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Spatial and temporal variability of enthalpy and its influence on the cloacal temperature of broilers

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Abstract. Strategies aimed at mitigating heat stress conditions pose a challenge for the poultry industry operating in tropical climate zones. The primary aim of this research was to characterize and analyze the specific enthalpy of air (h, in kJ kg of dry air^{-1}) in a broiler house using geostatistical techniques. In addition, its relationship with the cloacal temperature ($t_{cloacal}$, °C) of the broilers was evaluated. The study was carried out in Lavras, Minas Gerais, Brazil. A total of 720 Cobb-500 broilers were raised from 1 to 42 days old. When the broilers were 7, 21, 35 and 42 days old, the dry bulb temperature (t_{db}, °C) and relative air humidity (RH, %) were recorded at 08:00 a.m. and 01:00 p.m. by seven sensors distributed throughout the installation, and $t_{cloacal}$ measured. Subsequently, h computed, and the data were examined through kriging interpolation. The $t_{cloacal}$ data were superimposed on the h maps of the facility. The spatial distribution of h inside the aviary (box) and temporal distribution (time and days) were characterized, and its variability was visualized. $T_{cloacal}$ was directly related to the spatial as well temporal distribution of h, providing information about the thermal influence on production environment and the physiological responses of broilers.

Key words: body temperature, geostatistics, heat stress, thermal comfort.

INTRODUCTION

In Brazil, intensive broiler production is conducted mainly in semiclimatized or climatized barns (Lima & Silva, 2019; Sans et al., 2021) due to the high cost of technological facilities with controlled environments. This suggests that ideal thermal comfort conditions are not always possible throughout the production cycle. As a result, the oscillations in the dry bulb temperature (t_{db}, °C) and relative air humidity (RH, %) inside poultry facilities can result in heat-stressed broilers, which represents a challenge for industrial poultry farming, especially in tropical and subtropical regions (Liu et al., 2020; Abdel-Moneim et al., 2021).

According to Roushdy et al. (2018), chronic thermal stress (daily, 6 hours at 34 °C for three consecutive weeks) adversely influences feed intake and body weight gain among both Ross and Cobb broiler chickens. Castro Júnior & Silva (2021) reported that the rate of panting increased among broilers subjected to high temperatures (above 35 °C) as a strategy to enhance excess heat loss to the environment. This process corresponds to latent heat exchange, which depends on the RH. Thus, if the RH is high, this heat exchange process will be less efficient and may hinder thermoregulation of broilers (Castro Júnior & Silva, 2021).

For this reason, the reduced production performance due to heat stress has been associated with physiological and metabolic changes (Ahmed-Farid et al., 2021; Nawaz et al., 2021). According to Brown-Brandl et al. (2003), the physiological variable cloacal temperature ($t_{cloacal}$) is a suitable indicator of comfort or heat stress in broilers because it is directly related to the internal body temperature and is easy to measure.

Given the importance of the microclimate of the aviary for housed animals, the specific enthalpy of air (h, kJ kg of dry air^{-1}) is the only psychrometric variable that encompasses the concept of thermal energy in the environment, constituting the sum of the latent and sensible heat components, justifying its use for assessing the internal environment of poultry production due to the application of heat exchange physical concepts to animals and their environment (Queiroz et al., 2017; Castro Júnior & Silva et al., 2021).

Within this context, geostatistical techniques have been employed as efficient tools for evaluating thermal variables inside animal breeding facilities (Lopes et al., 2020; Faustino et al., 2021, Silva et al., 2021). Geostatistical analysis allows us to quantitatively characterize the spatial variability as much as the temporal variability in t_{db}, RH and h in installations, avoiding biased data interpretations and allowing the observation of spatial dependence through kriging maps (Oliveira et al., 2022). However, Sans et al. (2021) mentioned a lack of studies that include environmental (for example, h) and animal welfare ($t_{cloacal}$) indicators through geostatistical analysis and, when applied together, can allow the adoption of management strategies to improve animal welfare.

Silva et al. (2021) superimposed data of the respiratory rate and ear surface temperature of rabbits onto spatial distribution maps of the temperature and humidity index (THI) of a rabbit installation and concluded that the overlap between these datasets provided a viable alternative for evaluating environmental housing conditions and their impact on the physiological variables of these animals.

Therefore, the development of spatial distribution maps of h by kriging interpolation, as well as characterizing and evaluating its relationship with the physiological responses ($t_{cloacal}$) of broiler chickens, by applying the methodology of Silva et al. (2021), can be valuable for analyzing the environmental and physiological conditions of broilers due to the ease of interpretation of the developed maps and their application in the poultry industry. Thus, this strategy could provide an improvement in production rates, promote an increase in climate control management efficiency and facilitate the adjustment in daily equipment management in poultry facilities. Moreover, the reduction in production costs due to electricity savings contributes to more sustainable poultry farming (Coulombe et al., 2020).

Therefore, this study was conducted using geostatistical techniques to characterize and evaluate the psychrometric property *h* in a broiler installation, relating this factor to the $t_{cloacal}$ parameter of broilers by overlapping the collected data.

MATERIALS AND METHODS

The research was conducted in Brazil over 42 days, starting in August 2021 and ending in September 2021. Approval for the study was granted by the UFLA Ethics Committee for Animals Use (Protocol No. 006/2020). All the procedures performed with broilers were performed according to the guidelines recommended by this committee.

Experimental barn and broilers

The data for this experiment were obtained at a broiler farming facility situated within the Poultry Sector of the Animal Science Department at the Federal University of Lavras, Minas Gerais, Brazil (coordinates: 21° 14' S, 45° 00' W; altitude: 918 m). In accordance with the Köppen international classification system, the prevailing climate in this area can be categorized as Cwa, indicating a subtropical mesothermal climate with warm and rainy summers and cold and dry winters. The average air temperature is 22.5 °C during the hot season and 16.9 °C during the cold season (Sá Júnior et al., 2012).

The experimental semiclimatized barn is 44 m long and 6.35 m wide, exhibits a ceiling height of 2.90 m, is covered with asbestos tiles and has a concrete floor. Internally, the barn is divided into 30 boxes distributed on each side of the barn, totaling 60 boxes. Each box exhibits dimensions of 1.46 m (length) by 2.2 m (width) and is delineated by open wire meshing structures (4.19-mm wire thickness and 50-mm mesh). Between any two rows of boxes, there is a central corridor that is 44 m long and 1.95 m wide. Each box contains an incandescent lamp for heating (100 W and 220 V), a tubular feeder and a pendular drinker, and the floor is covered with wood shavings. Each side of the barn contains two fans (QLA85T6 model, Qualitas, São Paulo, Brazil) positioned approximately 1.70 m above the floor, with a diameter of 850 mm, a maximum flow of 15,000 $m^3 h^{-1}$ and a rotation speed of 1,110 rpm. These fans can be manually activated when necessary. On the sides of the barn, there are curtains to manually control ventilation and incident sunlight reaching the broilers (Fig. 1, a, b).

One-day-old male Cobb-500 broiler chicks were acquired from a commercial hatchery and were individually weighed (43.0 ± 0.64 g). The experimental design comprised randomized blocks with the right and left sides of the shed defined as blocks. The broilers were distributed in six replicates (experimental units; boxes) of 15 broilers each, totaling 48 experimental units and 720 broilers.

During distribution, the first 24 boxes on each side of the barn were used, and the average weights of the broilers in each box were similar (646.0 ± 5.7 g). The broilers were provided corn and soybean meal (Table 1) designed in accordance with their nutritional needs for 1–7 days, 8–21 days, 22–35 days and 36–42 days of age (Cobb, 2019). The broilers were provided unrestricted access to both feed and water throughout the entire experimental duration (1–42 days of age). The light regime comprised 1 hour of darkness (1–7 days old), 8 hours of darkness (8–20 days old), 7 hours of darkness (21–35 days old) and 6 hours of darkness (36–42 days old), according to the lineage manual (Cobb, 2019).

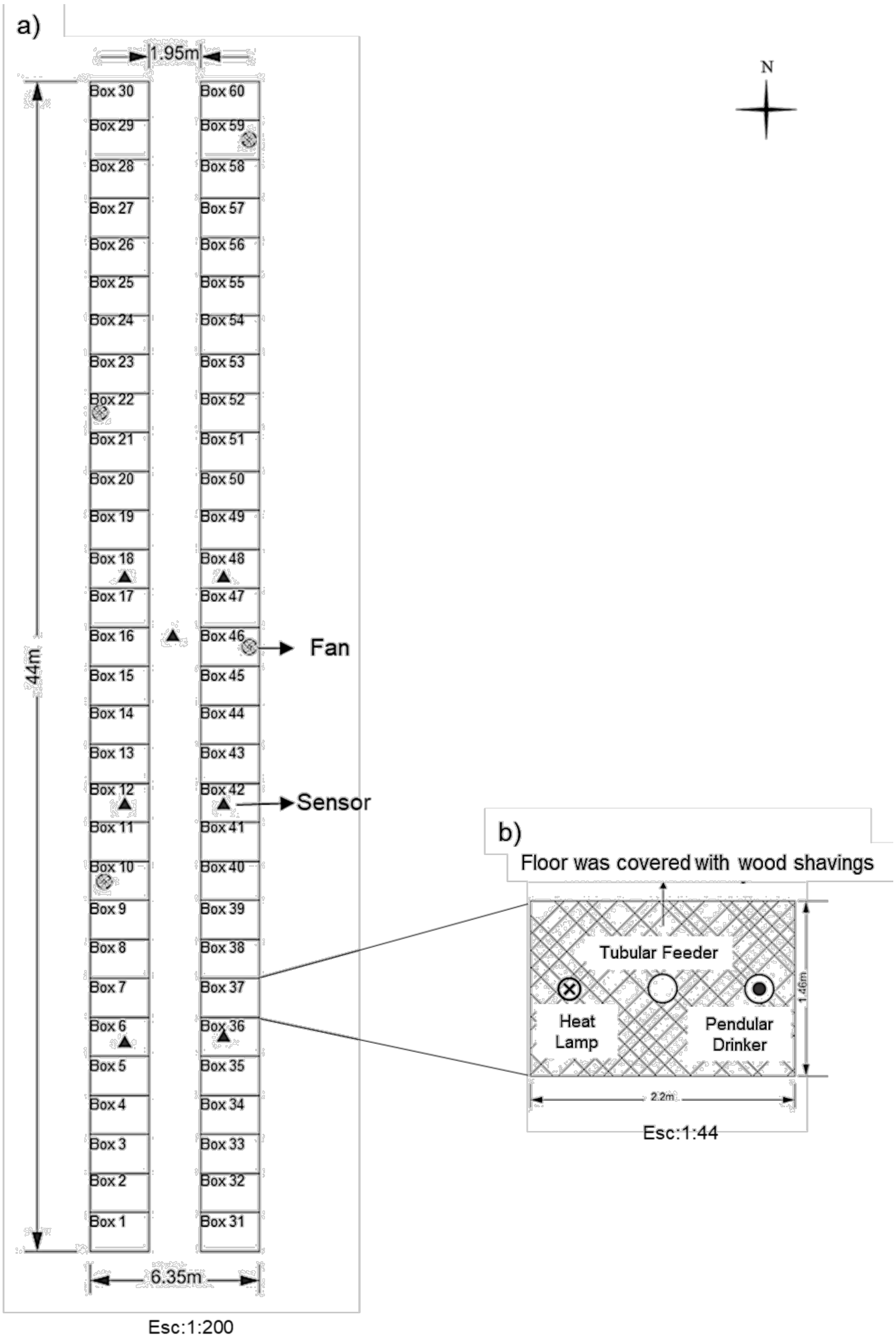

Figure 1. Diagram of the barn used: a) Location of boxes, sensors, and fans; b) Enlarged characterization of the box illustrating the floor type and the positions of the drinker, feeder and heat lamp.

Table 1. Ingredients and calculated nutritional composition (as-fed basis) of the basal diets provided to broilers in the different rearing periods

	Periods of broiler rearing (days of age)			
	1–7	8–21	22–35	36–42
Ingredients (g kg^{-1})				
Corn	562.60	614.55	624.82	645.15
Soybean meal, 45%	365.25	317.60	302.00	277.70
Soybean oil	25.60	24.20	33.29	37.60
Limestone	8.20	7.75	7.10	7.20
Dicalcium phosphate, 18.5%	18.75	17.50	15.45	15.60
Common salt	4.70	4.50	4.57	4.55
DL-Methionine, 99%	3.40	3.20	2.83	2.65
L-Lysine HCl, 99%	2.40	2.00	1.74	1.85
L-Threonine, 98.5%	1.10	0.70	0.20	0.20
Salinomycin, 12%	0.50	0.50	0.50	0.00
Choline chloride, 60%	0.50	0.50	0.50	0.50
Vitamin supplement [1]	1.00	1.00	1.00	1.00
Mineral supplement [2]	1.00	1.00	1.00	1.00
Nutritional composition				
AME (kcal kg^{-1})*	2,975	3,025	3,100	3,150
Crude protein (g kg^{-1})	214.91	196.60	189.52	180.07
Calcium (g kg^{-1})	9.04	8.41	7.61	7.61
Available phosphorus (g kg^{-1})	4.50	4.21	3.81	3.80
Sodium (g kg^{-1})	2.00	1.91	1.94	1.93
Digestible lysine (g kg^{-1})	12.22	11.21	10.22	9.72
Digestible methionine + cysteine (g kg^{-1})	9.13	8.54	8.03	7.63
Digestible threonine (g kg^{-1})	8.30	7.33	6.63	6.32
Digestible tryptophan (g kg^{-1})	2.42	2.18	2.10	1.97

*AME, Apparent metabolizable energy. [1] Levels per kg of supplement: folic acid 902.5 mg; pantothenic acid 12.0 g; biotin 77.0 mg; niacin 40.0 g; selenium 349.6 mg; vitamin A 8800,000.0 IU; vitamin B1 2499.0 mg; vitamin B12 16,200.0 mcg; vitamin B2 5,704.0 mg; vitamin B6 3998.4 mg; vitamin D3 3000000.0 IU; vitamin E 30000.0 IU; vitamin K3 2198.1 mg. [2] Levels per kg of supplement: copper 7000.0 mg; iron 50.0 g; iodine 1,500.0 mg; manganese 67.5 g; zinc 45.6 g.

Characterization of the thermal environment and measurement of the physiological response

Throughout the experiment, the curtains and heating lamps were manually controlled to maintain the internal temperature of the barn as elevated as possible between 9:00 a.m. and 5:00 p.m., ensuring that the value did not surpass an average of 32 °C during this period (Cheng et al., 2019). During the remaining hours of the day, the curtains, heating lamps, and fans were adjusted to maintain the temperature within the designated range for thermal comfort specific to each phase of broiler rearing, as outlined in the lineage manual (Cobb, 2019).

The t_{db} and RH values during broiler rearing were recorded by seven T/HR data loggers (Onset brand, HOBO, model H-08-003-02), which were located at a height compatible with the height of the broilers (0.30 m from the ground) (Curi et al., 2017); three loggers were placed on each side of the barn, and one was placed in the central corridor.

When the broilers were 7, 21, 35 and 42 days old, t_{db} and RH data were recorded at 08:00 a.m. and 01:00 p.m. by all seven sensors (Fig. 1, a, b). These four data collection days were established because they delineate the preinitial (1–7 days old), initial (8–21 days old), growth (22–35 days old) and final (36–42 days old) phases (Rostagno et al., 2017), including changes in feed formulations to satisfy the nutritional needs of the broilers (Table 1). The above two instances of recording were executed with the aim of detecting critical environmental conditions within the facility, following the adapted methodology by Andrade et al. (2022). Thus, h values were calculated from the environmental data registered by each sensor for each day (7-, 21-, 35- and 42-day-old broilers) and time (08:00 a.m. and 01:00 p.m.) using Eq. 1, as proposed by Albright (1990):

$$h = 1.006 \text{ x } t_{db} + \text{W x } (2501 + 1.805 \text{ x } t_{db}) \quad (1)$$

where h is the enthalpy in kJ kg of dry air^{-1}; t_{db} is the dry bulb temperature in °C; and W is the humidity ratio or mixing ratio (W, kg of water vapor kg of dry air^{-1}) of air.

The blending proportion was determined using Eq. 2, which depends on the water vapor pressure (ea, kPa) and the atmospheric pressure at the location (P_{atm}, kPa).

$$\text{W} = \frac{0.622 \text{ x } e_a}{P_{atm} - e_a} \quad (2)$$

The local altitude used to calculate P_{atm} was 918 m.

Moreover, at the ages of 7, 21, 35, and 42 days, a single chicken per enclosure was chosen based on the average weight of the group (with a standard deviation of ± 3%), resulting in a total of 48 broilers. The cloacal temperatures ($t_{cloacal}$, °C) of the chosen broilers were assessed using a digital thermometer (model TH1027, G-TECH, Duque de Caxias, RJ, Brazil), with an accuracy of ± 0.2 °C, inserted into the cloaca for a duration of one minute.

Dataset

A dataset comprising unprocessed h (kJ kg of dry air^{-1}) and $t_{cloacal}$ (°C) data from Cobb-500 broilers at 7, 21, 35 and 42 days of age was created. Subsequently, the variability in h within the barn was analyzed via geostatistical analysis and kriging interpolation to obtain h maps for the aforementioned age periods, which were then correlated with the physiological variable $t_{cloacal}$.

Data partitioning method for model validation

The spatial and temporal dependence of the data of environmental variable h was analyzed by semivariogram adjustment using a classical estimator and the restricted maximum likelihood method (REML) (Ferraz et al., 2019a; Ferraz et al., 2020; Silva et al., 2021).

Due to the small dataset, the chosen method is suitable because, according to Ferraz et al. (2019a), the REML produces estimates with reduced bias when applied to small sample sizes. Despite the small amount of data collected, the number of points used in this study is sufficient. Furthermore, within this context, kriging predictors could provide the best linear unbiased predictions (BLUPs) (Lark, 2009; Slaets et al., 2021).

The most effective model adjusted for sentiment is a wave model, as elucidated in the description of Webster & Oliver (2007) (Eq. 3):

$$\hat{\gamma}(\mathrm{h}) = C_0{}^2 + \frac{a}{h}\sin\left(\frac{h}{a}\right)^4 \quad (3)$$

where h is the distance between the samples, C_0 is the nugget effect, and a is the interval.

After obtaining the model and estimated semivariance parameters, the model suitability was verified through cross validation (CV), which is a technique that allows the assessment of estimation errors by comparing the predicted values of the samples, as reported by Isaaks & Srivastava (1989).

The criteria for choosing a model based on the CV technique include considering mean error (ME) and reduced mean error (RE) values that are closer to zero; in addition, the lowest standard deviation of the mean errors (SDME) and the standard deviation of the reduced mean errors (SDRE) closest to one should be selected, according to the methodology of Ferraz et al. (2012). Thus, the model fitted in this study corroborates the findings of Santos et al. (2020) and Silva et al. (2021), as this model is better adapted to studies of environmental variables. After model fitting, the data were interpolated by ordinary kriging to allow the creation of maps and the visualization of the spatial and temporal distributions of h within the poultry house.

For geostatistical analysis, semivariogram function adjustment and data interpolation by the ordinary kriging method, R statistical software and the geoR package (Ribeiro Junior & Diggle, 2001) were employed. Moreover, spatial and temporal distribution maps of h data were generated using QGIS software version 2.14.15.

Finally, the t_{cloacal} data obtained in the morning were superimposed onto maps of environmental data from the poultry facility.

RESULTS AND DISCUSSION

Table 2 indicates that the mean h value ranged from 33.69–53.63 kJ kg dry air^{-1}, considering the evaluation days and times. Table 3 indicates the ranges of t_{db} and RH relative to the thermal comfort of Cobb-500 broilers as a function of age, according to the lineage manual (Cobb, 2019), and the ranges of the variation in h calculated based on the ideal values of t_{db} and RH reported in the manual and obtained according to the equation proposed by Albright (1990).

When comparing the experimentally obtained and calculated ideal h values, it was observed that the h values recorded at 08:00 a.m. and 01:00 p.m. on days 7 and 21 (Table 2) were below the expected range, ranging from 61.08–70.26 kJ kg of dry air^{-1} on day 7 and from 53.77–53.83 kJ kg of dry air^{-1} on day 21 (Table 3). However, on day 35 at 01:00 p.m. and on day 42 at 08:00 a.m. and 01:00 p.m., when considering all the sensor measurements (Table 2), the h values exceeded the ideal ranges (Table 3) considered thermally comfortable for broilers. Furthermore, on day 35 at 08:00 a.m., the h values were 36.30 kJ kg of dry air^{-1} for sensor 2 and 36.75 kJ kg of dry air^{-1} for sensor 5. Notably, the h values were close to the comfortable range (36.38–36.63 kJ kg of dry air^{-1}) for rearing Cobb-500 broilers.

Table 2. The values of dry bulb temperature (t_{db}, °C), relative air humidity (RH, %) and specific enthalpy of air (h, in kJ kg of dry air^{-1}) at 08:00 a.m. and 1:00 p.m. recorded by sensors inside the conventional broiler house when the Cobb-500 broilers were 7, 21, 35 and 42 days old

8:00 a.m.					1:00 p.m.				
Day old	Sensors	t_{db}	RH	h	Day old	Sensors	t_{db}	RH	h
		°C	%	kg of dry air^{-1}			°C	%	kg of dry air^{-1}
7	1	20.76	62.65	45.95	7	1	27.92	31.90	47.25
	2	20.76	61.55	45.46		2	28.31	29.15	46.27
	3	20.76	61.05	45.24		3	28.11	30.85	46.99
	4	20.95	60.30	45.42		4	27.72	29.45	45.20
	5	20.19	68.00	46.69		5	27.72	32.20	47.00
	6	20.19	54.80	41.07		6	26.73	31.75	44.53
	7	20.76	66.70	47.75		7	26.93	37.40	48.53
21	1	20.95	50.10	40.90	21	1	32.35	23.70	50.87
	2	21.33	49.85	41.69		2	32.76	25.20	53.10
	3	20.95	56.00	43.50		3	32.14	23.90	50.58
	4	20.95	49.80	40.77		4	31.32	24.85	49.61
	5	20.00	59.25	42.46		5	31.32	23.60	48.60
	6	20.38	49.20	39.17		6	31.52	24.90	50.08
	7	20.57	59.25	43.94		7	30.71	24.20	47.80
35	1	22.10	36.40	37.27	35	1	31.93	25.00	51.06
	2	22.29	33.45	36.30		2	31.93	25.00	51.06
	3	22.10	36.90	37.50		3	31.93	25.00	51.06
	4	21.53	34.35	35.22		4	31.12	24.80	49.14
	5	21.52	37.85	36.75		5	30.92	24.30	48.31
	6	21.33	31.65	33.69		6	31.12	24.80	49.14
	7	21.53	41.70	38.48		7	31.32	23.85	48.80
42	1	21.52	66.50	49.87	42	1	26.54	44.15	51.80
	2	22.29	64.05	50.94		2	26.93	40.85	50.72
	3	21.90	66.95	51.21		3	26.54	42.40	50.70
	4	21.90	63.90	49.74		4	26.34	40.15	48.80
	5	21.90	69.60	52.49		5	26.34	44.80	51.68
	6	21.71	57.45	46.15		6	26.15	34.60	44.97
	7	21.52	74.45	53.63		7	25.76	49.75	53.12

Therefore, to better understand the influence of physical properties on the avian environment, h was calculated, with its values serving as a reference for decision-making. Although both t_{db} and RH are reference parameters for evaluating thermal stress in production animals, the change in the specific enthalpy of air (h, kJ kg of dry air^{-1}) can determine whether heat is released (exothermic) or absorbed (endothermic) during a given reaction (Correia & Oliveira, 2019).

Faustino et al. (2021) and Harada et al. (2021) suggested the psychrometric variable h for evaluating discomfort and animal ambience conditions since its calculation involves t_{db}, RH and atmospheric pressure, which are environmental variables normally available at meteorological stations. According to Pecoraro et al. (2024), for the productive performance of broiler chickens, in addition to the temperature within the comfort h range, adequate ranges of t_{db} and RH are necessary, especially at the final stages of rearing (21–42 days).

According to the information presented in Table 2, the *h* data exhibited variability throughout the analyzed period. However, this exploratory analysis does not provide a definitive assessment of the presence or absence of heterogeneity in both the spatial and temporal distributions of *h* within poultry houses, as described by Ferraz et al. (2019a). To address this issue, geostatistical analysis of *h* was conducted to systematically evaluate variability during the study period, following methods outlined in previous studies (Ferraz et al., 2020; Andrade et al., 2022; Oliveira et al., 2022).

Table 3. Relative air humidity (RH), dry bulb temperature (t_{db}) and specific enthalpy of air (*h*), which influence the thermal comfort of Cobb-500 broilers, as a function of age

Days old	RH (%)	t_{db} (°C)	*h* (kJ kg of dry air^{-1})
7	40–60	29–31	61.08–70.26
21	50–60	24–26	53.77–53.83
35	50–40	19–21	36.38–36.63
42	50–70	18–20	38.62–41.41

To enhance both quantitative and qualitative assessments of *h*, descriptive statistics and geostatistical techniques were employed. These methods aimed to provide crucial insights into the spatial distribution of each *h* class and to better understand the variability and impact of *h* within the investigated environment. Table 4 provides the model results and parameters derived from the experimental semivariograms adjusted for *h* in the poultry house on days 7, 21, 35, and 42 at 8:00 a.m. and 1:00 p.m.

Table 4. The REML method, wave model and the parameters estimated from experimental semivariograms applied to assess specific enthalpy of air (*h*, in kJ kg of dry air^{-1}) in a conventional barn utilized for raising Cobb-500 broilers

Days old	Hour	C_0*	C_1*	C_0+C_1*	a (m)*	DSD*		ME*	SDME*	RE*	SDRE*
7	8 a.m.	0.0	3.670	3.670	0.077	100%	strong	0.000	2.414	0.000	1.167
	1 p.m.	0.0	1.504	1.504	0.080	100%	strong	0.000	1.545	0.000	1.167
20	8 a.m.	0.0	2.322	2.322	0.145	100%	strong	0.000	1.920	0.000	1.167
	1 p.m.	0.0	2.557	2.557	0.667	100%	strong	0.000	2.015	0.000	1.167
35	8 a.m.	0.0	2.140	2.140	0.082	100%	strong	0.000	1.843	0.000	1.167
	1 p.m.	0.0	1.258	1.258	0.051	100%	strong	0.000	1.413	0.000	1.167
42	8 a.m.	0.0	4.775	4.775	0.078	100%	strong	0.000	2.753	0.000	1.167
	1 p.m.	0.0	5.997	5.997	0.078	100%	strong	0.000	3.086	0.000	1.167

* C0 – nugget effect; C1 – contribution; C0 + C1 – threshold; a – reach; DSD – degree of spatial dependence; ME – mean error; SDME – standard deviation of mean error; RE – reduced mean error; SDRE – standard deviation of reduced mean error.

The C_0 values for various days and times are provided in Table 4. As outlined by Ferraz et al. (2019a) and Santos et al. (2020), C_0 denotes the unexplained variability, considering the sampling distance as a significant parameter of the semivariogram. In other words, C_0 represents an unaccounted variable or random variance, typically attributable to measurement errors or variability in the measured property undetected at the sampling scale (Bhatti et al., 1991). Thus, for the purpose of comparing the magnitudes of the degree of spatial dependence (DSD) of the studied variable, the contributions of individual error were calculated, thereby expressing C_0 as a proportion of $C_0 + C_1$ (Table 4) (Trangmar et al.,1986).

Throughout the entire experimental period, C_0 equaled 0, indicating that the experimental error was practically null and that there was no significant variation at distances smaller than the sampling distance (Ferraz et al., 2019b), i.e., if the sensors were placed closer together, there would be no significant variation. Therefore, the sampling distance was suitable, and the experimental error was null when arranging the sensors to create a sampling network within the facility (Ferraz et al., 2019b).

Cajazeira & Assis Júnior (2011) characterized and geostatistically analyzed the spatial variations in the physical attributes of a Yellow Argisol across two soil layers. Surface maps were prepared using the kriging method. Their findings revealed that for the subsurface layer, the silt content exhibited a nugget effect close to 0%, suggesting a minimal experimental error. This indicates the insignificance of variable sampling at distances smaller than those employed. Thus, the results obtained by these authors corroborate the results of this study.

The reach values (a) of the semivariograms are significant for establishing the spatial dependence boundaries of *h,* as they represent the extent to which the sampling units exhibit correlations, as emphasized by Silva et al. (2021) and Oliveira et al. (2022). These parameters are instrumental in sampling design, aiding in identifying locations for environmental variable sampling, as described by McBratney & Webster (1983). The largest ranges (Table 4) were obtained on day 21 at 08:00 a.m. and 01:00 p.m. (0.145 and 0.667 m, respectively), while day 35 exhibited the lowest spatial continuity at 01:00 p.m. (0.051 m). Thus, it was found that the samples collected at distance a (Table 4), at which point the distance no longer influences the variable *h*, resulted in experimental semivariogram stability, which is agrees with the semivariogram behavior in the studies of Santos et al. (2020) and Silva et al. (2021).

The DSD was determined by assessing the ratio between C_0 and $C_0 + C_1$, following the classification proposed by Cambardella et al. (1994). In this classification, a DSD value is considered strong if the ratio between C_0 and $C_0 + C_1$ is $\leq 25\%$, moderate if the ratio is $> 25\%$ and $< 75\%$, weak if the ratio is $\geq 75\%$ and $<100\%$, and neutral if the ratio is equal to 100%. Notably, throughout the analysis period, the ratio between C_0 and $C_0 +C_1$ was $\leq 25\%$, and the DSD of the *h* variable could be considered strong.

According to Santos et al. (2020) and Silva et al. (2021), the strong DSD value of *h* obtained during the analysis period may be related to the wave model, which is better adapted to studies of environmental variables. In addition, on the analysis days and times, experimental semivariogram adjustment yielded ME and ER values close to zero, which conforms with the recommendations of Ferraz et al. (2012) and indicates the analysis quality and efficiency (Faraco et al., 2008) for assessing the comfort levels of animals in the production environment.

The obtained results suggested that the spatial distributions of the climatic attributes are not random since they exhibit strong DSD values, suggesting that geostatistical techniques are appropriate (Damasceno et al., 2019; Oliveira et al., 2019). Thus, the occurrence of spatial dependence allowed the interpolation of *h* data through kriging, which is commonly used to perform geostatistical mapping via spatial distribution maps (Damasceno et al., 2019).

Queiroz et al. (2017), Silva et al. (2021) and Andrade et al. (2022) suggested the use of isocolor maps of the spatial distribution of the THI and *h* in chicken, rabbit and dairy cattle production barns, respectively, with the objective of characterizing and identifying areas with different spatial variabilities in these environmental thermal control indicators. According to the authors, this visual tool allows the identification of environmental conditions harmful to the thermal comfort of the animals and their timely correction.

With the use of the values derived from kriging, isocolor maps were generated, which show the spatial distribution of *h* within the poultry house. This allowed for examining the magnitude and variability in this variable throughout the experimental period within the facility (Fig. 2, a, b, c, d, e, f, g, h).

Fig. 2 shows that on days 7, 21, 35 and 42 at 08:00 a.m. (Fig. 2, a–d), *h* ranged from <35.1 to > 51.9 kJ kg of dry air^{-1}. In addition, on the same experimental days, at 01:00 p.m. (Fig. 2, e–h), *h* varied between 45.6 and 51.9 kJ kg of dry air^{-1}. Thus, the obtained *h* variability maps revealed that under the environmental conditions, the broilers were kept in boxes (with spatial variability) and throughout the experimental period (with temporal variability).

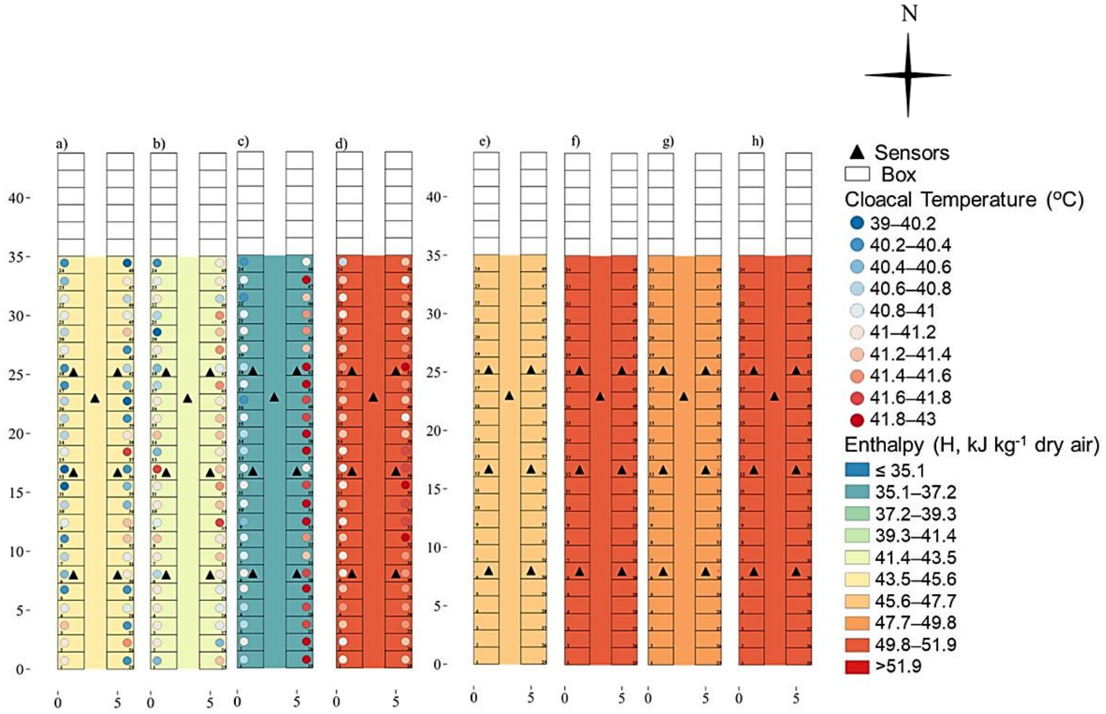

Figure 2. Spatial and temporal distribution of specific enthalpy of air (*h*, in kJ kg of dry air^{-1}) and cloacal temperature ($t_{cloacal}$, °C) in a conventional broiler house, according to the days and times studied: a) day 7, at 08:00 a.m.; b) day 21 at 08:00 a.m.; c) day 35 at 08:00 a.m.; d) day 42 at 08:00 a.m.; e) day 7 at 01:00 p.m.; f) day 21 at 01:00 p.m.; g) day 35 at 01:00 p.m.; and h) day 42 at 01:00 p.m.

On days 7 (Fig. 2, a, 4e) and 21 (Fig. 2, b, f), at both times, *h* ranged from 41.4–51.9 kJ kg of dry air^{-1}. The temperature in the entire poultry house was below the comfortable value for broilers in this age group (Table 3). Conversely, on day 35 at 01:00 p.m. (Fig. 2, g) and day 42 at 08:00 a.m. and 01:00 p.m. (Fig. 2, d, h), the thermal conditions inside the facility were high, with *h* varying between 47.7 and > 51.9 kJ kg of dry air^{-1}, demonstrating that during this period, the broilers may have experienced heat stress.

In Brazil, intensive broiler production is conducted mainly in semiclimatized or climatized barns (Lima & Silva, 2019; Sans et al., 2021). The type of semiclimatized barn used in our research is characterized by open sides, natural light complemented by artificial light, adjustable curtains and positive pressure fans, similar to the structure used in industrial commercially designed barns (Sans et al., 2021). There was transverse ventilation in the barn used in our study, and the curtains and fans were manually managed as necessary. Therefore, air exchange between the internal microenvironment of the barn and the external environment of the installation, as well as the limitations of the fans, may have contributed to the increase in enthalpy during this period.

Only on day 35 at 08:00 a.m. (Fig. 2, c) were the broilers exposed to thermal conditions (h varying between 35.1 and 37.2 kJ kg of dry air^{-1}) considered close to ideal for rearing, with h varying between 36.38 and 36.63 kJ kg of dry air^{-1} (Table 3).

Based on geostatistics analysis, it was noted that throughout the experimental duration (7, 21, 35 and 42 days old; 08:00 a.m. and 01:00 p.m.), there were variations in h (temporal variability) (Tables 2 and 4, Fig. 2, a–h) within the poultry house. The spatial variability, namely, the variations within the boxes in this study, was determined, as detailed in Table 2.

In Fig. 2, there was no variation in h between the boxes, and the scale used did not allow variation observation. This fact could be attributed to the number of samples collected, so studies are recommended to improve the distribution of sensors, studies should be conducted involving a greater number of sensors, and studies should be performed aimed at the direct identification of the spatial variability. However, understanding the spatial-temporal distribution of h within poultry houses is crucial for detecting potential fluctuations in the daily thermal conditions of the production microenvironment. This is significant because approximately ideal and consistent conditions are desirable to ensure that broilers can achieve their maximum productive performance throughout the housing period.

Sans et al. (2021) evaluated the spatial distributions of the environmental variables RH, t_{db}, air velocity, ammonia (NH_3) and carbon dioxide (CO_2) concentrations and illuminance in closed- and open-sided broiler chicken farms. The authors observed the heterogeneity in these variables within facilities using kriging maps, and it was demonstrated which indicators influenced the deterioration in the poultry house microclimate (higher temperatures and NH_3 and CO_2 concentrations). In this way, they could identify strategic points within the poultry house to manage the equipment to promote better ambience and minimize the occurrence of regions with little air exchange (dead spots), thus improving the quality and production of broiler batches. The authors also highlighted the importance of constant broiler welfare monitoring at key barn locations and the use of other environmental and physiological indicators for new observations of spatial distributions.

Within this context, the maps of the spatial and temporal distributions of h (Fig. 2, a–h) show different environmental conditions between the boxes, days and hours in the same broiler rearing barn. Therefore, the results demonstrated the need for greater control of the ambient temperature in the studied barn so that there is no compromise in the productive performance of future batches that will be housed in this facility. As such, the significance and practical utility of employing maps to visualize the spatial and temporal patterns of environmental variables are exemplified. Such maps are visual tools to support decision-making so that critical welfare and management points can be quickly identified and corrected, thus allowing higher efficiency in climate control management and daily equipment adjustments in poultry facilities (Sans et al., 2021).

Moreover, understanding the impact of environmental factors on the physiological reactions of broilers to heat stress (Moghbeli Damane et al., 2018; Siddiqui et al., 2020) is necessary for understanding the adverse effects of unfavorable thermal conditions on organism functions. These effects include changes in the body antioxidant capacity, immunity, and intestinal morphology and physiology (Sahin et al., 2017; Song et al., 2018).

Fast-growing broilers, such as Cobb-500 broilers, exhibit a high central body temperature due to their increased metabolic activity resulting from targeting genetic selection programs for increased growth rates (Jahejo et al., 2016). During the last weeks of the production cycle, when energy metabolism is accelerated and heat dissipation is hampered by body warming, broilers are more susceptible to heat stress when exposed to high room temperatures (Awad et al., 2020). Notably, during the first two weeks of life, broilers are more susceptible to cold stress, whereas during the last two weeks, they are prone to heat stress, emphasizing the crucial need to prevent excessive exposure of broilers to elevated temperatures (Lara & Rostagno, 2013; Pecoraro et al., 2024).

When the room temperature exceeds the thermoneutral zone, broilers rely on physiological responses that aim to reduce heat production and/or increase the dissipation of excess heat to the environment (Castro Júnior & Silva et al., 2021). According to Brown-Brandl (2003), $t_{cloacal}$ is a suitable indicator of comfort or thermal stress due to its direct relationship with the central body temperature and ease of measurement. The ideal body temperature of broilers varies according to age, with values ranging from 39.6–40.6 °C for 0- to 7-day-old broilers, 40.0–41.1 °C for 8- to 21-day-old broilers, 41.2–41.7 °C for 22- to 35-day-old broilers and 41.2–41.6 °C for 36- to 42-day-old broilers (Marchini et al., 2007; Pires et al., 2020; Olgun et al., 2021).

Thus, the $t_{cloacal}$ values recorded on days 7, 21, 35 and 42 were superimposed onto the spatial maps of the environmental variable *h* in the poultry facility during the morning period (Fig. 2, a–h). Fig. 2, c, and d show that the $t_{cloacal}$ values of the broilers housed on the west side of the barn on days 35 and 42 ranged from 41.6–43 °C and 41.2–43 °C, respectively, in most boxes. These temperatures exceed what is considered ideal for broilers over the period considered ($t_{cloacal}$ at 35 days old = 41.2–41.7 °C; $t_{cloacal}$ at 42 days old = 41.2–41.6 °C). Conversely, when considering the broilers housed on the east side of the barn, on day 35 (Fig. 2, c), $t_{cloacal}$ values between 40.2 and 41.0 °C were recorded, which are below the values (41.2–41.7 °C) considered ideal for the age group, while only on days 21 (Fig. 2, b) and 42 (Fig. 2, d) were the broilers exposed to potentially comfortable conditions for their development, with $t_{cloacal}$ values ranging from 40.2–41.2 °C and 41.2–41.6 °C, respectively.

However, on day 7 (Fig. 2, a), in most boxes on the east side of the barn, the $t_{cloacal}$ values remained between 40.6 and 41.2 °C, demonstrating that during this period, the broilers may have experienced difficulty maintaining their body temperature, as *h* ranged from 43.5–45.6 kJ kg of dry air^{-1}, i.e., below the values recommended for the age group (*h* = 61.08–70.26 kJ kg of dry air^{-1}, Table 3). A factor that may have contributed to this finding is that barn heating was not enough to maintain the ideal conditions for the broilers on day 7. Thus, in the presence of cold stress, broilers strive to maintain homeothermic conditions by increasing heat production and energy consumption (through feed) while minimizing heat loss, as noted by Hernandez et al. (2016).

It is important to highlight that the initial week of a broiler's life demands heightened care and attention from the producer. Errors in management during this phase, if recurrent, cannot be rectified later, impacting the ultimate performance of the broilers through delayed weight gain and/or the onset of diseases attributed to cold stress, as indicated by Tinôco et al. (2004). Recognizing the importance of warming the internal microenvironment of barns during the initial weeks of broiler life (Menegali et al., 2013), it is important to map the spatial distribution of *h* while incorporating physiological data from broiler chickens. This approach holds critical relevance in the animal-raising process, as it offers insights into the complex interactions between air properties and the physiological principles of animal thermoregulation. This method is both cost-effective and user-friendly, enabling adjustments in daily equipment management to enhance the thermal environment of the facility.

The observed values of $t_{cloacal}$ (Fig. 2, a, b, c, d) are consistent with the spatial and temporal distribution of *h* inside the barn (Fig. 2, a–h), and the physiological parameter $t_{cloacal}$ is directly related to the variation in *h*. This is due to the temporal distribution of *h* throughout the analysis period, demonstrating that the increase and/or reduction in *h* may have affected the ability of broilers to regulate their body temperature effectively.

During the experimental period, the broilers experienced thermal conditions outside their comfort range, posing an environmental challenge that, depending on its intensity and duration, could lead to a decline in their productive performance. It is widely acknowledged that thermoneutral environments allow animals to manifest their maximum genetic potential due to the lower energy deviation in thermoregulatory processes (Moghbeli Damane et al., 2018; Goo et al., 2019; Ahmed-Farid et al., 2021).

According to Awad et al. (2018) and Liu et al. (2020), a meta-analysis revealed adverse effects when broilers occurred outside their thermal comfort range. These effects include reduced body weight gain (GWG, g), diminished feed intake, and an elevated feed conversion rate (FC, g g^{-1}) in live broilers, ultimately leading to a subpar meat quality. In addition, adverse effects on the intestinal microbiome were detected in broilers under heat stress (Song et al., 2018). Therefore, to mitigate the harmful consequences of environmental stress, strategies for alleviating the impact of temperature on production and reducing economic losses in the poultry industry are urgently needed (Liu et al., 2020).

Therefore, studies have actively advanced new technologies for assessing thermal stress among broiler chickens. These studies focused on microclimatic air variables, with a particular emphasis on psychrometric properties such as t_{db} and RH (Sans et al., 2021; Cho et al., 2022). Although both t_{db} and RH are key parameters for assessing thermal stress in production animals, *h* is the only psychrometric parameter that comprehensively embodies the notion of thermal energy within the environment. Notably, *h* represents the combined latent and sensible heat, justifying its application considering these fundamental principles of heat exchange between animals and their surroundings (Castro Júnior & Silva, 2021; Pecoraro et al., 2024).

Britto (2010) described the possibility of devising strategies for environmental control based on the variation in psychrometric properties within a specific system (from sampling P to P'). Under this scenario, geostatistical analysis could aid in visualizing psychometric parameter variations by employing kriging maps. This tool enables the differentiation and visualization of areas with variations in microclimatic attributes across space, such as h. This tool could help in identifying problematic areas within poultry houses, as described by Sans et al. (2021) and Queiroz et al. (2017).

It is crucial to highlight that productivity and financial and animal welfare indexes can be improved when the use of electrical equipment, such as lamps, fans, evaporative cooling systems, exhaust fans and/or sprinklers, is optimized to promote better ambience. Moreover, electricity savings contribute to more sustainable poultry farming (Coulombe et al., 2020).

Sans et al. (2021) mentioned the lack of studies that include environmental indicators (for example, h) and well-being-related indicators ($t_{cloacal}$) of animals that can be assessed through geostatistical analysis, and their combined use could facilitate the implementation of strategies to enhance broiler production.

In summary, the utilization of spatial distribution maps for h enables the provision of more precise information to producers regarding variations in thermal conditions during broiler housing. This facilitates increased efficiency in climate control management and adjustments in daily operational management of equipment in poultry facilities, particularly those in areas with tropical climates.

CONCLUSIONS

The geostatistical analysis technique allowed verification of the occurrence of spatial and temporal variabilities in h in a conventional poultry barn, demonstrating that broilers possibly experienced thermal discomfort due to h oscillation.

Notably, $t_{cloacal}$ was directly related to the spatial distribution of h, highlighting the importance of interventions aimed at improving the ambient temperature for subsequent batches of broilers to be housed in the same facility.

Therefore, the optimization of data collection of microclimatic variables within poultry facilities (use of more sensors) and measurements of physiological variables of broiler chickens in real time would be necessary to enhance the database and the accuracy of this methodology in future studies. This would improve the information provided to producers and help them identify variations in the thermal environment and facilitate changes in daily equipment operation at poultry facilities.

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