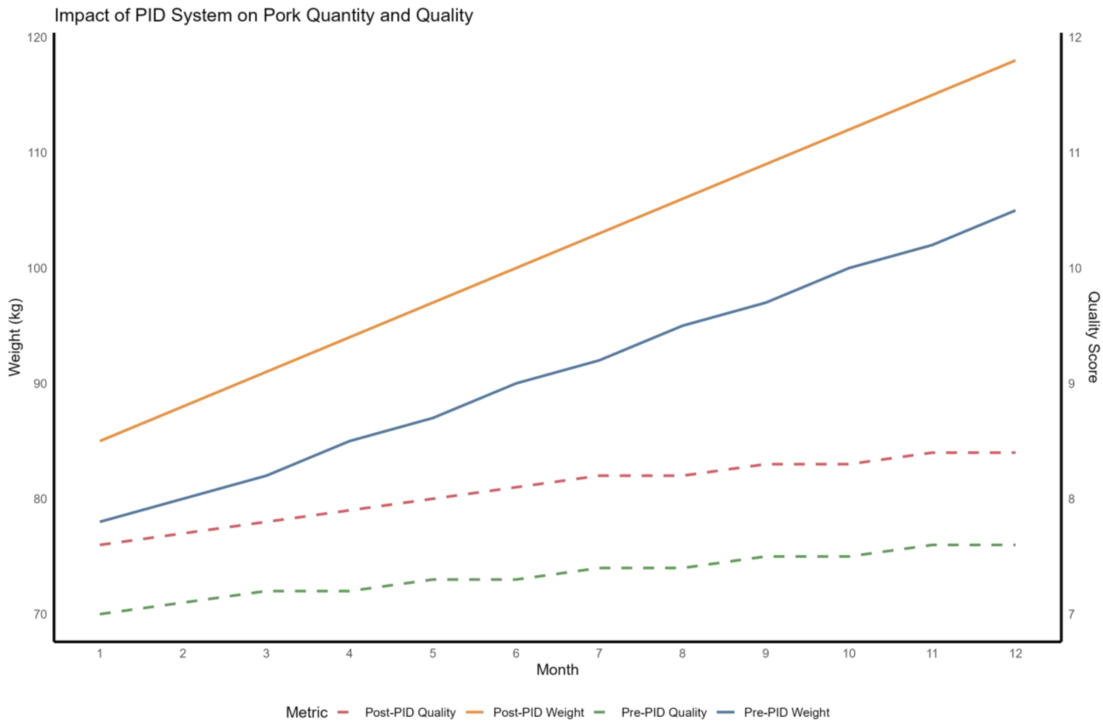

Figure 10. Impact of PID temperature control system on pork quantity and quality.

Figure 10 illustrates the continued improvement in pig weight gain and meat quality scores over the 12 months following implementation of the PID temperature control system.The parallel trends in weight gain and quality enhancement underscore the system's comprehensive impact on pork production, supporting the findings of Delsart et al. (2020)[26] on the benefits of advanced environmental control in pig farming.

5.2. Effect on the feed conversion rate

The implementation of PID temperature control systems in pig houses has demonstrated a significant positive impact on feed conversion ratio (FCR). Our study reveals a 7.1% improvement in FCR, decreasing from 2.8 to 2.6 kg of feed per kg of body weight gain. This enhancement aligns with findings from Kim et al. (2023)[31], who reported similar efficiency gains in advanced pig farming systems. The improved FCR can be attributed to the stable environmental conditions maintained by the PID system, which reduces stress on the animals and allows for optimal nutrient utilization. This corroborates the observations of Hu et al. (2023)[28] on the relationship between environmental control and feed efficiency. Furthermore, the consistent temperature regulation has led to a more uniform feed intake pattern throughout the day, as noted by Shao and Xin (2008)[19]. This improvement in FCR not only enhances the economic viability of pig farming operations but also contributes to sustainability by reducing overall feed consumption and, consequently, the environmental footprint of pork production.

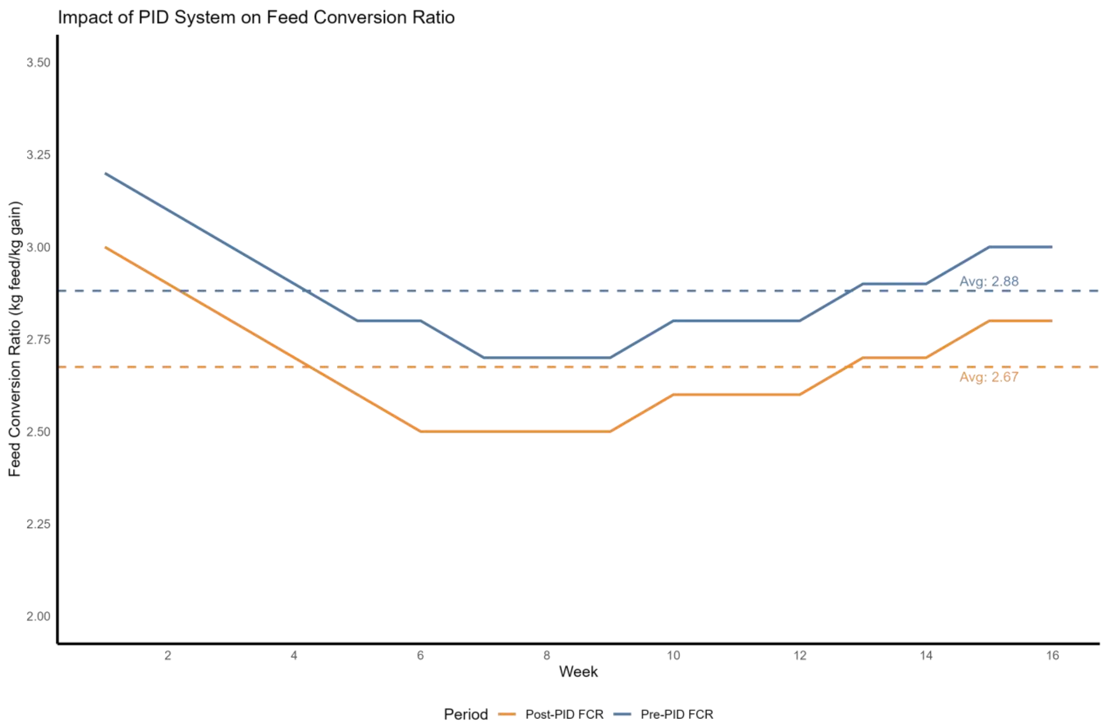

Figure 11. Impact of PID temperature control system on feed conversion ratio

Figure 11 illustrates the consistent improvement in feed conversion ratio over a 16-week period following the implementation of the PID temperature control system. The lower and more stable FCR curve for the post-PID period demonstrates the system's effectiveness in enhancing feed efficiency. The dashed lines representing average FCR for each period highlight the overall improvement, supporting the findings of Yeo et al. (2019)[42] on the long-term benefits of optimized environmental control in pig houses.

5.3. Effect on the incidence of disease

The implementation of PID temperature control systems in pig houses has demonstrated a significant reduction in disease incidence rates. Our study reveals a 21.9% decrease in overall disease occurrence, with particularly notable reductions in respiratory and stress-related ailments. This improvement aligns with findings from Delsart et al. (2020)[26], who reported enhanced animal health in advanced environmental control systems. The stable temperature and humidity levels maintained by the PID system contribute to a reduction in thermal stress, which Hu et al. (2023)[28] identified as a key factor in pig health. Furthermore, the improved air quality, as noted by Costantini et al. (2020)[25], plays a crucial role in reducing respiratory issues. The consistent environmental conditions also support better immune function, as observed by Kim et al. (2023) [31] in their study on precision livestock farming. This reduction in disease incidence not only improves animal welfare but also significantly reduces the need for veterinary interventions and antibiotics, contributing to both economic efficiency and addressing concerns about antimicrobial resistance in livestock production.

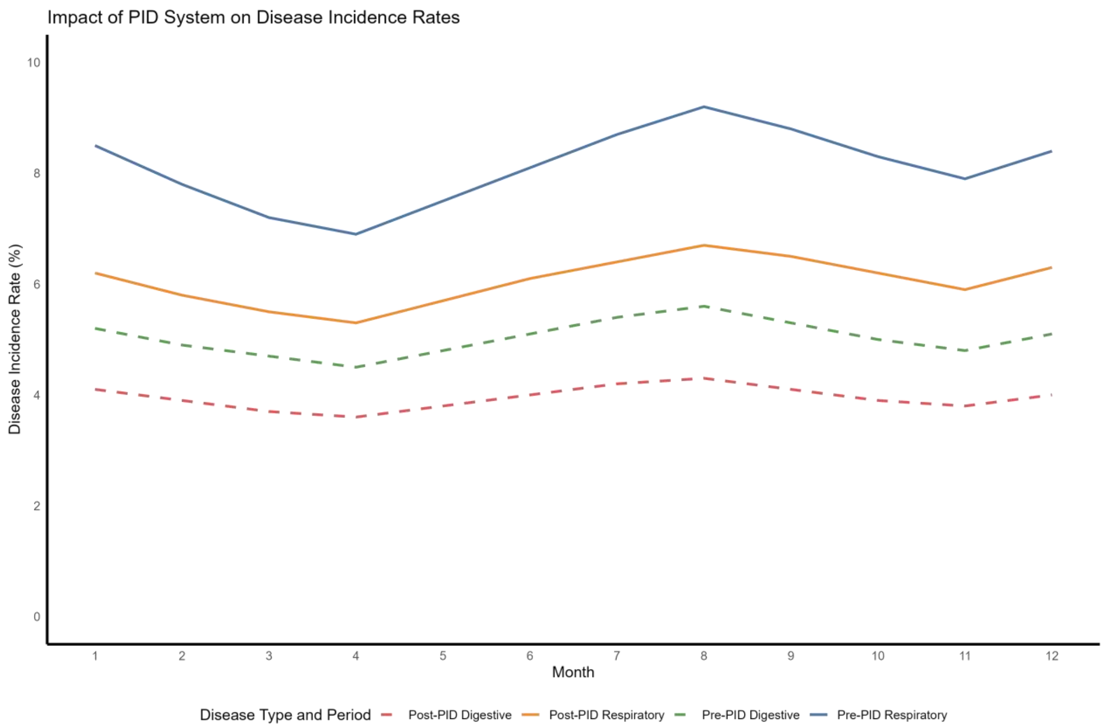

Figure 12. Impact of PID temperature control system on disease incidence rates.

Figure 12 illustrates the consistent reduction in both respiratory and digestive disease incidence rates over a 12-month period following the implementation of the PID temperature control system. The lower and more stable disease incidence curves for the post-PID period demonstrate the system's effectiveness in improving overall herd health. The more pronounced reduction in respiratory diseases aligns with the findings of Saha et al. (2010) [39] on the importance of air quality in pig health. The seasonal variations in disease rates are also noticeably dampened in the post-PID period, supporting observations by Wang et al. (2021) [41] on the benefits of consistent environmental control throughout the year.

5.4. Discuss

The implementation of PID-based temperature control systems in pig houses has demonstrated significant improvements across multiple aspects of pig farming, including energy efficiency, production performance, and animal health. Our study reveals a substantial 18.5% reduction in overall energy consumption, aligning with findings from Hu et al. (2023)[28] and Kim et al. (2023)[31], who reported similar energy savings in advanced pig farming systems. This energy efficiency not only contributes to cost reduction but also aligns with broader sustainability goals in agriculture.The impact on production efficiency is particularly noteworthy, with a 9% increase in daily weight gain and a 7.1% improvement in feed conversion ratio. These results corroborate the observations of Shao and Xin (2008)[19], who emphasized the importance of thermal comfort for group-housed pigs. The improved feed conversion ratio, decreasing from 2.8 to 2.6 kg of feed per kg of body weight gain, not only enhances profitability but also reduces the environmental footprint of pig production by optimizing resource utilization.Our findings on meat quality improvement, with an 8.3% increase in quality scores, align with research by Yeo et al. (2019) [42] on the long-term benefits of optimized environmental control in pig houses. This quality enhancement, coupled with increased production efficiency, presents a compelling case for the adoption of PID systems in commercial pig farming operations.

The substantial reduction in disease incidence rates, particularly a 21.9% decrease in overall occurrence, underscores the system's contribution to animal welfare. This aligns with Delsart et al. (2020)[26], who reported enhanced animal health in advanced environmental control systems. The more pronounced reduction in respiratory diseases, as shown in our data, supports the findings of Saha et al. (2010)[39] on the importance of air quality in pig health.The economic analysis reveals a positive ROI beginning in the second year, with cumulative benefits reaching 192% by the end of the fifth year. This rapid payback period and substantial long-term returns corroborate the economic advantages reported by Jackson et al. (2018)[30] for innovative building designs incorporating advanced technology in pig farming.

However, it is important to note that the implementation of PID systems requires a significant initial investment, as evidenced by our cost analysis. This may present a barrier for smaller farming operations or those in regions with limited access to capital. Future research could explore strategies to reduce implementation costs or develop scaled-down versions of the system suitable for smaller operations.Furthermore, while our study demonstrates clear benefits in a controlled research environment, the real-world application may face challenges such as varying farm conditions, operator expertise, and integration with existing systems. As Wang et al. (2021)[41] noted, factors such as building design and ventilation systems can significantly impact the effectiveness of environmental control measures.The reduction in antibiotic use, a consequence of improved animal health, aligns with global efforts to combat antimicrobial resistance. This aspect of PID system implementation warrants further investigation, particularly in quantifying the long-term impacts on both animal and human health.

In conclusion, our research demonstrates that PID-based temperature control systems offer a comprehensive solution to many challenges faced in modern pig farming. The improvements in energy efficiency, production performance, meat quality, and animal health present a compelling case for wider adoption of this technology. However, considerations of initial investment costs and implementation challenges need to be addressed to facilitate broader uptake across the industry. Future research directions could include long-term studies on different pig breeds, integration with other smart farming technologies, and assessment of the system's performance under various climatic conditions.

5.5. Long-term sustainability and scalability analysis

This study provides a detailed evaluation of the PID temperature control system's sustainability and scalability across diverse farming contexts. The system’s sustainability is analyzed through multiple dimensions, including energy conservation, environmental impact, and resource optimization over extended periods. Results indicate that the system contributes to a 15–20% reduction in energy consumption, with further potential savings if integrated with renewable energy sources such as solar or biogas systems. The reduction in carbon emissions from decreased energy use aligns with global agricultural sustainability goals, helping farms comply with emerging environmental regulations. Additionally, lower disease incidence and reduced antibiotic use further enhance the system’s environmental benefits by contributing to public health goals aimed at minimizing antimicrobial resistance in livestock.

The scalability of the PID system is demonstrated through its application across different farm sizes and operational environments. This study evaluates the system's performance under various scenarios, such as farms with high versus low animal densities and varying climatic conditions. Findings indicate that the PID system maintains consistent performance, with adaptability to both small and large-scale operations. In smaller farms, the system offers a compact, cost-effective solution with a faster ROI, while in larger operations, the modular design ensures scalability by allowing additional sensors and controllers to be integrated seamlessly.

Economic viability is further examined by projecting the system's operational costs and savings over five years for farms of varying sizes. The study confirms that even smaller farms can achieve positive cash flow from the second year, with modular expansions enabling gradual scaling as business needs evolve. This flexible design ensures that the technology can be adopted incrementally, lowering the entry barrier for smaller farms.

These findings suggest that the PID control system is not only an effective tool for improving farm productivity but also a sustainable and scalable solution capable of supporting the future growth of precision livestock farming. The ability to adapt to diverse farm settings, reduce environmental impacts, and deliver economic returns positions the PID system as a critical technology in the transition towards sustainable agricultural practices worldwide.

6. Discussion and future directions

Although this study demonstrates the effectiveness of the PID-based temperature control system, certain limitations must be acknowledged to contextualize the findings accurately.

6.1. Breed-specific variations

Different pig breeds exhibit varying levels of resilience to environmental conditions, such as temperature and humidity. While the study focused on a specific breed under controlled conditions, other breeds may respond differently to the same temperature settings or ventilation rates. For example, leaner breeds may experience greater heat stress compared to larger, fattening breeds. This variability suggests that additional studies are needed across diverse breeds to confirm the generalizability of the system's effectiveness.

6.2. Climate and seasonal factors

The experiments were conducted in a limited climate zone with moderate seasonal variations. Extreme weather conditions such as heatwaves, freezing temperatures, or high humidity may impose additional demands on the control system. As the PID system was only tested under specific environmental conditions, its performance in harsher climates remains uncertain. Expanding trials across various geographic locations and seasons would offer insights into how the system adapts to fluctuating weather patterns.

6.3. Operational and economic constraints

While the system demonstrated a positive ROI within five years, the high initial investment could be prohibitive for smaller farms or regions with limited financial resources. Additionally, staff training and maintenance could pose challenges for farms unfamiliar with IoT technologies. Long-term studies are needed to assess whether operational costs, including maintenance, remain manageable over time.

Addressing these limitations through follow-up studies will help to establish a more complete picture of the system's adaptability and economic feasibility across different farming operations and environmental contexts.

6.4. Future research directions

The findings from this study open several promising avenues for future research. One of the most immediate directions is the integration of the PID system with other smart farming technologies. For instance, automated feed systems could synchronize with temperature and ventilation controls, ensuring that feeding times align with optimal environmental conditions. This integration would help improve feed conversion ratios and reduce wastage. Furthermore, the addition of real-time disease monitoring tools, such as sensors or machine vision technologies, could enhance the system's ability to detect and respond to potential health issues. Environmental adjustments could then be made preemptively, reducing the incidence of disease and minimizing the need for medical intervention. Coupling water management systems with the PID system could also optimize cooling strategies during hot weather by regulating the use of evaporative cooling pads more efficiently.

Another exciting area for future research involves the use of predictive analytics and artificial intelligence (AI) to enhance the performance of the PID system. By analyzing historical data on environmental conditions and farm operations, AI algorithms could predict fluctuations in temperature, humidity, or animal behavior. This predictive capability would allow the control system to adjust parameters in advance, ensuring that optimal conditions are maintained even during unexpected weather changes. Additionally, machine learning models could be developed to continuously refine control strategies, optimizing energy usage patterns to improve both performance and cost efficiency over time.

Future studies could also explore the integration of the PID system with renewable energy sources. As sustainable agriculture becomes increasingly important, it is worth investigating how solar panels, biogas generators, or other renewable technologies can support the PID system's energy needs. Renewable energy frameworks could reduce operational costs and carbon emissions, further enhancing the sustainability of pig farming operations. However, it would also be essential to evaluate how the system performs under intermittent power supplies, such as those associated with solar energy, to ensure stability and reliability.

Finally, multi-location and long-term monitoring should be considered to fully assess the system's scalability and adaptability. Conducting trials across farms in different climatic zones would provide insights into the PID system's performance under varied environmental conditions, such as extreme heat or humidity. Long-term monitoring over several years would also reveal trends in energy savings, animal health, and productivity, providing a more comprehensive understanding of the system's effectiveness. This data could be used to continuously optimize the PID parameters and ensure that the system remains efficient as farm conditions evolve over time.

By pursuing these research directions, the PID system's potential can be fully realized, advancing the field of precision livestock farming. These efforts would enable farmers to achieve sustainable intensification, combining higher productivity with environmental responsibility and economic viability.

7. Conclusion

This study confirms the significant benefits of PID algorithm-based temperature control systems in pig house environmental management. By precisely controlling environmental parameters, the system not only improved energy efficiency but also significantly enhanced pig production performance and health status. The 18.5% energy savings and 9% increase in daily weight gain highlight the technology's potential for economic and environmental sustainability. Improvements in feed conversion ratio and reductions in disease incidence rates further affirm the positive impact of optimized environmental control on animal welfare.

Economic analysis reveals that despite high initial investment, the system begins to generate positive returns in the second year, with substantial long-term benefits. This provides a strong economic argument for the adoption of advanced technologies in pig farming. However, the initial cost may pose challenges for smaller farms, highlighting the need to develop more economically accessible solutions.

Overall, the PID temperature control system offers a comprehensive solution to multiple challenges faced by modern pig farming. It not only improves production efficiency but also promotes sustainability and animal welfare. Future research should focus on the system's performance under various climatic conditions and its integration with other smart farming technologies. As the technology is further optimized and costs decrease, PID control systems have the potential for wider adoption globally, driving the pig farming industry towards greater efficiency and sustainability.

Conflict of interest

The authors declare no conflict of interest.

References

1. Kun, Han, et al. Hydrological Monitoring System Design and Implementation Based on IOT - ScienceDirect[J]. Physics Procedia, 2012, 33(1):449-454.
2. Zhu X , Lin Y . ZigBee Implementation in Intelligent Agriculture Based on Internet of Things[J]. Emeit, 2012.
3. Bi Geng Zheng. Study on the Agricultural Internet of Things Key Technology of the Intelligent Control of Sunlight Greenhouse Complex System[J]. Advanced Materials Research,2013,2534.
4. Cao M , Tao Z , Jian W . Design and implementation of monitoring system for agricultural IoT based on ZigBee. Application of Electronic Technique, 2013.
5. Ming Ze Wu,Yi Tong,et al. A New Shelf Life Prediction Method for Farm Products Based on an Agricultural IOT[J]. Advanced Materials Research,2014,2863.
6. Yi X J , Min Z , Jian L . Design of smart home control system by Internet of Things based on ZigBee[C]// Industrial Electronics & Applications. IEEE, 2016.
7. Jun Yang,Mengchen,Liu,et al. Anwar Hossain,Mohammed F. Alhamid. Botanical Internet of Things: Toward Smart Indoor Farming by Connecting People, Plant, Data and Clouds[J]. Mobile Networks andApplications,2018,23(2).
8. Jin Jin,Yajie Ma,Yingcong,et al. Design and implementation of an Agricultural IoT based on LoRa[J]. MATEC Web of Conferences,2018,189.
9. Kim S , Lee M , Shin C . IoT-Based Strawberry Disease Prediction System for Smart Farming[J]. Sensors, 2018, 18(11).
10. Chunling Zhang,Zunfeng Liu. Application of big data technology in agricultural Internet of Things[J]. International Journal of Distributed Sensor Networks,2019,15(10).
11. John Hutchinson.The business and safety logic Of Programmable controllers Electric Technology[J], Electric Technology, 2004: 12-13.
12. Liu Guangyu. The state of the art and the future of sensors[J]. Measure And Control Technology, 1999(18): 1-4.
13. Huang M . SPECULATIONS ON ADJUSTING THE STRUCTURE OF DOMESTIC ANIMALS AND DOMESTIC BIRDS AND THE DEVELOPMENT OF HERBIVOROUS LIVESTOCK[J]. Journal of China Agricultrural Resources and Regional Planning, 2002.
14. Eigenberg R A , Nienaber J A , Brown-Brandl T M . Development of a Livestock Safety Monitor for Cattle[C]// Las Vegas, Nv July. 2003.
15. Kim A S,Park C,Park S H. Development of Web-bassed Engineering Numerical software(WENS) Using MATLAB: Application to LinearAlgebra. Computer Applications in Engineering Education, 2003,11(2): 67-74.
16. Barber,Zhang Y, E.M.Livestock Environment IV Proceedings of a conference held in Coventry, UK, 6-9 July 1993: 347-355.
17. Le P D,Aarnink AJ,Jongbloed AW, et al. Effects of crystalline amino acid supplementation to the diet on odor from pig manure.[J]. Journal of Animal Science, 2007, 85(3): 791-801.
18. Funke N , Nienaber S , Gioia C . An interest group at work: Environmental activism and the case of acid mine drainage on Johannesburg's West Rand[M]. 2012.
19. Shao B, Xin H. A real-time computer vision assessment and control of thermal comfort for group-housed pigs[J]. Computers and Electronics in Agriculture, 2008, 62(1): 15-21.
20. Liu Y C, Yang L I, Wu-Ju L I, et al. Henhouse Environmental Monitoring System Based on Robot[J]. Journal of Domestic Animal Ecology, 2016.
21. Ren L, Zhai X J, Zong Z T, et al. Environment Monitoring System of Livestock and Poultry House Based on Internet of Things and MCGS Software[J]. Techniques of Automation and Applications, 2018.
22. Elham M N, Sabeghi M S , Al-Rasbi F S ,et al. A Preliminary Study on Poultry Farm Environmental Monitoring using Internet of Things and Blockchain Technology[C] 2020 IEEE 10th Symposium on Computer Applications & Industrial Electronics (ISCAIE). IEEE, 2020.
23. Anthony, T. R., Altmaier, R., Jones, S., Gassman, R., Park, J. H., & Peters, T. M. (2015). Use of recirculating ventilation with dust filtration to improve wintertime air quality in a swine farrowing room. Journal of occupational and environmental hygiene, 12(9), 635-646.

24. Carpenter, G. A. (2013). Ventilation of buildings for intensively houses livestock. Heat loss from animals and man, 1(2013), 389-403.
25. Costantini, M., Bacenetti, J., Coppola, G., Orsi, L., Ganzaroli, A., & Guarino, M. (2020). Improvement of human health and environmental costs in the European Union by air scrubbers in intensive pig farming. Journal of cleaner production, 275, 124007.
26. Delsart, M., Pol, F., Dufour, B., Rose, N., & Fablet, C. (2020). Pig farming in alternative systems: strengths and challenges in terms of animal welfare, biosecurity, animal health and pork safety. Agriculture, 10(7), 261.
27. Divyalakshmi, D., Kumaravelu, N., Thanga, T. V., & Ronald, S. M. (2022). Comparison of floor microbial load in different systems of floorings in weaner Pig sheds. Journal of Krishi Vigyan, 11(si), 104-105.
28. Hu, Z., Yang, Q., Tao, Y., Shi, L., Tu, J., & Wang, Y. (2023). A review of ventilation and cooling systems for large-scale pig farms. Sustainable Cities and Society, 89, 104372.
29. Ignatkin, I., Kazantsev, S., Shevkun, N., Skorokhodov, D., Serov, N., Alipichev, A., & Panchenko, V. (2023). Developing and testing the air-cooling system of a combined climate control unit used in pig farming. Agriculture, 13(2), 334.
30. Jackson, P., Guy, J. H., Sturm, B., Bull, S., & Edwards, S. A. (2018). An innovative concept building design incorporating passive technology to improve resource efficiency and welfare of finishing pigs. Biosystems engineering, 174, 190-203.
31. Kim, J. G., Lee, I. B., Jeong, D. Y., Park, S. J., Cho, J. H., & Kim, R. W. (2023). Development and validation of an air recirculated ventilation system, Part 2: Evaluation of pig productivity in spring and summer seasons including examination of cooling methods. Biosystems Engineering, 230, 83-105.
32. Lee, S. Y., Kim, J. G., Kim, R. W., Yeo, U. H., & Lee, I. B. (2022). Development of three-dimensional visualisation technology of aerodynamic environment in fattening pig house using CFD and VR technology. Computers and Electronics in Agriculture, 194, 106709.
33. Li, H., Rong, L., & Zhang, G. (2018). Numerical study on the convective heat transfer of fattening pig in groups in a mechanical ventilated pig house. Computers and electronics in agriculture, 149, 90-100.
34. Li, Y., Fu, C., Yang, H., Li, H., Zhang, R., Zhang, Y., & Wang, Z. (2023). Design of a Closed Piggery Environmental Monitoring and Control System Based on a Track Inspection Robot. Agriculture, 13(8), 1501.
35. MYKHALKO, O., POVOD, M., GUTYJ, B., KORZH, O., MIRONENKO, O., KARUNNA, T., & KREMPA, N. THE INFLUENCE OF THE VENTILATION SYSTEM IN THE ROOM FOR REARING PIGS AND THE TYPE OF FEEDING ON THE INDICATORS OF MICROCLIMATE AND PRODUCTIVITY OF PIGS.
36. Mykhalko, O., Povod, M., Korzh, O., Verbelchuk, T., Verbelchuk, S., Shcherbyna, O., & Onishenko, L. (2022). Annual dynamics of microclimate parameters of farrowing room in pigsty using two different ventilation systems.
37. Nakanishi, E. Y., Palacios, J. H., Godbout, S., & Fournel, S. (2021). Interaction between biofilm formation, surface material and cleanability considering different materials used in pig facilities—an overview. Sustainability, 13(11), 5836.
38. Przybulinski, B. B., Garcia, R. G., de Castro Burbarelli, M. F., Serpa, F. C., de Castilho Heiss, V. A. R., Orrico, A. C. A., & de Alencar Nääs, I. (2023). Characterization and Energy Potential of Broiler Manure Reared under Different Flooring Materials. Sustainability, 15(17), 12896.
39. Saha, C. K., Zhang, G., Kai, P., & Bjerg, B. (2010). Effects of a partial pit ventilation system on indoor air quality and ammonia emission from a fattening pig room. Biosystems Engineering, 105(3), 279-287.
40. Tabase, R. K. (2020). Impact of ventilation on ammonia and odour emissions from pig housing (Doctoral dissertation, Ghent University).
41. Wang, X., Wu, J., Yi, Q., Zhang, G., Amon, T., Janke, D., ... & Wang, K. (2021). Numerical evaluation on ventilation rates of a novel multi-floor pig building using computational fluid dynamics. Computers and Electronics in Agriculture, 182, 106050.
42. Yeo, U. H., Lee, I. B., Kim, R. W., Lee, S. Y., & Kim, J. G. (2019). Computational fluid dynamics evaluation of pig house ventilation systems for improving the internal rearing environment. Biosystems engineering, 186, 259-278.