SCIENTIA AGROPECUARIA

Scientia Agropecuaria

Web page: http://revistas.unitru.edu.pe/index.php/scientiaagrop

Facultad de Ciencias Agropecuarias

Universidad Nacional de Trujillo

RESEARCH ARTICLE

Energy efficiency of heating machines and its effects on broiler's performance and welfare

Diandra Masurana-Jahn[1]; Angélica Signor-Mendes[1]*; Cléverson de Souza[1]; Ygor Caldeira-Canterle[1]; Edgar de Souza-Vismara[1]; Isadora Bischoff-Nunes[2]; Irenilza de Alencar-Nääs[3]

[1] Universidade Tecnológica Federal do Paraná, Dois Vizinhos (PR), Brazil.
[2] University of Guelph, Guelph (ON), Canada.
[3] Universidade Paulista, São Paulo (SP), Brazil.

* Corresponding author: angelica@utfpr.edu.br (A. Signor-Mendes).

Received: 3 October 2024. Accepted: 7 March 2025. Published: 24 March 2025.

Abstract

The increasing global demand for animal protein has driven the broiler industry to optimize production systems and better understand limiting factors affecting performance. This study evaluated four different heating systems to determine their correlation with climatic variables, zootechnical performance, pellet fuel consumption, and energy usage. Data were obtained from a private broiler integration company in Southwest Paraná, Brazil, specializing in the griller broiler category. The study covered a 28-day housing period for 12 flocks (both male and female), each consisting of approximately 120,000 birds, for 28 days. The analyzed variables included indoor and outdoor environmental temperature, relative air humidity, carbon dioxide (CO_2) concentration inside the poultry houses, feed conversion ratio, weight gain, pellet fuel consumption, and energy consumption. Statistical analyses were performed using descriptive statistics and Principal Component Analysis (PCA) in R software. Results indicated that correlations among variables were generally weak. However, environmental conditions had the greatest influence on broiler performance. The first principal component explained 74.1% of the total variance, with minimum CO_2 concentration, external temperature, minimum and maximum internal temperature, and pellet fuel consumption being key contributing factors. The second principal component included maximum CO_2 concentration, weight gain, and minimum internal and external relative humidity. Among the evaluated heating systems, the fourth machine tested exhibited the lowest pellet fuel consumption while maintaining satisfactory weight gain and feed conversion rate despite its relatively high energy consumption. These findings suggest that temperature control and pellet fuel consumption are critical factors in optimizing broiler production efficiency, ultimately contributing to improved growth performance and resource utilization.

Keywords: poultry production; thermal comfort; heat system; productivity; gases concentration.

DOI: https://doi.org/10.17268/sci.agropecu.2025.017

Cite this article:
Masurana-Jahn, D., Signor-Mendes, A., de Souza, C., Caldeira-Canterle, Y., de Souza-Vismara, E., Bischoff-Nunes, I., & de Alencar-Nääs, I. (2025). Energy efficiency of heating machines and its effects on broiler's performance and welfare. *Scientia Agropecuaria*, *16*(2), 203-213.

1. Introduction

Brazil is one of the countries with the largest poultry production in the world and one of the primary sources of relevant information regarding broilers' thermal comfort in tropical climates. However, there is a lack of information regarding the energy consumption efficiency of different animal welfare heating/ventilation/cooling systems. Broiler production is one of the leading agricultural activities developed in Brazil, with significant consumption of production inputs, such as energy, grains, and labor force. In 2020, Brazil produced 13.845 million tons of broiler meat. Of this production, 69% were destined for internal market and 31% for exportation (ABPA, 2020).

The efficient production performance of a broiler flock is affected by ambient temperature, humidity, heating or cooling system, and the environment of the broiler house. These factors may be critical in tropical and subtropical areas. Researchers have shown that cold stress significantly influences the health, welfare, and production performance of animals in the coldest regions of the world (Li et al., 2006; Choi et al., 2012), the same way heat stress influences broiler's immune system functioning (Apalowo et al., 2024), nutrition due to lower food intake (Sgavioli et al., 2023; Apalowo et al., 2024), and egg production (Sesay, 2022). Thus, it is fundamental to integrate adaptive solutions, genomic selection, and sustainable approaches to ensure the welfare of broilers inside growing installations.

Regarding the expenses involved in the poultry sector in Paraná state, Brazil, housing sheds equipped with positive pressure air conditioning have an average production cost of R$ 4.89 per kilogram of live broiler produced. The costs of producing broiler meat fluctuate from the world economy, reaching a 6.89% increase in just one month. Many production costs are related to energy use, directly interfering with the adequate provision of the environmental well-being of broilers (EMBRAPA, 2021). Given this scenario, machines with efficient and cheaper heat sources are being tested and used to maintain or improve production at a reduced cost.

A promising alternative is heating machines that use pellets as energy sources since they are a low-cost material. Pellets are biofuels derived from organic matter from forest cleaning and waste and leftovers from the wood industries. In addition, pellets represent an attractive energy source since they do not need specialized labor, so they have been classified as a renewable energy source and an ecologically correct option. Among some advantages of using pellets, particularly more precise control of the temperature in the broiler housing, there is lower emission of odor from wood burning and reduced maintenance of the machines as they are not built with reinforced iron structures, unlike a wood-fired machine (Ismail et al., 2023; Pełka et al., 2023). Therefore, this study aimed to evaluate the influence of different heating machines concerning the thermal comfort and productive performance of broilers placed in the housing shed.

2. Methodology

Animals and Husbandry

The study was conducted by analyzing the database of an integrator company in the Southwest of Paraná, Brazil, with Köppen-Geiger Cfa climate classification (Humid subtropical climate) (Alvares et al., 2013). There were evaluated 28 days-old broilers (griller category for exportation) with a live weight of around 1.400 kg, both males and females, from the linages Male TM4 (M TM4), Female TM4 (F TM4), Female Coob (F COOB), Female AP95 (F AP95), Female Ross TM4 (F Ross TM4). Environmental data was obtained from a meteorological station located at the Universidade Tecnológica Federal do Paraná (UTFPR) Dois Vizinhos campus in Paraná, Brazil, as it is the closest available station to the location of the evaluated broiler houses.

Automatic curtains, evaporative plates, inlets, and exhaust fans controlled the thermal balance inside the housing sheds. Feeding was done by automatic feeders and drinkers every 25 m, with two silos for each housing shed supplied by the integrating company, and the water comes from an artesian well. The sanitary interval took place for 12 to 15 days. Lightening followed the standardized program of the integrating company. Each housing was equipped with two heating machines (Figure 1). House 1 had two heating machines 1 (Mach1A and Mach1B), house 2 had two heating machines 2 (Mach2A and Mach2B), house 3 had two heating machines 3 (Mach3A and Mach3B), and house 4 had two heating machines 4 (Mach4A and Mach4B) (Table 1).

Table 1

Description of components and dimensions of the heating machines evaluated in this study, made available by the suppliers

Machines	Description
Machine 1 (Mach1)	Dimensions: 2.50 m x 2.55 m x 1.85 m (LxWxH) with the door closed. Silo capacity: 400 kg. Components: 1 stoker 0.75 hp; 1 geared motor 1/15 hp; 1 engine of 3 or 4 hp. Minimum dimensions to shelter the heating machine: 6.0 m x 3.0 m x 2.5 m (LxWxH). Minimum door size: 1.80 m x 2.20 m (WxH).
Machine 2 (Mach2)	Dimensions: 5.0 m x 1.40 m x 1.98 m (LxWxH) Silo capacity: 1 m^3 or 2 m^3. Components: 1 stoker of 0.5 hp and 1 of 0.25 hp; 1 engine of 3 hp; 1 geared engine of 0.5 hp; 1 helicoid of 1.5 hp; 1 underground hopper with screw feeder. Minimum dimensions to shelter the heating machine: 10.0 m x 4.0 m x 2.8 m (LxWxH). Minimum door size: 1.80 m x 2.20 m (WxH).
Machine 3 (Mach3)	Dimensions: 1.7 m x 2.0 m x 1.43 m (LxWxH) Silo capacity: 1.6 m^3 to 3 m^3. Components: 1 high-performance engine of 3 hp; 1 electric engine of 1.5 hp and 24 h autonomy; effective flow of 18,000 m^3h^{-1}. Dimensions of the supplier: 1.25 m x 1.84 m x 1.25 m (LxWxH).
Machine 4 (Mach4)	Dimensions: 3.70 m x 2.20 m x 1.25 m (LxWxH) Silo capacity: 200 kg (autonomy of 8 h). Components: 2 engines of 4 hp; 1 stoker of 0.75 hp; 1 stoker for pellets of 0.75 hp; refrigerated tubular grilles; 1 furnace holding 1.2 m firewood. Minimum dimensions to shelter the heating machine: 6.0 m x 3.50 m x 2.40 m (LxWxH). Minimum door size: 0.44 m in diameter.

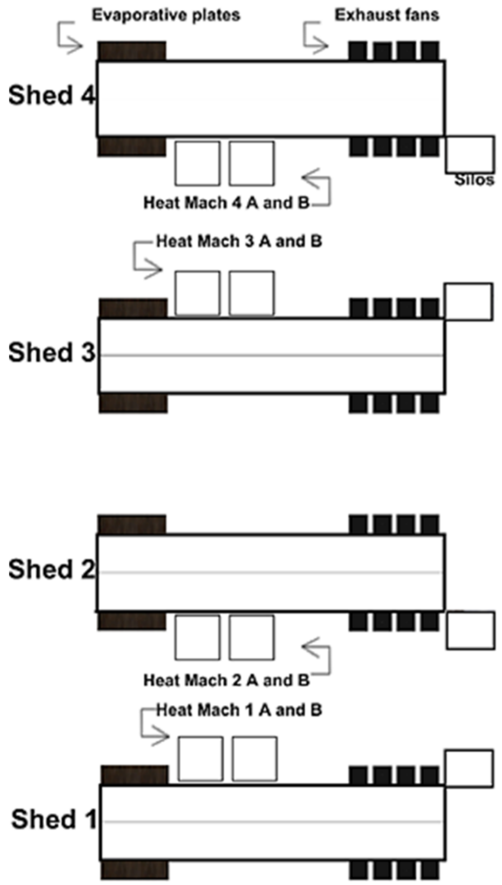

Figure 1. Aerial view of the locations of the housing sheds and disposition of heating machines.

Data assessment and analysis

The database comprised data between August 2019 and July 2020 and contained the following information: internal minimum and maximum relative air humidity (IRHmin and IRHmax, respectively, in %) measured daily through probes located inside the housing shed; internal minimum and maximum temperature (ITmin and ITmax, respectively, in °C) measured daily through probes located inside the housing shed; internal minimum and maximum carbon dioxide levels (CO_2min and CO_2max, respectively, in ppm) measured daily using probes located inside the houses; external relative air humidity (ERH, in %) measured daily by the UTFPR-DV meteorological station; external temperature (ET, in °C) measured daily at the UTFPR-DV meteorological station. For air temperature and relative humidity collections, dual internal and external thermo-hygrometer sensors from Akso brand and model AK29 were used; for CO_2 collections, sensors from the Impact brand, model Datalogger IP-2000C were used.

The birds' performance were: weight gain (WG, in kg) carried out weekly; feed conversion (FC, kgC kgW^{-1}, kilogram of dry food consumed, kgC, per kilogram of weight gain, kgW) obtained at the end of the batch; energy consumption (EC, in kWh) obtained at the end of the batch; pellet consumption (PC, in kg), which is the average pellet consumption of the two machines ($Mach_i$ A and B) in each housing shed, measured daily.

Data was recorded daily and weekly from four housing sheds with equivalent dimensions, facilities, and equipment. The collected data was subjected to statistical analyses, including analysis of variance (ANOVA) and Tukey's test to compare means ($p < 0.05$). This allowed for assessing significant differences in the response variables across the different housing sheds. Furthermore, a Principal Component Analysis (PCA) was performed to gain insights into the data with many response variables. The PCA helped reduce the data's dimensionality and identify patterns and relationships among the variables, providing a comprehensive understanding of the dataset. The scree plot was used to visually assess how much total variance is explained by each principal component. This approach helps decide how many components are necessary to capture substantial information in the original data (Ledesma et al., 2015). Scree plot is a diagnostic tool in PCA, aiding in the interpretation and dimensionality reduction of complex datasets, thus making it easier to visualize and analyze high-dimensional data (Silva et al., 2020; Zhang & Tong, 2020). All statistical analyses, including ANOVA, Tukey's test, and PCA, were conducted using R statistical software (R Core Team, 2024).

3. Results and discussion

Descriptive analysis

Environmental conditions from the minimum and maximum relative air humidity (IRHmin and IRHmax, respectively), indoor minimum and maximum temperature (ITmin and ITmax, respectively), outdoor relative air humidity (ERH), and outdoor temperature (ET) are shown in Figure 2. IRHmin ranged from 54.2% to 62.1%, ITmin ranged from 26.3 ºC to 26.7 ºC, ITmax from 31.9 ºC to 32.5 ºC, ERH remained steady at 70.6%, and ET from 21.4 ºC to 21.8 ºC. IRHmax was the only environmental variable that differed, ranging from 79.8% to 91%, with Mach1 and Mach4 having higher values (91% and 88.6%, respectively).

Relative air humidity greatly influences the broiler's welfare during broiler husbandry (Xiong et al., 2017). Ideally, internal relative air humidity indoors should be kept within 50% to 70% or 80% (Czarick & Fairchild, 2012; Kanjilal et al., 2014).

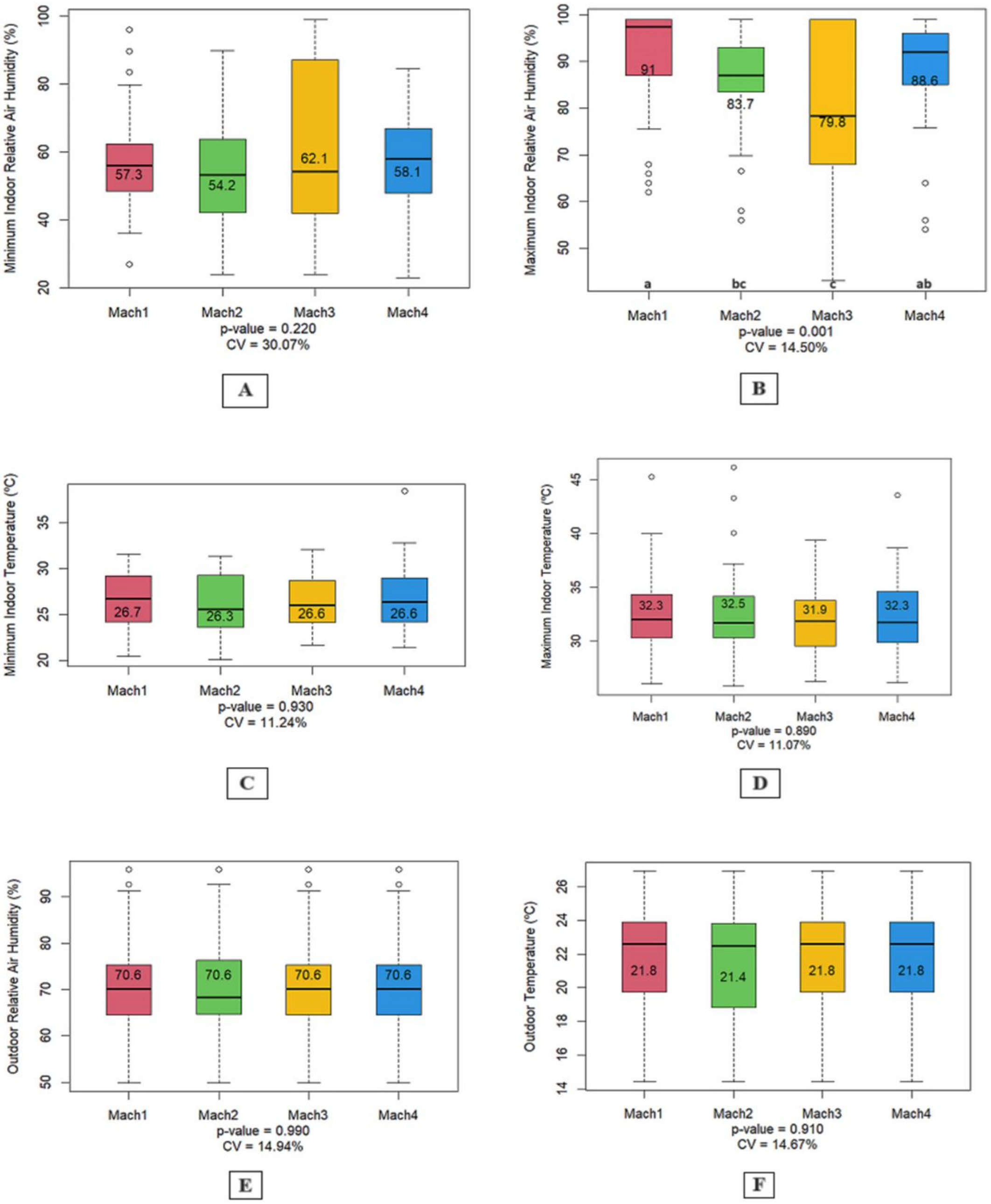

Figure 2. Means of the variables (A) IRHmin (minimum indoor relative air humidity), (B) IRHmax (maximum indoor relative air humidity), (C) ITmin (minimum indoor temperature), (D) ITmax (maximum indoor temperature), (E) ERH (outdoor relative air humidity), and (F) ET (outdoor temperature). Treatments differ significantly by Tukey's test ($p < 0.05$) when followed by different letters.

In the current study, Mach1 was shown to have average values of IRHmin according to the literature, but the highest one for IRHmax did not differ ($p>0.05$) from Mach4 in the latest. Mach2 was shown to have the lowest value for IRHmin, which reflected a better control when compared to Mach1, and the second lowest for IRHmax, not differing from Mach3 and Mach4 in the latest. Mach3 displayed the best control of IRHmax, while Mach4 displayed a low performance on IRHmax, not differing from Mach1 (Figure 2). As expected, outdoor relative air humidity (ERH) did not vary significantly since all housing sheds are on the same property and were evaluated during the same period (Figure 2). IRHmin was within the minimum recommended values for all the machines tested. However, IRHmax was registered above the recommended limit for Mach1 (91%), Mach4 (88.6%), and Mach2 (83.7%), with only Mach3 within the range (79.8%) (Figure 2). Relative air humidity can be directly correlated with infectious diseases, growth, and production, and along with temperature, it is correlated with animal stress (Jones et al., 2005; Line, 2006; Xiong et al., 2017). Thus, Mach3 was the only one maintaining stable optimal conditions in the housing shed.

The second most critical variable in broiler husbandry is temperature. The average comfort zone is 15 °C to 25 °C (El Boushy & Van Marle, 1978). Stress by temperature can be life-threatening in addition to poor performance (Bendheim et al., 1992; Shlosberg et al., 1992; Zhang et al., 2012; Chand et al., 2016; Rehman et al., 2018). The indoor temperatures of the housing sheds (ITmin and ITmax) were well controlled by all the machines tested. In this study, ET, ITmin, and ITmax did not vary significantly, as expected, since all housing sheds are on the same property and were evaluated during the same period (Figure 2). The machines tested had a similar performance in maintaining stable internal temperatures. As artificial heating is not used during the whole husbandry period (only when broilers are younger or during cold seasons), it was observed that temperatures varied between 26.3 ºC and 32.5 ºC for the 28 days of husbandry, being inside the comfort zone preconized by Cassuce et al. (2013) of 23.2 °C to 31.3 °C between the first and third week. In addition, the lowest ITmax in this study showed that the lower the temperature, the higher the feed intake (Figure 2).

Figure 3 shows the zootechnical variables comprising weight gain (WG) and feed conversion (FC). No significant difference was observed for WG, which remained steady at 0.7 kg. FC was the only zootechnical variable that varied significantly with Mach3, Mach2, and Mach3 with the highest values (1,536.7 kgC kgW^{-1}, 1,502.3 kgC kgW^{-1} and 1,493.6 kgC kgW^{-1}, respectively).

The two most important measures for poultry productivity are average live weight and feed conversion, which directly influence production costs. Feed conversion (FC) directly influences the rentability of broiler production since it is affected by the amount of dry food consumed by the broiler metabolism, subsequently negatively impacting broilers' performance (Hurnik et al., 1977). This parameter directly correlates with the broiler's dry food consumption and weight gain. Mach1 resulted in the second highest WG average but without significant difference from the other machines tested. This is also reflected in the high value for FC, which did not differ significantly from Mach2 and Mach3. Mach2 had the lowest average for WG and the second lowest for FC, with no difference between Mach1 and Mach3 (Figure 3). In addition, Mach3 presented the lowest energy consumption (EC), which led to the lowest FC with the lesser energy consumption. Mach3 presented the lowest value for FC on top of the highest value for EC, which resulted in the best FC but at the expense of high energy consumption (Figures 3 and 4, respectively). Both FC and WG suffer from the direct influence of environmental conditions. Thus, broiler growth and performance are favored under optimal husbandry conditions. After evaluating different heating systems by the first week of growth, it was observed that dry food consumption was the same for all systems tested by Cordeiro et al. (2011). However, feed conversion differed, proving that heating systems directly influence broiler performance. In this study, Machines 4, 2, and 1 obtained the lowest values (1,478.7, 1,493.6, and 1,502.3 kgC kgW^{-1}, respectively), not differing significantly among each other (Figure 3).

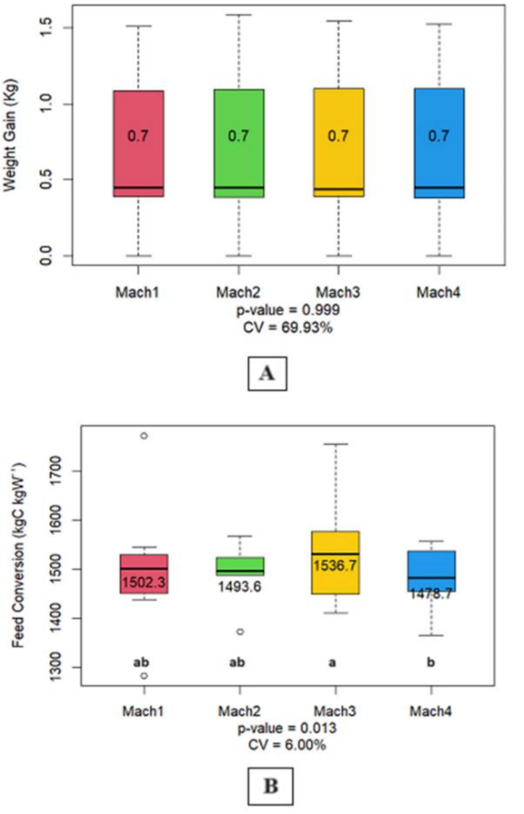

Figure 3. Means of the variables (A) WG (weight gain) and (B) FC (feed conversion). Treatments differ significantly by Tukey's test ($p < 0.05$) when followed by different letters.

The final objective of poultry production is to ensure the broiler's weight gain, which is especially important in the griller category, where birds must be slaughtered with a whole carcass between 1.3 to 1.5 kg destined for exportation (Barbosa Filho et al., 2017). Broilers in the griller category must gain at least 51 g per day for 29 days to achieve around 1.5 kg at the time of slaughter (Butcher and Nilipour, 2005).

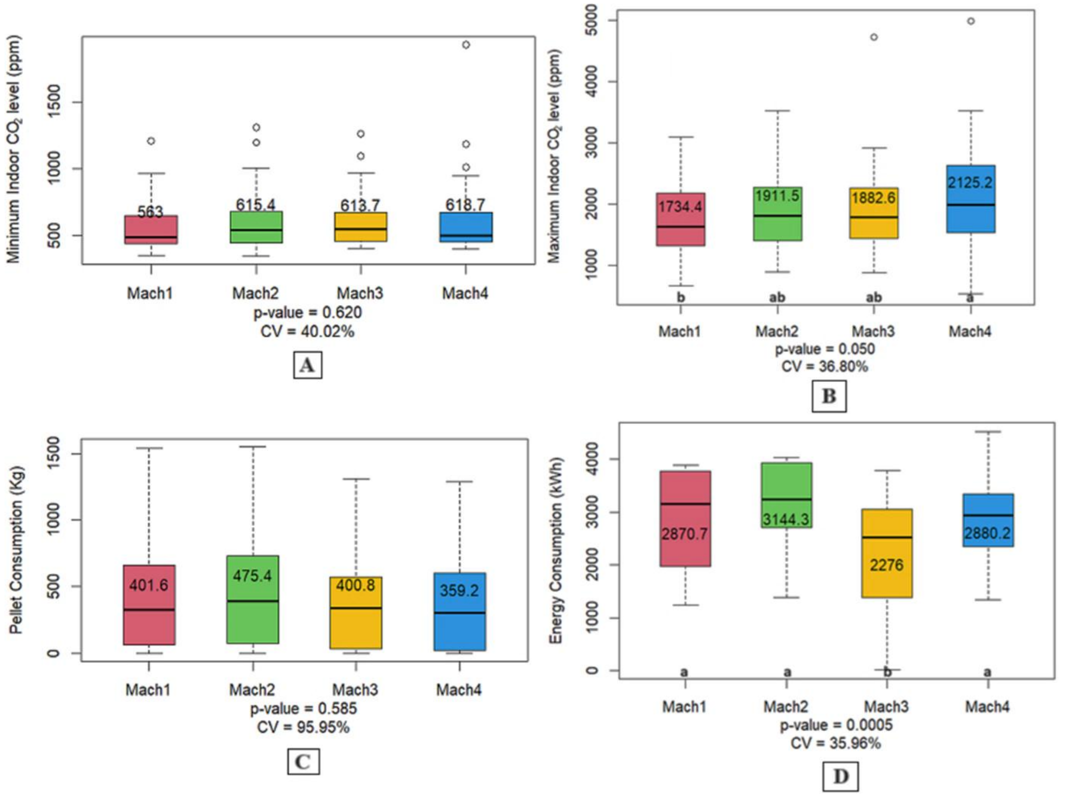

Figure 4. Means of the variables (A) CO_2min (minimum indoor carbon dioxide level), (B) CO_2max (maximum indoor carbon dioxide level), (C) PC (pellet consumption), and (D) EC (energy consumption). Treatments differ significantly by Tukey's test ($p < 0.05$) when followed by different letters.

In this study, the broilers gained an average of 0.670 g to 0.685 g weekly, above the established reference, with all machines being considered equivalent for WG. Thus, Mach4 showed the best results regarding the zootechnical variables once it resulted in the lowest FC value and the second highest WG (Figure 3). This result shows that a high value for weight gain can be obtained with low dry food consumption, which shows this machine's efficiency. The variables for machine efficiency composed of minimum and maximum indoor carbon dioxide levels (CO_2min and CO_2max, respectively), pellet consumption (PC), and energy consumption (EC) are presented in Figure 4. No difference was observed in CO_2min, with values ranging from 536 ppm to 618.7 ppm, nor for PC, which ranged from 359.2 kg to 475.4 kg. CO_2max varied significantly with Mach4, Mach2, and Mach3 with the highest values (2,152.2 ppm, 1,911.5 ppm, and 1,882.6 ppm, respectively), so did EC with Mach2, Mach4, and Mach1 at 3,144.3 kWh, 2,880.2 kWh, and 2,870.7 kWh, respectively.

Carbon dioxide (CO_2) is a harmful gas for animals in high concentrations. Its levels vary according to the broiler's stocking density, age, activity, type of feed, consumption rate and temperature, ventilation efficiency, and use of open-flame heating machines (Reece & Lott, 1980; Yasmeen et al., 2019). The registered CO_2 levels frequently exceed 3,000 ppm due to heating systems during cold seasons or reduced ventilation for lesser energy consumption to heat the housing shed (Olanrewaju et al., 2008). However, the observed CO_2 concentrations averaged 884 ppm. This value falls within the established safety parameters. Wathes (1999) stipulates a maximum continuous exposure limit of 3,000 ppm for avian environments. Similarly, the Humane Farm Animal Care (HFAC, 2009) guidelines mandate that CO_2 levels remain below 3,000 ppm, with an absolute upper threshold of 5,000 ppm. The recorded 884 ppm is consistent with the CO_2 standard set forth by Cobb Vantress (2021), which also specifies a limit of 3,000 ppm.

Mach1 was also shown to have the best control for CO_2 concentration inside the housing shed (CO_2min and CO_2max) (Figure 4). Mach2 also had the second lowest value for CO_2min but one of the highest for CO_2max, not differing significantly from Mach3 and Mach4. Mach3 displayed the best control of IRHmax and the second lowest value for CO_2max, not differing from Mach2 for both variables ($p>0.05$). Mach4 had the highest value for CO_2max; however, it did not differ from Mach2 and Mach3. Values in this study for CO_2min did not differ within the machines tested, while CO_2max did with values that did not exceed the 3,000 ppm limit standardized (COBB, 2021). Also, the highest value for CO_2max did not reflect the lowest value for WG but for FC, while the lowest value for CO_2max reflected the highest value for WG but not for FC (Figures 3 and 4). The CO_2 concentrations found in the present study showed that pellets are a good option for broilers heating once it was below when firewood (1427.3 and 1527.7 ppm in systems with and without ventilation, respectively) or gas open flame (1247 to 1663 ppm for indirect and directly heated sheds, respectively) were used (Vigoderis et al., 2010; Smith et al., 2016). In addition, CO_2 concentrations can be lowered by increasing ventilation in the housing shed, and this study did not interfere significantly with our results, being within the preconized limits in the Brazilian poultry industry.

Another factor that can make broiler production more expensive is the energy consumption by the housing sheds, and heating systems can represent a big part of this consumption. Adopting technology that combines high production standards with reduced costs should always be considered in poultry production (Barbosa Filho et al., 2017). Providing external heating sources to broilers is essential to ensure proper performance and growth since those animals do not have well-developed thermoregulation and are very sensitive to cold temperatures in the first days of life (Baêta & Souza, 2010). Broilers are homeothermic and need a constant temperature of around 41.5 °C to ensure proper metabolic functions (Ferreira, 2011; Ryu et al., 2016). Despite ITmin and ITmax being below that threshold (between 26.3 °C and 32.5 °C), the results still reflected good weight gain (up to 0.685 g week^{-1}) and feed conversion (down to 1,478 kgC kgW^{-1}).

Systems based on sustainable energy sources for heating systems are currently on topic for broiler production (Cui et al., 2020; Cui et al., 2021). Handayani et al. (2025) provide valuable insights for farmers in selecting suitable technologies that meet their specific needs, thereby improving the efficiency of broiler chicken farming. Oscillation in gas prices makes pellets an attractive option given the easy access and multiple biomass sources, no need for specialized labor, and being a sustainable and renewable energy source (Ismail et al., 2023; Pełka et al., 2023). Mach1 had the highest energy consumption (EC), along with Mach2 and Mach4 (Figure 4). No difference was observed for pellet consumption between the two machines in the housing shed (PCMA and PCMB) or ERH and ET (Figure 3). In addition, Mach3 presented the lowest energy consumption (EC), which led to the lowest FC with the lesser energy consumption (Figure 4). Mach3 presented the lowest value for FC on top of the highest value for EC, which resulted in the best FC but at the expense of high energy consumption. Even with the highest EC mean, using Mach4 led to the best flock performance (low FC with high WG) while consuming the lowest quantity of pellets (between 350 kg and 368.4 kg) (Figure 4). This result indicates that researching and investing in some heating machines in the market can reflect good production metrics, even with a slightly increased.

Pearson's correlation results are presented in Figure 5. It was observed that all variables in this study are weakly correlated. Both indoor relative air humidity (IRHmin and IRHmax) and indoor temperatures (ITmin and IT max) are the variables with the higher positive correlation coefficients, 0.56 and 0.69, respectively. PC and CO_2min were also positively correlated (0.48), and WG and IRHmax (0.40). The most expressive negative correlations were between ET, CO_2min (-0.52), and PC (-0.52), and WG with PC (-0.69), IT min (-0.67), and ITmax (-0.57).

Thermal comfort is the primary factor to be considered when producing broilers. The estimation and understanding of how the parameters evaluated in this study influence broiler production might aid the development of more efficient heating models for farmers. Mach4 showed the best efficiency in pellet consumption with satisfactory weight gain and feed conversion results. The lack of significant difference for IRHmin, ERH, ITmin, ITmax, ET, WG, and PC shows that all machines tested have a similar heating performance under the same environmental conditions. The strong influence of thermal comfort variables in data variance shows that this is the most critical aspect to be observed to ensure good performance results.

Principal Components Analysis (PCA)

The contribution of each component (Figure 6A) and each variable (Figure 6B) are shown below. The lineages used in this study were not used as a variable since no significant difference or contribution was observed. The variables with the higher weight to represent the study's data were WG, PC, ITmin, and ITmax, thus clearly supporting the current literature that temperature is the most critical parameter to control in the broiler industry, reflecting directly on weight gain. The consumption of pellets is directly linked to the temperature control of housing sheds. Thus, it is advantageous for the farmer to consider using a heating machine that can effectively control the internal temperature of the housing shed with the minimum economic impact of pellet consumption.

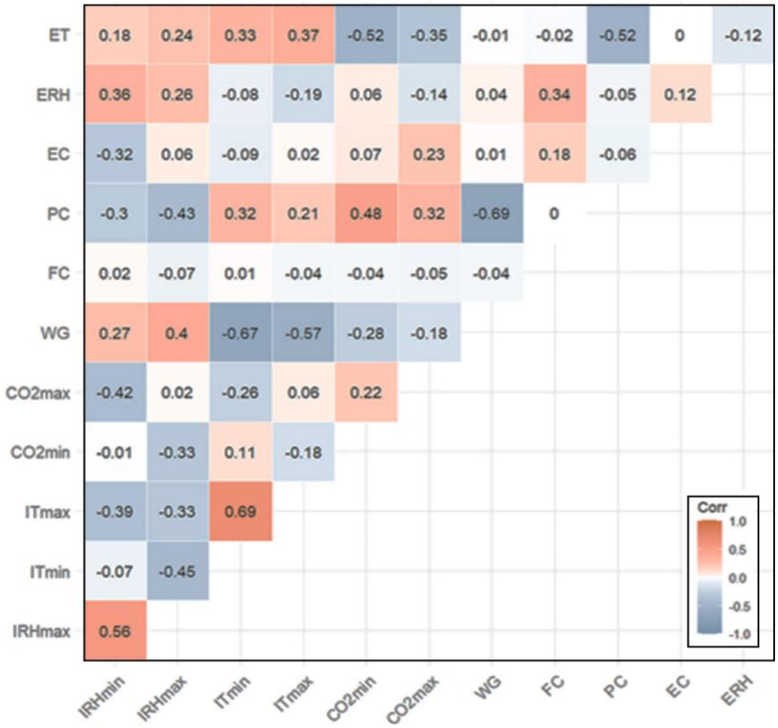

Figure 5. Pearson's correlation between all evaluated variables in this study.

The PCA results show that PC1 explained 50.2%, and PC2 explained 23.9% of the total variance (Figure 7). PC1 comprises IRH min and IRHmax, ERH, WG, and PC. Despite being negatively correlated, WG and PC are the two variables that most influenced PC1, followed by IRHmax, IRHmin, and ERH. PC2 encompasses ITmin and ITmax, ET, CO_2min and CO_2max, FC and EC. ET, ITmax, and ITmin are the variables that most influenced PC2, all positively correlated, followed by CO_2min, CO_2max, EC, and FC, all negatively correlated. PC1 can be translated as the need for the best cost/efficiency relationship when considering a heating machine for the housing shed once it can keep constant temperatures inside, with minimum pellet consumption. PC2 can be translated as the need to keep broilers comfortable in an environment that, besides temperature, is kept not too dry and has low concentrations of CO_2 with minimal energy consumption to ensure proper weight gain.

Without surprise, PC was positive and closely correlated with CO_2 concentration (CO_2min and CO_2max) (Figures 6 and 7). The fact that pellet consumption was more closely related to CO_2min rather than CO_2max reinforces that pellets are a reasonable option for heating systems as a more sustainable heat source. However, it is good to reinforce that the higher the internal relative air humidity and temperature, the higher the microbial activity, resulting in higher CO_2 levels.

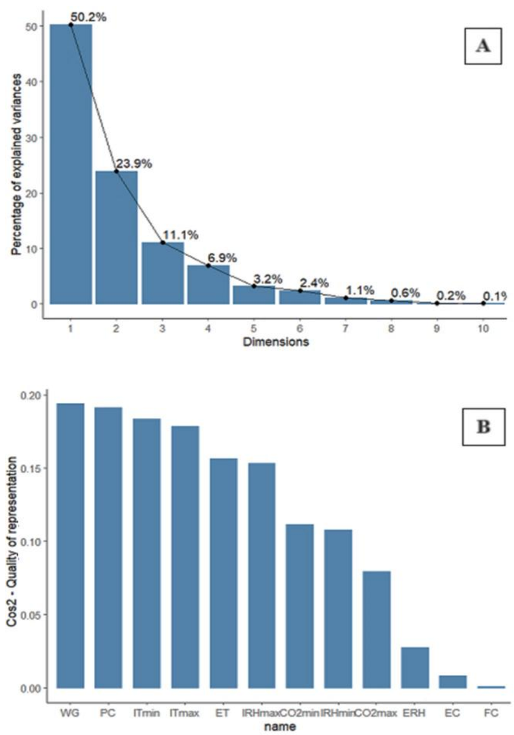

Figure 6. Scree plots indicating (A) the influence of each principal component (PC) and (B) each variable on explaining the total variance of the data.

In this case, ventilation can decrease that condition, especially during hot seasons (Qiu et al., 2022). Relative air humidity (IRHmin and IRHmax) correlated more closely to EC than ITmin and ITmax

(Figures 6 and 7). Given the high humidity levels needed in the houses for broiler welfare, such a scenario was expected, which reflected no significant variation in the internal temperatures. In addition, broilers that are kept under thermal comfort tend to result in a greater productive return (Lott et al., 1998).

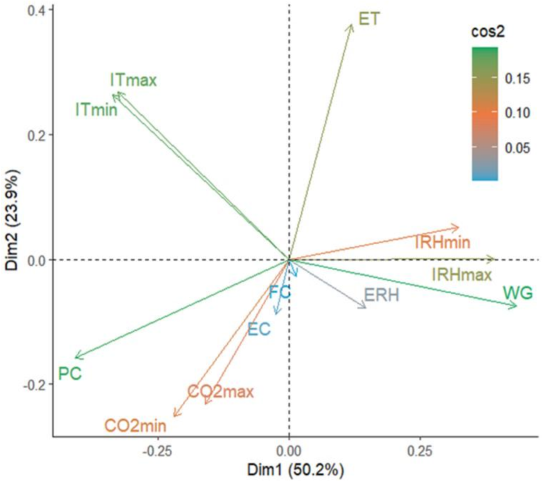

Figure 7. Principal Components Analysis (PCA) loading plot showing the multivariate variation among all evaluated broilers in terms of environmental, zootechnical, and consumption variables. Vectors indicate the direction, and the colors indicate the contribution strength of each evaluated variable. The first two principal axes explained 74.1% of the total data variance.

The strong influence of thermal comfort in broilers explains why WG also composed PC1 while FC composed PC2. The weak correlation between pellet consumption and energy consumption reflects the reduced need for heating machines during hot seasons, resulting in the almost null influence of pellet consumption in PC2. Organisms tend to experience an increased rate of weight gain under lower temperatures and the opposite under higher temperatures, resulting in a feed conversion ratio directly related to temperature in broilers above 0.8 kg; thus, the higher the weight, the higher the temperature effect (Lott et al., 1998).

When analyzing quails' performance and carcass, the PCA approach explained 75% of the original variance with the first four components (Leite et al., 2009). By studying the performance of three broiler lineages, it was observed that two PCs could explain 65% of the variance of the Arbor Acre lineage, three to explain 74,76% for the Marshal lineage, and 70% for the Ross lineage (Udeh and Ogbu, 2011). In the present study, the first two principal components were able to explain almost 80% of the data variance, with WG, PC, ITmin, and ITmax being the variables with the most influence (Figures 6 and 7). Despite the weak correlation observed, all variables in this study had some degree of interference in the growth and performance of broilers and can be affected by heating systems in the housing sheds, the difference being whether this interference is positive or negative (Figure 5). In addition, the current results elucidate the close relationship of these variables, even if not strongly significant.

4. Conclusions

The fourth machine tested in this study showed the best efficiency in pellet consumption with acceptable weight gain and feed conversion results. The lack of significant difference for minimum internal relative humidity, external relative humidity, minimum and maximum internal temperatures, and pellet consumption between the first and second machines tested in this study shows that all machines tested have a similar heating performance under the same environmental conditions. Although affected by thermal comfort, the zootechnical variables evaluated in the present study were still satisfactory and within the parameters preconized by the strain manuals. The strong influence of thermal comfort variables in data variance shows that this is the most critical aspect to be observed to ensure good production results. Further research is recommended regarding sustainable approaches to ensure the broiler's thermal comfort with pellets from different combustible sources.

Author contributions

Conceptualization, A. S. M. and D. M. J.; methodology, A. S. M. and D. M. J.; investigation, Y. C. C.; writing — original draft, I. B. N and I. A. N.; writing — review and editing, C. S. and Y. C. C.; funding acquisition, A. S. M.; resources, I. B. N., C. S. and E. S. V.; supervision, A. S. M. and I. A. N.; software and formal analysis, E. S. V.

Funding statement

No funds, grants, or other support was received.

Competing interests

The authors declare no conflicts of interest.

Ethical standards

The authors state that the procedures followed the ethical standards of the National Committee on Animal Experimentation.

ORCID

D. Masurana-Jahn https://orcid.org/0000-0002-0617-0444
A. Signor-Mendes https://orcid.org/0000-0001-6644-1907
C. de Souza https://orcid.org/0000-0003-0858-5237
Y. Caldeira-Canterle https://orcid.org/0000-0003-1798-1231
E. de Souza-Vismara https://orcid.org/0000-0002-0200-1117
I. Bischoff-Nunes https://orcid.org/0000-0002-0697-6456
I. de Alencar-Nääs https://orcid.org/0000-0003-0663-9377

References

ABPA. (2020). *Annual report*. Brazilian Association of Animal Protein. https://abpa-br.org/wp-content/uploads/2022/02/abpa-relatorio-anual-2020.pdf

Alvares, C. A., Stape, J. L., Sentelhas, P. C., & Gonçalves, J. L. M. (2013). Modeling monthly mean air temperature for Brazil. *Theoretical and Applied Climatology*, *113*(3-4), 407-427. https://doi.org/10.1007/s00704-012-0799-2.

Apalowo, O. O., Ekunseitan, D. A., & Fasina, Y. O. (2024). Impact of heat stress on broiler chicken production. *Poultry*, *3(2)*, 107-128. https://doi.org/10.3390/poultry3020010

Baêta, F. C., & Souza, C. F. (2010). *Ambiência em edificações rurais: conforto animal* (2nd ed.). Viçosa: Editora UFV.

Barbosa Filho, J. A., Almeida, M., Shimokomaki, M., Pinheiro, J. W., Silva, C. A., Michelan Filho, T., & Oba, A. (2017). Growth performance, carcass characteristics, and meat quality of griller-type broilers of four genetic lines. *Brazilian Journal of Poultry Science*, *19*, 109-114. https://doi.org/10.1590/1806-9061-2016-0310

Barbosa, R. C., Dalólio, F. S., Amorim, M. L., Silva, J. N., & Gonzaga, D. A. (2017). Analysis of economic feasibility of heating systems in agricultural facilities during broiler breeding. *Revista Engenharia na Agricultura*, *25*(3), 212-222. https://doi.org/10.13083/reveng.v25i3.780

Bendheim, U., Berman, E., & Zadikov, I. (1992). The effects of poor ventilation, low temperatures, type of feed, and sex of bird on the development of ascites in broilers. *Avian Pathology*, *21*(3), 383-388. https://doi.org/10.1080/03079459208418854

Butcher, G. D., & Nilipour, A. H. (2005). Broiler production goals - important numbers: VM134/VM099. https://edis.ifas.ufl.edu/publication/VM099

Cassuce, D. C., Tinôco, I. F. F., Baêta, F. C., Zolnier, S., Cecon, P. R., & Vieira, M. F. A. (2013). Thermal comfort temperature update for broiler chickens up to 21 days of age. *Engenharia Agrícola*, *33*, 28-36. https://doi.org/10.1590/S0100-69162013000100004

Chand, N., Muhammad, S., Khan, R. U., Alhidary, I. A., & Rehman, Z. U. (2016). Ameliorative effect of synthetic gamma-aminobutyric acid (GABA) on performance traits, antioxidant status, and immune response in broilers exposed to cyclic heat stress. *Environmental Science and Pollution Research*, *23*, 23930-23935. https://doi.org/10.1007/s11356-016-7604-2

Choi, H. C., Salim, H. M., Akter, N., Na, J. C., Kang, H. K., Kim, M. J., Kim, D. W., Bang, H. T., Chae, H. S., & Suh, O. S. (2012). Effect of heating system using a geothermal heat pump on the production performance and housing environment of broiler chickens. *Poultry Science*, *91*, 275-281. https://doi.org/10.3382/ps.2011-01573

COBB. (2021). *Cobb broilers – management guide*. Cobb-Vantress. https://www.cobb-vantress.com/assets/Cobb-Files/045bdc8f45/Broiler-Guide-2021-min.pdf

Cordeiro, M. B., Tinôco, I. F. F., Silva, J. N., Vigoderis, R. B., Pinto, F. A. C., & Cecon, P. R. (2010). Conforto térmico e desempenho de pintos de corte submetidos a diferentes sistemas de aquecimento no período de inverno. *Revista Brasileira de Zootecnia*, *39*(1), 217-224. https://doi.org/10.1590/S1516-35982010000100030

Cordeiro, M. B., Tinôco, I. F. F., Mesquita Filho, R. M., & Sousa, F. C. (2011). Digital image analysis for young chicken's behavior evaluation. *Engenharia Agrícola*, *31*(3), 418-426. https://doi.org/10.1590/S0100-69162011000300003

Cui, Y., Theo, E., Gurler, T., Su, Y., & Saffa, R. (2020).A comprehensive review on renewable and sustainable heating systems for poultry farming. *International Journal of Low-Carbon Technologies*, *15*, 121–142, https://doi.org/10.1093/ijlct/ctz048

Cui, Y., Xue, X., & Riffat, S. (2021). Cost Effectiveness of Poultry Production by Sustainable and Renewable Energy Source. IntechOpen. . https://doi.org/10.5772/intechopen.97543

Czarick, M., & Fairchild, B. (2012). Relative humidity: the best measure of overall poultry house air quality. https://www.poultryventilation.com/wp-content/uploads/vol24n2.pdf

El Boushy, A. R., & Van Marle, A. L. (1978). The effect of climate on poultry physiology in tropics and their improvement. *World Poultry Science Journal*, *34*, 155-171. https://doi.org/10.1017/S0043933907000268

EMBRAPA. (2021). Custos de produção de frangos de corte e de suínos acumulam alta de mais de 48% nos últimos 12 meses. Empresa Brasileira de Pesquisa Agropecuária. https://www.embrapa.br/busca-de-noticias/-/noticia/60135950/custos-de-producao-de-frangos-de-corte-e-de-suinos-acumulam-alta-de-mais-de-48-nos-ultimos-12-meses

Ferreira, R. A. (2011). *Maior produção com melhor ambiente: para aves, suínos e bovinos*. Viçosa: Editora Aprenda Fácil.

Handayani, D., Haryono, H., Prihatiningsih, T., Hikmah, N. (2025). Evaluation of the Performance of Automatic Temperature Control Technology in a Closed House Broiler Chicken Production System. *Journal of Industrial Engineering and Halal Industries*, *5*(2), 24–31. https://doi.org/10.14421/jiehis.4954

HFAC Humane Farm Animal Care. (2009). Padrões do HFAC para a produção de Frangos de Corte. Fev.

Hurnik, J. F., Summers, J. D., Walker, J. P., & Szkotnicki, W. (1977). Production traits influencing the individual feed conversion ratio. *Poultry Science*, *56*(3), 912-917. https://doi.org/10.3382/ps.0560912

Ismail, R. I., Khor, C. Y., & Mohamed, A. R. (2023). Pelletization temperature and pressure effects on the mechanical properties of *Khaya senegalensis* biomass energy pellets. *Sustainability*, *15(9)*, 7501. https://doi.org/10.3390/su15097501

Jones, T. A., Donnelly, C. A., & Stamp, D. M. (2005). Environmental and management factors affecting the welfare of chickens on commercial farms in the United Kingdom and Denmark stocked at five densities. *Poultry Science*, *84*, 1155-1165. https://doi.org/10.1093/ps/84.7.1155

Kanjilal, D., Singh, D., Reddy, R., & Mathew, J. (2014). Smart farm: extending automation to the farm level. *International Journal of Scientific & Technology Research*, *3*(7), 109-113.

Ledesma, R., Valero-Mora, P., & Macbeth, G. (2015). The scree test and the number of factors: a dynamic graphics approach. *The Spanish Journal of Psychology*, *18*, E11. https://doi.org/10.1017/sjp.2015.1

Leite, C. D. S., Corrêa, G. S. S., Barbosa, L., Melo, A. L. P., Yamaki, M., Silva, M. A., & Torres, R. A. (2009). Avaliação de características de desempenho e de carcaça de codornas de corte por meio da análise de componentes principais. *Arquivo Brasileiro de Medicina Veterinária e Zootecnia*, *61*(2), 498-503. https://doi.org/10.1590/S0102-09352009000200014

Li, S. Z., Ren, B. B., Yang, H. M., Yang, Y. Y., Ji, H., & Ni, J. (2006). Effect of cold stress with different intensities on HSP70 expression in Wistar rat muscle, spleen, and liver. *Chinese Journal of Applied Environmental Biology*, *12*, 235-238.

Line, J. E. (2006). Influence of relative humidity on transmission of Campylobacter jejuni in broiler chickens. *Poultry Science*, *85*(7), 1145-1150. https://doi.org/10.1093/ps/85.7.1145

Lott, B. D., Simmons, J. D., & May, J. D. (1998). The effect of environmental temperature and body weight on growth rate and feed: gain ratio of broilers. *Poultry Science*, *77*(3), 347-351. https://doi.org/10.1093/ps/77.3.347

Olanrewaju, H. A., Dozier, W. A., Purswell, J. L., Branton, S. L., Miles, D. M., Lott, B. D., Pescatore, A. J., & Thaxton, J. P. (2008). Growth performance and physiological variables for broiler chickens subjected to short-term elevated carbon dioxide concentrations. *International Journal of Poultry Science*, *7*, 738-742. https://doi.org/10.3923/ijps.2008.738.742

Pełka, G., Jach-Nocoń, M., Paprocki, M., Jachimowski, A., Luboń, W., Nocoń, A., Wygoda, M., Wyczesany, P., Pachytel, P., & Mirowski, T. (2023). Comparison of emissions and efficiency of two types of burners when burning wood pellets from different suppliers. *Energies*, *16*(4), 1695.

Qiu, Y., Zhou, Y., Chang, Y., Liang, X., Zhang, H., Lin, X., Qing, K., Zhou, X., & Luo, Z. (2022). The effects of ventilation, humidity, and temperature on bacterial growth and bacterial genera distribution. *International Journal of Environmental Research in Public Health*, *19*(22), 15345. https://doi.org/10.3390/ijerph192215345

R Core Team. (2024). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available at: https://www.R-project.org/.

Reece, F. N., & Lott, B. D. (1980). Effect of carbon dioxide on broiler chicken performance. *Poultry Science*, *59*(11), 2400-2402. https://doi.org/10.3382/ps.0592400

Rehman, Z. U., Chand, N., & Khan, R. U. (2018). An assessment of the growth and profitability potential of meat-type broiler strains under high ambient temperature. *Pakistan Journal of Zoology*, *50*(2), 429-435. https://doi.org/10.17582/journal.pjz/2018.50.2.429.435

Ryu, S. T., Park, B. S., Bang, H. T., Kang, H. K., & Hwangbo, J. (2016). Effects of anti-heat diet and inverse lighting on growth performance, immune organ, microorganism and short chain fatty acids of broiler chickens under heat stress. *Journal of Environmental Biology*, *37*(2), 185-192. https://doi.org/10.22438/jeb/37/2/MN-1363

Sesay, A. R. (2022). Impact of heat stress on chicken performance, welfare, and probable mitigation strategies. *International Journal of Environment and Climate Change*, *12*(11), 3120-3133. https://doi.org/10.9734/IJECC/2022/v12i111360

Sgavioli, S., Santos, E. T., Domingues, C. H. D. F., Castiblanco, D. M. C., Rodrigues, P. H. M., Zeferino, C. P., Almeida, A. R., & Boleli, I. C. (2023). Broiler behavior: Influence of thermal stress, age, and period of the day. *Revista Brasileira de Zootecnia*, *52*, p.e20200239. https://doi.org/10.37496/rbz5220200239

Shlosberg, A., Pano, G., Handji, V., & Berman, E. (1992). Prophylactic and therapeutic treatment of ascites in broiler chickens. *British Poultry Science*, *33*(1), 141-148. https://doi.org/10.1080/00071669208417473

Silva, R., Oliveira, D., dos Santos, D. P., Santos, L. F. D., Wilson, R. E., & Bedo, M. (2020). Criteria for choosing the number of dimensions in a principal component analysis: An empirical assessment. Research paper presented at the Simpósio Brasileiro de Banco de Dados (SBBD) 35th Annual Meeting, Porto Alegre, Rio Grande do Sul, 28 September – 1 October 2020. *SBBD Annals*, *35*, 145-150. https://doi.org/10.5555/1234567890

Smith, S., Meade, J., Gibbons, J., McGill, K., Bolton, D., & Whyte, P. (2016). Impact of direct and indirect heating systems in broiler units on environmental conditions and flock performance. *Journal of Integrative Agriculture*, *15*(11), 2588-2595. https://doi.org/10.1016/S2095-3119(16)61351-4 · Udeh, I., & Ogbu, C. C. (2011). Principal component analysis of body measurements in three strains of broiler chicken. *Science World Journal*, *6*(2), 11-14. https://doi.org/10.4314/swj.v6i2.68340

Vigoderis, R. B., Cordeiro, M. B., Tinôco, I. D., Menegali, I., Souza Júnior, J. P., & Holanda, M. C. (2010). Avaliação do uso de ventilação mínima em galpões avícolas e de sua influência no desempenho de aves de corte no período de inverno. *Revista Brasileira de Zootecnia*, *39*, 1381-1386. https://doi.org/10.1590/S1516-35982010000600009

WATHES, C. M. Strive for clean air in your poultry house. World Poultry, v.15, n.3, p.17-19, 1999.

Xiong, Y., Meng, Q. S., Jie, G. A., Tang, X. F., & Zhang, H. F. (2017). Effects of relative humidity on animal health and welfare. *Journal of Integrative Agriculture*, *16*(8), 1653-1658. https://doi.org/10.1016/S2095-3119(17)61715-4

Yasmeen, R., Ali, Z., Tyrrel, S., & Nasir, Z. A. (2019). Estimation of particulate matter and gaseous concentrations using low-cost sensors from broiler houses. *Environmental Monitoring and Assessment*, *191*, 1-10. https://doi.org/10.1007/s10661-019-7408-y

Zhang, X., & Tong, H. (2020). Some cautionary comments on principal component analysis for time series data. *arXiv*, 2008.01496. https://doi.org/10.48550/arXiv.2008.01496

Zhang, Z. Y., Jia, G. Q., Zuo, J. J., Zhang, Y., Lei, J., Ren, L., & Feng, D. Y. (2012). Effects of constant and cyclic heat stress on muscle metabolism and meat quality of broiler breast fillet and thigh meat. *Poultry Science*, *91*, 2931-2937. https://doi.org/10.3382/ps.2012-02336