Jurnal Ilmu Pertanian Indonesia (JIPI), September 2026
(Indonesian Journal of Agricultural Sciences)
ISSN 0853-4217 EISSN 2443-3462

Vol. 31 (4): 718–725
http://journal.ipb.ac.id/index.php/JIPI
DOI: 10.18343/jipi.31.4.718

The Impact of IoT-Based Cyber-Physical Systems on Broiler Farming in Closed-House Systems

Anas Alvandika[1]*, Ismoyowati Ismoyowati [1], Novie Andri Setianto[1], Ardiansyah Ardiansyah [2], Elly Tugiyanti[1], Nurul Hidayat[3]

(Received March 2026/Accepted August 2026)

ABSTRACT

Broiler chicken production requires appropriate environmental control to maintain productivity and animal welfare. This study evaluated the effect of implementing an IoT-based cyber-physical system on microclimate stability and broiler chicken performance under semi-industrial conditions. A total of 4,200 CP-707 broiler chickens were reared for 33 days in a closed-house facility using a before-and-after design that compared a non-system controller with an IoT-based cyber-physical system that integrated environmental sensors, a programmable logic controller, and cloud-based monitoring. This system maintained stable environmental conditions and reduced deviations from standard operating procedures. Average house temperature and feed conversion ratio (FCR) did not differ significantly before and after implementation ($p = 0.080$ and $p = 0.645$, respectively). However, mortality rates decreased significantly from 5.09% to 2.36% ($p = 0.005$), and body weight increased from 846.29 g to 895.43 g ($p < 0.001$). The Performance Index (PI) also increased, although the difference was not statistically significant ($p = 0.088$). These findings indicate that the IoT-based cyber-physical system improves the survival and growth of broiler chickens whilst maintaining feed efficiency through more stable environmental control. This system offers a practical and adaptable approach to improving productivity, sustainability, and animal welfare within modern closed-house broiler chicken production systems.

Keywords: **broiler chickens, closed-house system, cyber-physical system, internet of things, precision livestock farming**

INTRODUCTION

Broiler chicken production is one of the fastest-growing livestock sectors in Indonesia, with continuous increases in poultry meat production across all 38 provinces. National statistics show that broiler chicken meat production reached 3.18 million tonnes in 2021, 3.76 million tonnes in 2022, and 3.99 million tonnes in 2023, reflecting a steady upward trend (BPS 2023). This growth highlights the importance of efficient housing and management systems to optimise productivity and maintain animal welfare. Housing conditions play a decisive role in production success, with environmental parameters such as temperature, humidity, air quality, and oxygen concentration being critical factors for broiler chicken performance (Yasi *et al.* 2022; Prayogi 2014).

[1] Department of Animal Science, Faculty of Animal Science, Jenderal Soedirman University, Purwokerto 53122, Indonesia
[2] Department of Agricultural Engineering, Faculty of Agriculture, Jenderal Soedirman University, Purwokerto 53122, Indonesia
[3] Department of Computer Science, Faculty of Engineering, Jenderal Soedirman University, Purwokerto 53371, Indonesia
* Corresponding Author:
Email: anas.a@mhs.unsoed.ac.id

The development of digital technology has driven the transformation of livestock production systems towards the Smart Precision Farming paradigm, which integrates sensors, computing, data communication, and automated decision-making to improve production efficiency and animal welfare. Technological advances have led to the introduction of IoT-based cyber-physical systems that enable real-time monitoring and automated control in broiler chicken houses. These IoT-based cyber-physical systems can reduce mortality rates, improve operational efficiency, and support scientific management through precise microclimate control that can be tailored to the needs of the livestock (Li *et al.* 2015; Chivarov *et al.* 2023; Bai 2006; Mirzaee-Ghaleh *et al.* 2015; Lashari *et al.* 2023; Iriani *et al.* 2024).

Cyber-Physical Systems (CPS) have been developed as an architecture that integrates physical and cyber components within a closed-loop control system. The physical components consist of sensors, actuators, and data acquisition equipment, whilst the cyber components include computing units, control algorithms, biological models, and communication networks. Data generated by sensors is processed in real-time to determine control decisions, which are then executed by actuators, and the results are measured again as system feedback (Bumanis *et al.* 2022). CPS can manage the microclimate with precision, enabling the concept of actual temperature and the temperature perceived by the chickens based on a combination of humidity and wind speed, so that control decisions are more aligned with the physiological needs of the livestock than if relying solely on actual air temperature (Chivarov *et al.* 2023).

The integration of Internet of Things (IoT)-based automation systems in closed-house systems offers opportunities to improve feed utilisation, growth performance, and production indices in broiler chicken farming. IoT, originally formulated by Ashton in 1999, refers to a network of connected smart objects capable of collecting and transmitting data without direct human interaction, thereby facilitating intelligent decision-making at the operational level (Eltaieb & Min 2015; Saragih *et al.* 2020; Lashari *et al.* 2018). The development of IoT-based automated systems to control and monitor the temperature of closed chicken houses has been undertaken by Elwakeel *et al.* (2025); Komaludin (2024); Masriwilaga *et al.* (2019); and Mulia *et al.* (2022), with positive results. Despite existing research and its potential, the application of IoT in poultry production remains limited, particularly at the semi-industrial and industrial scales (Stoica *et al.* 2005; Huang *et al.* 2011). This study develops an Internet of Things (IoT)-based cyber-physical system (CPS) for closed-house systems at a semi-industrial scale moving towards industrial-scale operations, equipped with sensors, logic controllers, interface computing, and a web-based cloud IoT platform. This system provides an integrated environmental monitoring tool that offers a sustainable approach to improving performance in broiler chicken farming. This study will also examine the impact on chicken performance before and after the use of an Internet of Things-based automation system to obtain more in-depth results.

METHODS

Time and Location of Research

This research was conducted at a closed-house experimental farm with a capacity of 4,000–5,000 birds, owned by the Faculty of Animal Science at Jenderal Soedirman University, between January and August 2025.

Experimental Animals and Housing

A total of 4,200 one-day-old CP-707 broiler chicks were reared in a closed-house system (40 × 8 × 2.1 m) for a maximum of 33 days. The poultry house was equipped with cooling pads, exhaust fans, and automatic heaters to maintain the microclimate, which was controlled by an IoT-based cyber-physical system. Feed was provided manually in measured quantities, whilst water was provided ad libitum. Vaccination and general management followed standard commercial protocols, and all procedures complied with welfare and biosecurity guidelines. Temperature data was recorded under controlled conditions to ensure consistency before and after the implementation of the IoT-based cyber-physical system.

IoT-Based Cyber-Physical System

The environment is controlled using an Internet of Things (IoT)-based cyber-physical system (CPS) designed to monitor and regulate the microclimate conditions in closed-house poultry houses in real time. This system consists of four main layers: the physical layer, comprising SHT30 sensors to measure air temperature and humidity; the control layer, comprising an Omron PLC integrated with a Haiwell HMI to process sensor inputs and execute control logic; a communication layer comprising an IoT gateway that transmits data to a cloud database and a website; and an application layer comprising a web-based dashboard for real-time monitoring, historical data storage, and remote access. The control algorithm utilises finite state machine (FSM) logic with a hysteresis threshold to prevent the actuators from switching repeatedly within a short period. Based on the pre-set temperature set point, the system automatically activates or deactivates fans, cooling pads, and heaters to maintain environmental conditions within the optimal range required for the physiological needs of broiler chickens.

Data Collection and Statistical Analysis

Temperature data was collected over 33 days of observation covering two conditions: before and after the implementation of an IoT-based cyber-physical system in a closed broiler house. Each day of observation yielded a single average temperature value derived from continuous sensor readings taken in the morning, afternoon, evening, and night. Temperature data under non-system conditions were recorded manually, whilst under the IoT-based cyber-physical system conditions, they were recorded automatically via a web-based monitoring system synchronised daily. In addition to temperature parameters, chicken performance data such as feed intake, body weight, and daily weight gain were also recorded daily to support production performance analysis. Descriptive statistics (mean, standard deviation) were calculated to provide an overview of the dataset. Inferential analysis was conducted to examine the impact of the IoT-based cyber-physical system on feed efficiency, growth performance, and production indices. Data cleaning and simplification were performed using Python, whilst statistical analysis was carried out using SPSS.

RESULTS AND DISCUSSION

Paired T-Test (Temperature)

A paired t-test showed that the IoT-based cyber-physical system did not significantly affect the temperature on average (p = 0.080). Although the temperature after implementation was slightly lower than before, the reduction was not statistically significant. These results indicate that the closed-loop system was already capable of maintaining suitable thermal conditions prior to implementation. However, the slight decrease in temperature suggests that real-time monitoring and automatic control improve the precision and responsiveness of environmental regulation. A strong positive correlation between pre- and post-implementation measurements (r = 0.812) indicates that temperature patterns remain consistent, suggesting that the IoT-based cyber-physical system accurately tracks environmental changes. These findings suggest that the primary contribution of the IoT-based cyber-physical system lies in improving monitoring accuracy and control reliability rather than substantially altering the average temperature (Table 1).

The results showing no significant difference in temperature following the implementation of the IoT-based cyber-physical system do not imply that this control system is ineffective. The average coop temperature before and after implementation was in the range of 28–29℃, which is still within the comfort zone for broiler chickens in the growth phase (starter to grower) according to the thermoneutral zone theory (Fairchild 2009). Within this temperature range, the chickens do not require additional energy for cooling mechanisms (panting) or heating, so energy can be used more efficiently for growth.

A paired t-test revealed a difference in average temperature of 0.41℃ between the periods before and after the system was implemented. This difference was not statistically significant, as indicated by the 95% confidence interval (−0.051 to 0.872) and a t-value of 1.811. The homogeneity of variances indicates environmental stability within the housing, consistent with the concept of microclimate management, which states that environmental stability is more important than extreme fluctuations. This stability is one indicator of the success of the IoT system in controlling the climate, although it has not yet resulted in a statistically significant difference.

Comparison of SOP Temperatures with Actual Data from Non-Automated Systems

A comparison between the standard operating procedure (SOP) temperature and the actual temperature prior to the implementation of the IoT-based cyber-physical system showed that the house temperature was significantly higher than the recommended standard. The Wilcoxon Signed Ranks test revealed a significant difference (p = 0.001), confirming that non-systematic environmental control systems are unable to maintain the temperature within the target range. These results indicate that manual or conventional controls are inadequate for regulating the microclimate of enclosed houses. Temperatures above the recommended threshold can increase heat stress and force broiler chickens to allocate more energy to thermoregulation than to growth. Therefore, deviations from SOP temperatures highlight the need for a more accurate and responsive environmental control system, such as an IoT-based cyber-physical system.

Comparison of SOP Temperatures with Actual Data from an IoT-based Cyber-Physical System

A comparison between the temperatures specified in the SOP and the actual temperatures following the implementation of the IoT-based cyber-physical system showed that the indoor temperature remained significantly higher than the recommended standard (p = 0.016). However, the deviation from the SOP was smaller than that observed prior to the system's implementation, indicating that the IoT-based cyber-physical system improved the accuracy of environmental control. Temperature deviations of approximately 0.8–1.2℃ from the SOP still fall within the thermoneutral zone for broiler chickens, as described by Fairchild (2009). Under these conditions, poultry are generally able to maintain their body temperature without significant heat stress, allowing metabolic energy to be allocated to growth rather than thermoregulation.

Although the actual temperature does not exactly match the SOP target, the IoT-based cyber-physical system reduces deviations compared to conditions without the system. Prior to implementation, temperatures more frequently exceeded the recommended range, thereby increasing the risk of thermal stress. Following implementation, smaller deviations indicate improved control precision and a more stable environment. These findings suggest that, although the system has not yet fully achieved the target temperature setpoint, real-time monitoring and automatic actuator control reduce the discrepancy between actual and recommended conditions. From a practical perspective, this improvement reflects better microclimate regulation and demonstrates the system's potential to enhance environmental precision within broiler chicken production systems.

Table 1 Average temperature in the poultry house before and after the implementation of an IoT-based cyber-physical system (n = 33)

Treatment	Average (°C) ± SD	Std. error	CI 95% (lower–upper)
Before IoT	29.01 ± 1.85	0.32	28.44–29.61
After IoT	28.60 ± 2.23	0.39	27.87–29.36

Comparison of Mortality Rates Before and After the Implementation of an IoT-based Cyber-Physical System

The results of the descriptive analysis prior to the implementation of the IoT-based cyber-physical system showed that mortality rates were relatively high and variable, indicating inconsistent environmental conditions and spikes in mortality figures. The right-skewed distribution showed that, during the observation period, mortality rates were significantly higher than the overall average, reflecting greater risks associated with environmental stress and health issues (Table 2).

Following the implementation of the IoT-based cyber-physical system, mortality rates fell and became more stable, indicating an increase in livestock survival rates and greater stability in environmental management. Narrower confidence intervals and a more symmetrical data distribution indicate that the system reduces fluctuations in daily mortality rates. The Wilcoxon Signed-Rank test showed lower mortality rates following the implementation of the system, confirming that the IoT-based Cyber-physical system makes a positive contribution to reducing mortality rates in broiler chickens under closed-house conditions.

The Wilcoxon signed-rank test revealed a significant reduction in mortality following the implementation of IoT ($Z = -2.792$; $p = 0.005$). These results confirm that the IoT-based cyber-physical system effectively improves livestock survival by reducing both mortality rates and their daily variation. From a production perspective, the mortality rate following the implementation of the IoT-based cyber-physical system, at 2.36%, is below the target of ≤3–5% commonly used in commercial broiler chicken production (Aviagen 2025; Cobb-Vantress 2018), indicating excellent performance and proving that this system can improve production efficiency whilst reducing the risk of economic losses due to livestock mortality.

Broiler mortality rates reflect the effectiveness of rearing management and the stability of the microclimate within the house. Environmental factors such as ventilation, temperature, humidity, and sanitation play a key role in chicken survival rates. Yerpes *et al.* (2020) state that poor ventilation and low temperatures during the rearing phase increase the risk of mortality by up to 17% compared to houses with optimally controlled ventilation. Well-controlled environmental conditions are a key factor in reducing mortality rates in broiler chickens. The reduction in mortality rates from 5.09% to 2.36% following the implementation of an IoT-based cyber-physical system demonstrates the system's effectiveness in controlling environmental factors affecting chicken health. Arif *et al.* (2024) reinforce these findings by stating that an IoT-based closed-house system reduced mortality rates in Cobb-strain chickens from 10.16% to 8.30%, with a stable temperature of 26–27℃ and humidity of 68–84%. The integration of an IoT-based cyber-physical system into poultry house environmental management improves the efficiency of chicken health monitoring. This statement is supported by Depuru *et al.* (2024), who found that technological innovations enable mortality rates to be minimised.

Comparison of Body Weight Before and After the Implementation of an IoT-based Cyber-Physical System

The results of the descriptive analysis show that, prior to the implementation of the IoT-based cyber-physical system, body weight exhibited considerable variation, indicating differences in growth between individuals as well as inconsistent flock performance. The right-skewed and relatively flat distribution suggests that some birds reached significantly higher body weights than others, reflecting inconsistent environmental conditions and management practices. This variability suggests that unsystematic control methods may have led to unstable conditions in efforts to achieve uniform growth in broiler chickens.

After the implementation of the IoT-based cyber-physical system, body weight increased, and data distribution became more symmetrical, indicating improved growth performance and better flock uniformity. The wider confidence interval following implementation suggests that broiler chickens achieved a higher average body weight under more stable environmental conditions. These results indicate that the IoT-based cyber-physical system makes a positive contribution to growth by improving the precision and consistency of microclimate control within the closed-house system (Table 3).

The results of the Wilcoxon signed-rank test yielded a Z-value of -3.529 with a significance level of $p < 0.001$

Table 2 Descriptive statistical comparison of mortality rates before and after the implementation of an IoT-based cyber-physical system (in % and number of birds)

Statistics	Mortality before IoT_13	Mortality after IoT_16
N	33	33
Minimum	0	0
Maximum	22	6
Mean	5.09	2.36
Std. deviation	5.064	1.578
Skewness	2.035	0.623
Kurtosis	4.590	-0.252
BCa 95% CI (lower – upper)	3.55–6.83	1.79–2.95

Table 3 Descriptive statistical comparison of body weight (BW) before and after the implementation of an IoT-based cyber-physical system

Statistics	BW before IoT_13 (g)	BW after IoT_16 (g)
N	33	33
Minimum	54.87	60.91
Maximum	2300.00	2269.00
Mean	846.29	895.43
Std. Deviation	668.45	711.99
Skewness	0.610	0.545
Kurtosis	-0.768	-1.030
BCa 95% CI (Lower–Upper)	640.20–1081.69	678.89–1150.32

($p < 0.05$). These results indicate that there is a highly significant difference between the weight of broiler chickens before and after the implementation of the IoT-based cyber-physical system. The research results show that the implementation of this system has been proven to significantly increase the weight of broiler chickens. These results are consistent with research conducted by Dwipradipta *et al.* (2024), which found that the implementation of an IoT-based smart enclosed coop is capable of maintaining stable coop temperature and humidity in real-time. The implementation of this system resulted in a 2.84% increase in broiler chicken weight compared to non-system houses. Zammit and Park (2023) reported that the implementation of an IoT-based digital poultry system increases weight and improves the feed conversion ratio (FCR) as it can reduce levels of the stress hormone corticosterone through microclimate stabilisation. These research findings are supported by Rowe *et al.* (2019), Jiang *et al.* (2023), and Pratama and Candra (2024), who found that the implementation of modern technology in closed houses facilitates real-time monitoring and control, thereby enhancing production efficiency and the welfare of broiler chickens. These findings confirm that the implementation of an IoT-based cyber-physical system is associated with a significant increase in broiler chicken weight.

Comparison of Feed Conversion Ratios (FCR) Before and After the Implementation of an IoT-based Cyber-Physical System

The descriptive analysis shows that prior to the implementation of the IoT-based cyber-physical system, FCR values exhibited moderate variability, indicating differences in feed utilisation efficiency during the observation period. The slightly left-skewed distribution suggests that most FCR values were concentrated at relatively higher levels, whilst the near-normal kurtosis indicates a stable overall distribution. These results suggest that feed efficiency in the non-system management system is relatively consistent, although there is still room for improvement through more precise environmental control.

Following the implementation of the IoT-based cyber-physical system, the average feed conversion ratio (FCR) decreased slightly, indicating improved feed efficiency, as a lower FCR value suggests that less feed is required to produce each unit of body weight. Furthermore, the smaller standard deviation indicates that feed utilisation became more consistent throughout the observation period. However, this decrease was not statistically significant ($p > 0.05$), and the effect size was negligible (Cohen's $d = 0.081$). This suggests that whilst the IoT-based cyber-physical system tends to improve feed efficiency, the magnitude of this improvement was relatively small during the study period. From a practical perspective, even a slight reduction in FCR has economic significance in commercial broiler chicken production as it reduces feed costs, which constitute the largest component of production costs. These findings suggest that the primary benefit of implementing this system is the creation of a more stable environmental condition that supports slightly more efficient and consistent feed utilization (Table 4).

Farrell (2013) adds that this stability has direct implications for production cost efficiency, as feed accounts for around 60–70% of total operating costs. The results of this study show no significant difference between the two periods. Leeson and Summers (2009) and Aviagen (2019) state that FCR is influenced by feed quality, chicken age, and rearing management. These findings suggest that an IoT-based cyber-physical system is capable of maintaining a balance between feed intake and weight gain through precise control of the microenvironment. The statement by Martinez *et al.* (2022) reinforces this interpretation, suggesting that feed conversion efficiency is more influenced by the chickens' ability to utilise nutrients optimally than by increased feed intake. The meta-regression results indicate that a 1% increase in weight gain reduces feed requirements by 23.5 g/kg live weight. The use of an IoT-based cyber-physical system in this study effectively maintains ideal housing conditions. The physiological characteristics of chickens with low FCR reported by Huang *et al.* (2022) support these findings, indicating that chickens with high feed efficiency have larger stomachs, longer caeca, and relatively smaller livers compared to those with high FCR. This anatomical structure supports better digestive efficiency and nutrient absorption. The IoT-based cyber-physical system has been shown to maintain microclimate stability, enabling optimal digestive organ function and preventing metabolic disorders caused by thermal stress. The implementation of IoT has transformed the broiler chicken production system towards the concept of Precision Livestock Farming 4.0, which is simultaneously focused on efficiency, sustainability, and animal welfare.

Comparison of Performance Index (PI) Before and After the Implementation of an IoT-Based Cyber-Physical System

The descriptive analysis indicates that the Performance Index (PI) increased following the implementation of the IoT-based cyber-physical system, signalling an overall improvement in broiler chicken production performance. Higher PI values reflect the combined effect of increased body weight, reduced mortality rates, and improved feed efficiency under more stable environmental conditions. The bootstrap confidence intervals for both periods are relatively clear and do not include zero, indicating that the observed improvement was consistent throughout the study period. These findings suggest that the positive effects of IoT are not limited to isolated observations but are reflected in sustained improvements in flock performance. As PI integrates several key production indicators into a single measure, an increase in PI indicates that the IoT-based cyber-physical system contributes to improved biological and economic efficiency. These results demonstrate that precise environmental monitoring and automated control can improve overall production outcomes and support the implementation of precision farming in closed-house broiler systems (Table 5).

Performance Index (PI) tends to increase following the implementation of an IoT-based cyber-physical system. This trend indicates an overall improvement in broiler performance, reflecting the combined effects of higher body weight, lower mortality rates, and slightly better feed efficiency. However, the Wilcoxon Signed-Rank Test indicates that this increase is not statistically significant ($Z = -1.706$; $p = 0.088$). This suggests that whilst the IoT-based cyber-physical system has a positive influence on production performance, the magnitude of the increase is insufficient to demonstrate a significant difference over the study period. This is because the PI integrates key biological and economic indicators; consequently, this upward trend remains practically significant. The research findings suggest that this system has the potential to improve overall flock performance by maintaining a more stable environmental condition, even though statistical evidence does not confirm a significant effect.

The average Performance Index (PI) increased following the implementation of the IoT-based cyber-physical system, indicating an overall improvement in broiler chicken production performance. However, the Wilcoxon Signed-Rank test showed that this increase was not statistically significant ($Z = -1.706$; $p = 0.088$). Although the numerical trend was positive, the available evidence was insufficient to confirm a significant effect of the system's implementation during the study period. Most observation days showed higher PI values following implementation, suggesting that the IoT-based cyber-physical system helped maintain a more stable environmental condition and supported consistent flock performance. According to Darwish *et al.* (2017), environmental comfort has a direct effect on the health and productivity of broiler chickens, whilst Aviagen (2019) and Leeson and Summers (2009) emphasise the importance of temperature, humidity, and ventilation in maintaining physiological balance and preventing heat stress. These findings align with the concept of Precision Livestock Farming, which integrates sensor technology and automated control to optimise productivity and animal welfare through actuator control (Berckmans 2017). Higher cumulative time-based PI values following the implementation of an IoT-based cyber-physical system further support the practical significance of the observed trend, suggesting that this system has the potential to improve biological and economic performance, although the statistical differences are not yet significant.

Table 4 Descriptive statistical comparison of the feed conversion ratio (FCR) before and after the implementation of an IoT-based cyber-physical system

Variable	N	Minimum	Maximum	Mean	Std. Deviation	Skewness	Kurtosis
FCR before IoT_13	33	0.651	1.579	1.264	0.274	-0.872	-0.214
FCR after IoT_16	33	0.582	1.480	1.256	0.220	-1.547	2.019

Table 5 Descriptive statistical comparison of performance index (PI) before and after the implementation of an IoT-based cyber-physical system

Statistics	PI before IoT_13	PI after IoT_16
N	33	33
Minimum	194.14	227.80
Maksimum	843.00	1047.71
Mean	339.59 ± 19.24 (SE)	358.29 ± 24.90 (SE)
Std. Deviation	110.53	143.03
Skewness	3.139 (SE = 0.409)	3.613 (SE = 0.409)
Kurtosis	13.660 (SE = 0.798)	17.248 (SE = 0.798)

CONCLUSION

The implementation of an IoT-based cyber-physical system in closed poultry houses improves broiler production performance through enhanced environmental stability and more precise control. Although the average house temperature and feed conversion ratio (FCR) showed no significant differences before and after implementation ($p = 0.080$ and $p = 0.645$, respectively), the system reduced deviations from standard operating procedures and maintained more consistent microclimatic conditions. Mortality rates decreased significantly from 5.09% to 2.36% ($p = 0.005$), and body weight increased significantly from 846.29 g to 895.43 g ($p < 0.001$). The Performance Index (PI) also showed an upward trend, although the difference was not statistically significant ($p = 0.088$). These findings indicate that the IoT-based cyber-physical system effectively improves livestock survival and growth whilst maintaining efficient feed utilisation. Therefore, this system represents a practical and reliable approach to advancing broiler chicken production in closed-house systems towards more efficient, sustainable, and animal-welfare-oriented farming.

ACKNOWLEDGMENTS

The authors would like to express their gratitude for the support from the Faculty of Animal Science, Jenderal Soedirman University, as well as all parties who have contributed to the completion of this research and manuscript.

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