Ciência Rural, Santa Maria, v.51:8, e20200941, 2021 http://doi.org/10.1590/0103-8478cr20200941
ISSNe 1678-4596
ANIMAL PRODUCTION

Efficiency of cooling systems in broiler houses during hot days

Maurício Portella dos Santos[1] **Matheus Deniz**[2] **Karolini Tenffen de Sousa**[2] **Daniela Regina Klein**[1*] **Tatiane Branco**[3] **Paulo Santana Pacheco**[4] **Marcos Martinez do Vale**[5]

[1]Programa de Pós-graduação em Zootecnia, Universidade Federal de Santa Maria (UFSM), 97105-000, Santa Maria, RS, Brasil. E-mail: danniwk@yahoo.com.br. *Corresponding author.
[2]Programa de Pós-graduação em Zootecnia, Universidade Federal do Paraná (UFPR), Curitiba, PR, Brasil.
[3]Departamento de Construções Rurais e Ambiência, Universidade Estadual de Campinas (FEAGRI/ UNICAMP), Campinas, SP, Brasil.
[4]Departamento de Zootecnia, Universidade Federal de Santa Maria (UFSM), Santa Maria, RS, Brasil.
[5]Departamento de Zootecnia, Universidade Federal do Paraná (UFPR), Curitiba, PR, Brasil.

ABSTRACT: *This study evaluated: (1) the vulnerability of broiler houses with different cooling systems, and (2) the spatial distribution of environmental variables during hot days. Four potentially vulnerable commercial broiler houses in southern Brazil were selected according to the following parameters: absence or presence of different cooling systems, broilers older than 28 days, and outside air dry-bulb temperature over 30°C. Broiler house vulnerability was classified according to the cooling and mechanical ventilation system: cellulose pad cooling (CPC), sprinkling (SPK), fogging (FOG), and mechanical ventilation without evaporative cooling system (VTL). The air dry-bulb temperature (T_{db}, °C) and relative humidity (RH, %) were recorded every 10 min. For each broiler house, we evaluated: (1) relative cooling efficiency (RCE) and (2) inside spatial distribution of microclimate variables using a geostatistical technique. The CPC and SPK did not differ (P<0.05) in RCE (81.6% and 80.7%, respectively), but both differed from FOG (23.8%) and VLT (1.87%) systems. The highest variations in indoor T_{db} were recorded in the FOG (7 °C), followed by the SPK (4 °C) and CPC (3 °C). In the CPC, there was an increase in RH from the middle to the end of the broiler house near the exhaust fans. In conclusion, the relative cooling efficiency and the inside spatial distributions of environmental variables in the broiler houses were influenced by the existing cooling system.*
Key words: *biometeorology, geostatistics, heat stress, indoor, environment, vulnerability.*

Eficiência dos sistemas de resfriamento em aviários durante dias quentes

RESUMO: *Os objetivos deste estudo foram (1) comparar a vulnerabilidade de aviários com diferentes sistemas de resfriamento, e (2) avaliar a distribuição espacial interna das variáveis ambientais durante dias quentes. Quatro aviários comerciais potencialmente vulneráveis no sul do Brasil foram selecionados de acordo com os seguintes parâmetros de elegibilidade: ausência ou presença de diferentes sistemas de resfriamento; frangos de corte com mais de 28 dias de idade; e temperatura de bulbo seco do ar externa acima de 30 °C. A vulnerabilidade do aviário foi classificada de acordo com o sistema de resfriamento e ventilação mecânica, sendo: resfriamento por pad cooling (CPC), aspersão (SPK), nebulização (FOG) e ventilação mecânica sem sistema de resfriamento evaporativo (VTL). A temperatura de bulbo seco do ar (T_{bs}, °C) e a umidade relativa do ar (UR, %) foram coletadas por registradores de dados autônomos a cada 10 min. Para cada aviário foram avaliados: (1) eficiência relativa de resfriamento (RCE) e (2) distribuição espacial interna das variáveis ambientais por técnica de geoestatística. O CPC e SPK não diferiram (P>0,05) na RCE (81,6% e 80,7% respectivamente), mas ambos diferiram do FOG (23,8%) e VLT (1,87%). As maiores variações na T_{bs} do ar interno foram registradas no FOG (7 °C), seguido pelo SPK (4 °C) e CPC (3 °C). No CPC, houve um aumento da umidade relativa do meio para o final do aviário, próximo aos exaustores. Em conclusão, a eficiência relativa de resfriamento, assim como a distribuição espacial das variáveis ambientais internas foram influenciadas pelo sistema de resfriamento de cada aviário.*
Palavras-chave: *ambiente interno, biometeorologia, estresse por calor, geoestatística, vulnerabilidade.*

INTRODUCTION

The economic and productive efficiencies of poultry are related to facilities and climatic conditions, which can severely affect broilers welfare. Heat stress promotes behavioral (BRANCO et al., 2019), physiological, and biochemical (AHMAD et al., 2008; GHANIMA et al., 2020) changes in broilers, resulting in economic losses (SALAS et al., 2016). Thus, deficiencies in facilities can result in vulnerabilities in

Received 10.19.20 Approved 12.17.20 Returned by the author 02.10.21
CR-2020-0941.R1

broiler houses that require mitigating actions to ensure productive performance and welfare.

The vulnerability of broiler houses is influenced by the quality of facilities, type of thermal insulation, conservation state (AL-SULAIMAN, 2002; LIAO & CHIU, 2002; VIGODERIS et al., 2007), and susceptibility of broilers to adapt to weather events. The Intergovernmental Panel on Climate Change (IPCC) defines different climate scenarios (for more information, access: IPCC, 2007, 2012) that can affect the vulnerability and adaptation of the poultry industry to climate change. This vulnerability can be related to the type of facilities and broiler's age; therefore, broiler houses can present different vulnerability situations in extreme climates (WMO, 2013; NAWAB et al., 2018).

The effects of weather events and thermal vulnerability of broiler houses are more significant in broilers older than 28 days, requiring the maximum capacity of cooling systems (CHEPETE et al., 2005; MARCHINI et al., 2007; ABREU et al., 2012; CASSUCE et al., 2013; COUMOU & ROBINSON, 2013). The occurrence of climatic extremes requires efficient cooling systems to maintain thermal comfort conditions inside the broiler house (OSORIO et al., 2016; SANTOS et al., 2017; COELHO et al., 2019). Tunnel ventilation (in positive or negative pressure) and cooling systems are alternatives for controlling the airspeed and the inside relative humidity (RH) in facilities (BUCKLIN et al., 2009; SALAS et al., 2016), thus mitigating the effects of heat stress in broilers by the loss of convective and latent heat.

Investments in poultry technology can improve environmental conditions for rearing and enhance animal productivity (NAZARENO et al., 2009; MOURA et al., 2010). Thus, evaluating the efficiency of cooling systems enables the determination of the broiler house vulnerability to extreme weather events as well as the modeling of thermal response related to outside temperatures. This modeling can assist in the mitigation of production losses and in the implementation of meteorological warning systems for heat extremes (VALE, 2008; PEREIRA et al., 2010).

Understanding the spatial variability of climate factors inside the broiler house in vulnerable conditions can assist the decision process for mitigation actions, as evaluating the spatial variability allows the quantification of cooling systems efficiency in different climate conditions (MIRAGLIOTTA et al., 2006; CARVALHO et al., 2012), ensuring the quality management of thermal and aerial environments (BOURNET & BOULARD, 2010; CURI et al., 2014). This study evaluated (1) the vulnerability of broiler houses with different cooling systems and (2) the spatial distribution of environmental variables during hot days.

MATERIALS AND METHODS

Location and climate

This study was performed in commercial broiler farms located in three Brazilian cities: *Westfalia* – RS (29° 22' 55.895" S, 51° 43' 54.239" W, 447 m height), *São Jorge do Oeste* – PR (25° 38' 46.054" S, 52° 58' 44.454" W, 509 m height), and *Dois Vizinhos* – PR (25° 41' 44.765" S, 53° 5' 44.243" W, 520 m height). The climate was characterized as Cfa - with hot summer (ALVARES et al., 2013).

Parameters of eligibility for the selection of broiler houses

In this study, the parameters of eligibility were the broiler susceptibilities to heat stress and facilities typology. Thus, four broiler houses were selected with different degrees of vulnerability to hot days. The minimum conditions for broiler house selection were the presence of broilers over 28 days of age and outside air dry-bulb temperature above 30 °C. In addition, the broiler houses were selected according to facility vulnerability: type of ventilation system and presence of an evaporative cooling system. Our selection criteria were based on the recommendations of the Cobb® broiler management manual (COBB, 2014), which describes housing density related to the broiler house type, ventilation, and cooling systems.

Description of broiler houses

All broiler houses had East-West orientation, wood shaving litter, Cobb® broilers genetics and were classified according to the existing cooling system: cellulose pad cooling (CPC), a cooling system by evaporative cellulose pad with 9 exhaust fan (average wind speed 2.5 m/s); sprinkling (SPK): sprinkler cooling system at the air inlet, adapted with a shade net (15 x 2.80 m) with 50% light retention mesh, equipped with 54 low-pressure nozzles (range: 75 to 120 pound square inch (PSI); average water flow 6.5 L/h) on the sides of the air inlet and 7 exhaust fan (average wind speed 2.5 m/s); fogging (FOG), a broiler house without cooling system at the air inlet and equipped with nine lines containing 125 low-pressure nozzles inside (range: 75 to 120 PSI; average water flow 6.5 L/h) and 8 exhaust fan (average wind speed 2.5 m/s); and ventilation (VTL), a broiler house without an evaporative cooling system at the air inlet and with a positive pressure type mechanical ventilation system (12 fans and wind speed range: 1.8 to 2.2 m/s) (Table 1, Figure 1).

Environmental measurements

The measured variables were air dry-bulb temperature (T_{db}, °C) and relative humidity (RH, %), recorded every 10 min. by five dataloggers (Instrutherm HT-500), three located inside and two outside the broiler house. The measurements were performed during the period of the day with maximum temperatures (12 p.m. to 3 p.m.). Each broiler house was evaluated via two procedures: 1) the relative efficiency of the cooling system, evaluated by the measured T_{db} and RH (inside and outside) and 2) the homogeneity of the inside environment using a geostatistical technique.

For the collections, days with the air dry-bulb temperature above 30 °C were selected, based on meteorological forecasts (maximum temperature) of the day, provided by the National Institute of Meteorology of Brazil (INMET), The Weather Channel®, and Accuweather®. The measurement of environmental variables was combined with the critical age of broilers (≥28 days), because in this age they are more vulnerable to heat stress. This combination of temperature (≥30 °C) and age (≥28 days) requires the maximum capacity of the cooling system.

Data collection points

Environmental variables were collected both inside and outside each broiler house. Three dataloggers were located inside at 0.3 m height from the broiler litter, being: P_i1 – 2 m away from the air inlet, P_i2 - at the center of the building, and P_i3 – 2 m before the opposite end. Outside the facility, two dataloggers were located: P_o1 - at the air inlet, and P_o2 – 15 m away from the wall, both protected by a solar radiation diffuser. The data from the three dataloggers located inside the broiler house were used to calculate the average inside T_{db} for each broiler house.

Relative cooling efficiency (RCE)

The efficiency of cooling systems was evaluated by the relative cooling efficiency (RCE), calculated using equation 1 (DAĞTEKIN et al., 2009). Wet-bulb temperatures were calculated using the data provided by the dataloggers, according to the methodology proposed by STULL (2011).

$$RCE = \frac{(Outside\,T_{db} - Inside\,T_{db})}{(Outside\,T_{db} - Inside\,T_{wb})} \times 100 \qquad (1)$$

Where:

T_{db} is the air dry-bulb temperature of outside or inside the broiler house, recorded at the air inlet

T_{wb} is the wet-bulb temperature measured outside the broiler house, calculated from the datalogger allocated at the air inlet.

Environmental homogeneity inside the broiler houses

To determine the thermal homogeneity inside the broiler houses, measurements were successively performed in 75 points (3 points for each 4m), from one end to the other, from the north to the south side and back to the north side. To correct the time lag between first and last point measurements, a numerical correction for the air dry-bulb temperature was applied based on the methodology proposed by GABRIEL FILHO et al. (2011).

Analysis

Analysis of variance (ANOVA) and homogeneity tests were performed in the variables studied (T_{db} and RH). When the result of the ANOVA was significant, a Tukey test was used to compare the average values inside and outside the broiler house

Table 1 - Description of evaluated broiler house: CPC- cellulose pad cooling, SPK - sprinkling, FOG - fogging, e VTL - ventilation.

Broiler house	Broiler house density[1](kg/ m^2)	Age (days)	Ventilation system[2]	Lateral insulation
CPC	13.0 (29.5 kg)	35	NP	Closed curtain
SPK	18.0 (29.1 kg)	28	NP	Closed curtain
FOG	14.5 (32.9 kg)	35	NP	Closed curtain
VTL	11.0 (26.1 kg)	36	PP	Open curtain

[1]Density of housing in unit and weight (kg) of broilers per square meter (m^2) estimated as a function of age and expected weight for the lineage; [2]Mechanical ventilation system performed by exhaust fans for negative pressure (NP) or fans for the positive pressure system (PP).

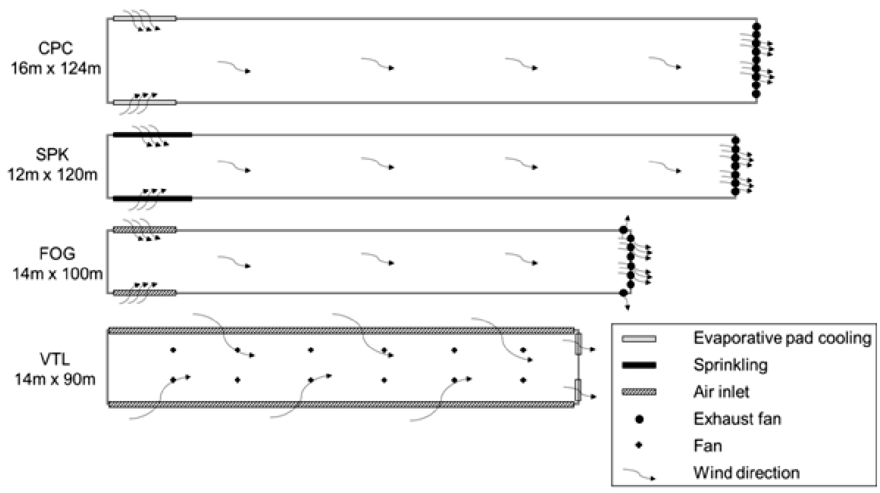


Figure 1 - Schematic representation of evaluated broiler house: CPC - cellulose pad cooling, SPK - sprinkling, FOG - fogging, e VTL - ventilation.

and inter-broiler house, at a significance level of 5%. The analyses were performed using the Statistical Analysis System (SAS).

The spatial variability was determined using semivariograms obtained and adjusted to theoretical models to obtain the parameters: nugget effect, plateau, coverage, degree of spatial dependence, coefficient of determination, and sum of squares of residues (Equation 2).

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i-l}^{N(h)} [Z(xi) - Z(xi+h)]^2 \quad (2)$$

Where:
N(h) denotes the observation pairs Z (xi) and Z(xi+h), and h is a lag distance.

The selection of the theoretical model that best describes the dependence between the measurement points was performed based on the sum of squares of residuals (SSR), coefficient of determination (R^2), and degree of spatial dependence (DSD). To analyze the DSD of the variables, the ratio C/(C+C0) was used, proposed by ROBERTSON (1998), which classifies the dependence as strong (GDE≥0.75), moderate (0,25≤GDE<0,75), and low (GDE<0.25). After adjusting the semivariograms, the data were directly applied to kriging interpolation to obtain spatial distribution maps of T_{db} and RH isoline maps representing the spatial distribution of the variables were obtained using the Surfer® program (GOLDEN SOFTWARE, 1999).

RESULTS

Environmental variables of broiler houses – inside and outside

All measurements were performed under thermal conditions higher than predicted by meteorological forecasts. The highest values ($p < 0.05$) of T_{db} (37.1 °C ± 0.4) and the lowest RH (42.7% ± 1.9) were recorded by the dataloggers located outside the FOG. There was a difference ($p < 0.05$) in the inside T_{db} and RH among broiler houses (Table 2).

Relative cooling efficiency (RCE)

There was no difference ($p < 0.05$) in the RCE between CPC (81.6%) and SPK (80.7%) broiler houses. However, CPC and SPK differed ($p < 0.05$) from FOG (23.8%) and VLT (1.87%) broiler houses. The FOG was less efficient in reducing T_{db}, whereas the VLT had no capacity, as expected.

The highest reductions of inside T_{db} were recorded in CPC (5.9 °C) and SPK (6.1 °C). The VLT broiler house presented the lowest potential for reducing T_{db}, as expected, due to the absence of an evaporative cooling system (Figure 2).

All broiler houses exhibited high DSD for T_{db} and RH, except for the RH of the FOG, which

Table 2 - Forecast maximum air dry-bulb temperature ($T_{db}max$) for the collection days and observed mean values ± standard deviation (SD) of the variables: air dry-bulb temperature (T_{db}) and relative humidity (RH, %) evaluated in inside (i) and outside (e) of the broiler houses (CPC - cellulose pad cooling, SPK - sprinkler, FOG - fogging, and VLT - ventilation).

Broiler house	---------------------------Air dry-bulb temperature (°C)-------------------------------				--------Relative humidity (%)--------	
	$T_{db}max$	$T_{db}e \pm SD$	$T_{wbe}^{*} \pm SD$	$T_{db}i \pm SD$	$RHe \pm SD$	$RHi \pm SD$
CPC	32.0	32.8 ± 1.12^b	25.6 ± 0.46^b	26.9 ± 0.32^c	55.1 ± 3.3^a	83.1 ± 1.4^a
SPK	32.0	32.1 ± 0.57^b	24.5 ± 0.25^c	26.0 ± 0.82^d	52.4 ± 1.8^b	79.0 ± 3.6^b
FOG	33.0	37.1 ± 0.47^a	26.8 ± 0.35^a	34.6 ± 0.92^a	42.7 ± 1.9^c	49.2 ± 2.8^c
VLT	32.0	32.7 ± 0.41^b	25.5 ± 0.45^b	32.5 ± 0.61^b	55.2 ± 0.47^a	59.2 ± 1.8^d

Means followed by the same letter on the line, did not differ by the Tukey-Kramer test (P<0.05). $^{*}T_{wbe}$ means calculated wet-bulb for outside environment.

presented a regular DSD (Table 3). The adjusted models explained more than 80% of the variability in the estimated values of the semivariogram.

Variability in environmental parameters inside broiler houses responded differently according to the cooling system. The lowest variability in T_{db} and RH was recorded in the VLT. There was an increase in RH towards the end of the CPC. In the SPK, the cooling system combined with the nozzles led to variability in RH, being approximately 70% around the air inlet and higher than 80% at the air outlet of the facility (Figure 3).

DISCUSSION

A broiler house equipped with an evaporative pad cooling (CPC) or a sprinkler (SPK) at the air inlet were less vulnerable due to the higher relative efficiency of the evaporative cooling system. Evaporative cooling systems can help reduce the effects of heat stress, improve feed conversion, weight gain, and reduce mortality (DAĞTEKIN et al., 2009). A broiler house equipped with tunnel ventilation, an evaporative cooling system, and adequate insulation present constant temperatures (CURI et al., 2014),

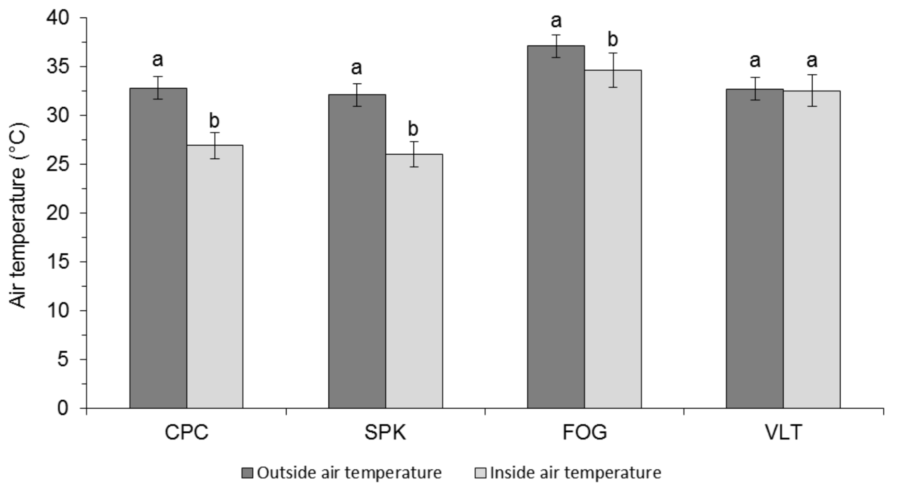


Figure 2 - Mean values of the outside and inside air dry-bulb temperature in the evaluated broiler houses (CPC - cellulose pad cooling, SPK - sprinkler, FOG - fogging, and VLT - ventilation). Means followed by the same letter, not differ from each other by the Tukey test (p < 0.05).

Table 3 - Models and estimated parameters of the experimental semivariograms for the variables air dry-bulb temperature (T_{db}, °C) and relative humidity (RH, %) in the evaluated broiler houses (CPC - cellulose pad cooling, SPK - sprinkler, FOG - fogging, and VLT - ventilation).

Variables	Broiler house	Models	--Parameters----------------------------------					
			NE[1]	Pa[2]	Co[3]	DSD[4]	R^2[5]	SSR[6]
T_{db}	CPC	Gaussian	0.19	1.06	23.71	0.81	0.99	0.0001
	SPK	Gaussian	0.01	5.07	18.25	0.99	0.96	0.764
	FOG	Spherical	0.03	0.65	42.09	0.96	0.91	0.026
	VLT	Gaussian	0.08	1.06	105.3	0.91	0.99	0.0001
RH	CPC	Gaussian	1.72	26.34	56.27	0.93	0.99	2.1
	SPK	Gaussian	1.8	171.3	37.37	0.98	0.99	25.3
	FOG	Gaussian	1.97	6.74	102.01	0.7	0.85	0.74
	VLT	Gaussian	0.9	72.8	62.18	0.98	0.99	9.2

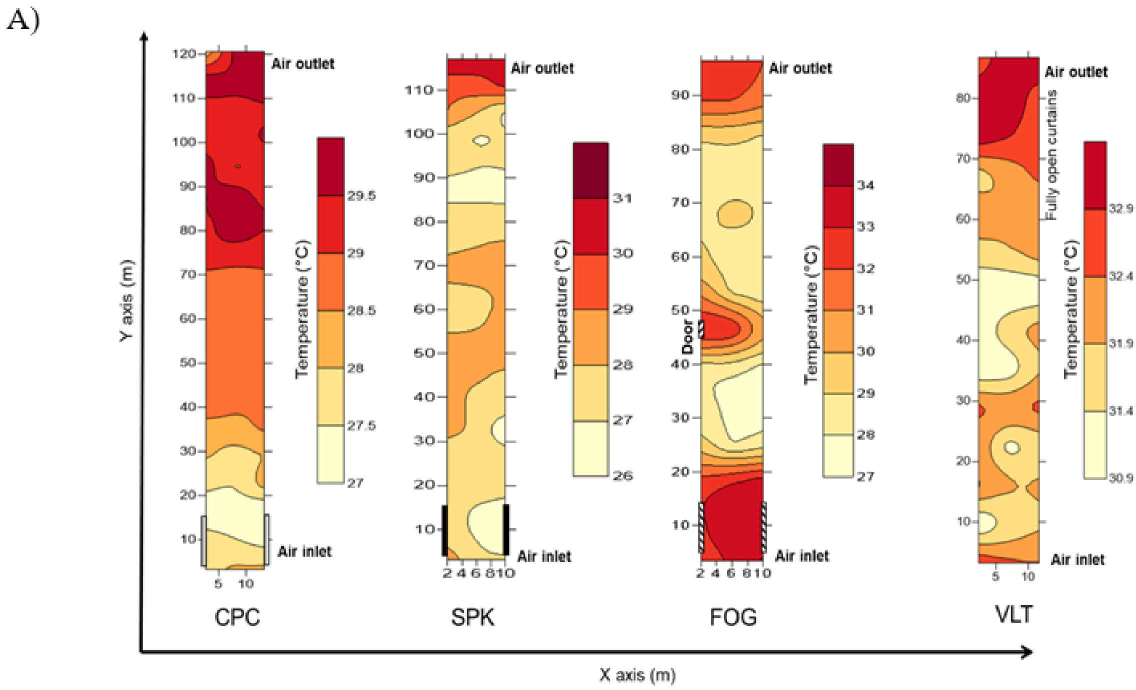
[1]NE - Nugget effect; [2]Pa - Plateau; [3]Co - Coverage; [4]DSD - Degree of Spatial Dependence; [5]R^2- coefficient of determination; [6]SSR - Sum of Squares of Residues.

as observed in the CPC and SPK in this study. In contrast, we confirmed the VLT's inability to reduce the inside air dry-bulb temperature. In the hotter hours of the day, the inside air dry-bulb temperature was higher than the outside. The facilities equipped only with tunnel ventilation (positive pressure) are not as effective in maintaining thermal comfort conditions for broilers on days with high temperatures (LEE et al., 2003). This facility can demonstrate a high vulnerability to stressful environments for broilers due to the low efficiency in dissipating the inside temperature, which can be aggravated by the heat generated by animals (SHARIF et al., 2019) and broiler litter (NAWALANY et al., 2010).

The recommended comfort temperature for broilers older than 28 days is between 21 °C and 23 °C (ALJUOBORI et al., 2016). In this study, the broiler houses analyzed were not efficient in maintaining the recommended comfort temperature, being vulnerable to extreme heat. However, facilities with an evaporative cooling system were more efficient in reducing the inside air dry-bulb temperature, when compared to the VLT. Evaporative cooling systems can be recommended as a support component for reducing the inside air dry-bulb temperature in broiler houses during the summer (DAĞTEKIN et al., 2009).

Heat waves are conditions of extreme risk of thermal challenge that can last for days or weeks. As the heat waves have been increasing across the globe in intensity, frequency, and duration (PERKINS et al., 2012; BITENCOURT et al., 2016; MAZDIYASNI et al., 2019), reduction of vulnerabilities in facilities is essential, as observed in this study. MEDA et al. (2012) used a model to predict the environmental and economic performance of broiler farming systems (MOLDAVI) and to model the response of broiler houses (with and without evaporative cooling systems), and verified a condition similar to the observed in this study: facilities equipped with evaporative cooling systems mitigated the extreme impact of heat, but did not guarantee environmental comfort within the recommended period for broilers. Thermal-related challenging conditions require systems that approach the maximum efficiency of cooling systems, such as those of broiler houses equipped with a CPC or FOG system. This fact strengthens IPCC alerts (2001, 2007), as facilities that rely on traditional systems (e.g., positive tunnel ventilation) to maintain their inside air dry-bulb temperature are more vulnerable to climate change. Within the principles of vulnerability of facilities, under the challenging conditions considered in this study, broiler houses lacking an evaporative cooling system or equipped with less efficient systems are the most vulnerable to heat extremes.

The thermal variables inside the facilities demonstrated high spatial dependence, mainly on the air dry-bulb temperature. The distribution of microclimate variables within a facility is influenced by the building material such as masonry, wood, side closure – curtain, and insulating panel, in addition to thermal insulation, air leakage, ventilation system, and outside conditions of air dry-bulb temperature and relative humidity (CARVALHO et al., 2012; SARAZ et al., 2012). The air dry-bulb temperature and



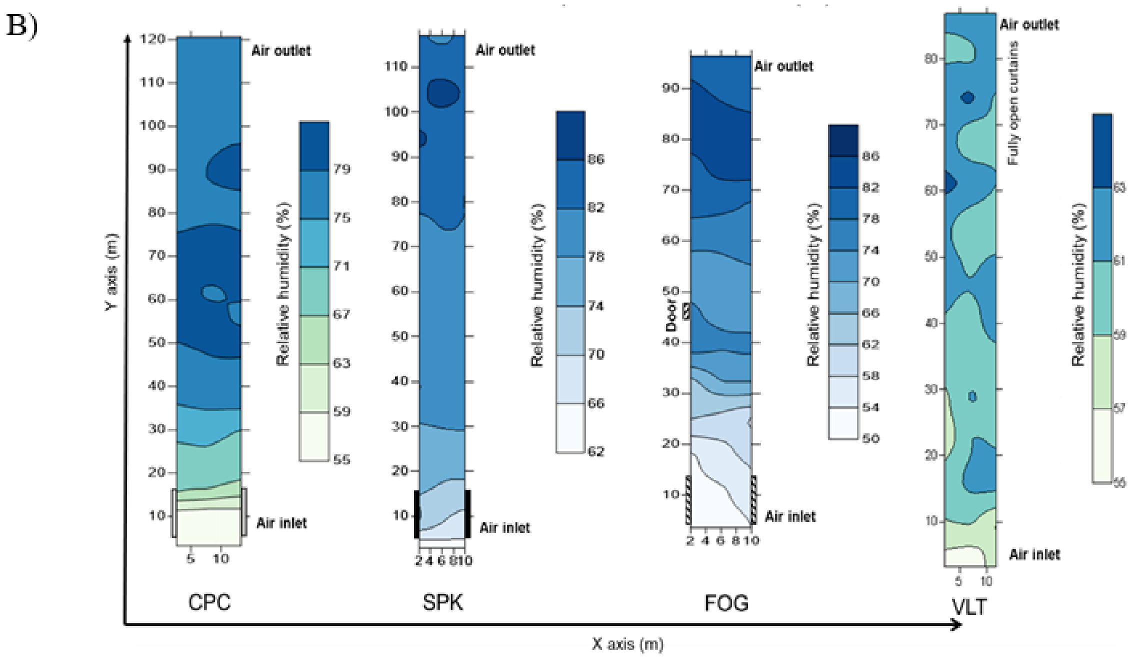


Figure 3 - Spatial distribution of environmental variables (A - air dry-bulb temperature (Tdb, °C); B - relative humidity (RH, %) evaluated inside of the broiler houses (CPC - cellulose pad cooling, SPK - sprinkler, FOG – fogging, and VLT - ventilation)).

relative humidity observed in the spatial dependence maps inside the CPC and FOG broiler houses indicate the vulnerability of these facilities to heat conditions, possibly due to a failure in thermal insulation and sealing. Thermal insulation is inefficient in many Brazilian broiler houses, mainly due to the higher initial building cost (COELHO et al., 2019).

The FOG system was inefficient in reducing the temperature near the air inlet, as indicated by the highest values recorded in this area. The VLT demonstrated lower spatial variability and was inefficient in reducing the temperature, maintaining high values along the facility. Facilities with positive pressure ventilation are more susceptible to the influence of external conditions (OSORIO et al., 2016) being less efficient in maintaining the inside air dry-bulb temperature within the ideal limits for broilers; thus, due to the cooling system present in the VLT, the broiler house considered in the study demonstrated a high vulnerability to extreme climate conditions of heat.

In contrast, negative pressure broiler houses provided better thermal comfort and less vulnerability than the VLT. However, CPC and SPK demonstrated high temperatures near the air outlet, whereas in FOG high temperature was recorded near the air inlet. This condition can cause thermal discomfort to the broilers and lead to economic losses. Additionally, different temperatures inside the facilities lead to heterogeneity in the weight of broilers (SILVA et al., 2013). The CPC and SPK presented critical values for the thermal comfort of broilers due to high RH (>70%) associated with high AT (>30 °C). This condition negatively affects the thermal exchanges of the broiler with the environment, reducing the efficiency of heat loss mechanisms (ROCHA et al., 2010; OLIVEIRA & GAI, 2016).

The air dry-bulb temperature on data collection days was close to or higher than the weather forecast (T_{db}>30 °C). In this study, we used weather forecasts to select days with extreme temperatures and a high risk of heat stress, as the inside environment of the most vulnerable facilities can reflect the outside environmental conditions. Expert systems such as fuzzy logic, data mining, and artificial neural networks (VALE et al., 2010; JHA et al., 2019; LOURENÇONI et al., 2019) can be used to develop warning systems based on weather forecasts (ACEVEDO & FITZJARRALD, 2003; MARTO, 2005; CARDOSO et al., 2010). These models assist in the decision-making of specific actions, such as adding potassium chloride supplementation in drinking water (AHMAD et al., 2008), environmental modifications (e.g., activation of cooling systems), and nutritional strategies (e.g., restriction of feed and fat addition) (see review: NAWAB et al., 2018) for minimizing broiler mortality on high-temperature days (VALE et al., 2008).

CONCLUSION

The relative cooling efficiency and the inside spatial distributions of environmental variables were influenced by the cooling system of each broiler house. The cooling system reflects the degree of vulnerability of facilities, as the absence of evaporative cooling systems was decisive for the high vulnerability to hot days. On days with temperatures above 30 °C, evaporative cooling systems mitigate thermal discomfort, but did not ensure temperatures within the recommended comfort zone for broilers older than 28 days.

ACKNOWLEDGEMENTS

To the “Coordenação de Aperfeiçoamento de Pessoal de Nível Superior” (CAPES), Brazil – Finance Code 001, and by the “Conselho Nacional de Desenvolvimento Científico e Tecnológico” (CNPq), Brazil.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

All authors contributed equally for the conception and writing of the manuscript. All authors critically revised the manuscript and approved of the final version.

REFERENCES

ABREU, P. G. et al. Morphologic measures as a function of the weight and broiler age by means of images. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v.16, n.7, p.795–801, 2012. Available from: <https://www.alice.cnptia.embrapa.br/bitstream/doc/934576/1/MorfologiaagriambiPauloAbreu.pdf>. Accessed: Jul. 07, 2020. doi: 10.1590/S1415-43662012000700014.

ACEVEDO, O. C.; FITZJARRALD, D. R. In the core of the night-effects of intermittent mixing on a horizontally heterogeneous surface. **Boundary-Layer Meteorology**, v.106, p.1–33, 2003. Available from: <https://link.springer.com/article/10.1023/A:1020824109575>. Accessed: Jul. 07, 2020. doi: 10.1023/A:1020824109575.

AHMAD, T. et al. Effect of potassium chloride supplementation in drinking water on broiler performance under heat stress conditions. **Poultry Science**, v.87, n.7, p.1276–1280, 2008. Available from: <https://www.sciencedirect.com/science/article/pii/S0032579119400291>. Accessed: Jul. 07, 2020. doi: 10.3382/ps.2007-00299.

ALJUOBORI, A. et al. Higher inclusion rate of canola meal under high ambient temperature for broiler chickens. **Poultry Science**, v.95, n.6, p.1326–1331, 2016. Available from: <https://www.sciencedirect.com/science/article/pii/S0032579119321790>. Accessed: Jul. 07, 2020. doi: 10.3382/ps/pew023.

AL-SULAIMAN, F. Evaluation of the performance of local fibers in evaporative cooling. **Energy Conversion and Management**, v.43, n.16, p.2267–2273, 2002. Available from: <https://www.sciencedirect.com/science/article/abs/pii/S0196890401001212>. Accessed: Jul. 07, 2020. doi: 10.1016/S0196-8904(01)00121-2.

ALVARES, C. A. et al. Köppen's climate classification map for Brazil. **Meteorologische Zeitschrift**, v.22, n.6, p.711–728, 2013. Available from: <https://www.schweizerbart.de/papers/metz/detail/22/82078/Koppen_s_climate_classification_map_for_Brazil?af=crossref>. Accessed: Jul. 07, 2020. doi: 10.1127/0941-21 2948/2013/0507.

BITENCOURT, D. P. et al. Frequency, Duration, Spatial Coverage, and Intensity of Heat Waves in Brazil. **Revista Brasileira de Meteorologia**, v.31, n.4, p.506–517, 2016. Available from: <https://www.scielo.br/scielo.php?pid=S0102-77862016000800506&script=sci_arttext&tlng=pt>. Accessed: Jul. 07, 2020. doi: 10.1590/0102-778631231420150077.

BOURNET, P. E.; BOULARD, T. Effect of ventilator configuration on the distributed climate of greenhouses: a review of experimental and CFD studies. **Computers and Electronics in Agriculture**, v.74, n.2, p.195–217, 2010. Available from: <https://www.sciencedirect.com/science/article/abs/pii/S0168169910001511>. Accessed: Jul. 07, 2020. doi: 10.1016/j.compag.2010.08.007.

BRANCO, T. et al. Detection of broiler heat stress by using the generalised sequential pattern algorithm. **Biosystems Engineering**, p.1–6, 2019. Available from: <https://www.sciencedirect.com/science/article/abs/pii/S1537511019308554>. Accessed: Jul. 07, 2020. doi: 10.1016/j.biosystemseng.2019.10.012.

BUCKLIN, R. A. et al. Tunnel ventilation of broiler houses. **Florida Cooperative Extension Service, Institute of Food and Agricultural Sciences, University of Florida**, PS-46, 2009. Available from: <http://edis.ifas.ufl.edu/pdffiles/PS/PS04100.pdf>. Accessed: Jul. 07, 2020.

CARDOSO, A. O. et al. Extended time weather forecasts contributes to agricultural productivity estimates. **Theoretical and Applied Climatology**, 102, p.343–350, 2010. Available from: <https://link.springer.com/article/10.1007/s00704-010-0264-0>. Accessed: Jul. 07, 2020. doi: 10.1007/s00704-010-0264-0.

CARVALHO, T. M. R. et al. Use of geostatistics on broiler production for evaluation of different minimum ventilation systems during brooding phase. **Revista Brasileira de Zootecnia**, v.41, n.1, p.194–202, 2012. Available from: <https://www.scielo.br/scielo.php?pid=S1516-35982012000100028&script=sci_arttext>. Accessed: Jul. 07, 2020. doi: 10.1590/S1516-35982012000100028.

CASSUCE, D. C. et al. Thermal confort temperature update for broiler chickens up to 21 days of age. **Engenharia Agrícola Jaboticabal**, 2013. v.33, n.1, p.28–36, 2013. Available from: <https://www.scielo.br/scielo.php?pid=S0100-69162013000100004&script=sci_arttext>. Accessed: Jul. 07, 2020. doi: 10.1590/S0100-69162013000100004.

CHEPETE, H. J. et al. Production performance and temperature-humidity index of Cobb 500 broilers reared in open-sided naturally ventilated houses in Botswana. **American Society of Agricultural and Biological Engineers**, 2005. Available from: <https://elibrary.asabe.org/abstract.asp?aid=18408>. Accessed: Jul. 07, 2020. doi: 10.13031/2013.18408.

COBB. **Manual de Manejo de Frangos de Corte COBB**, 2014, p.70.

COELHO, D. J. D. R. et al. Thermal environment of masonry-walled poultry house in the initial life stage of broilers. **Revista Brasileira de Engenharia Agricola e Ambiental**, v.23, n.3, p.203–208, 2019. Available from: <https://www.scielo.br/scielo.php?pid=S1415-43662019000300203&script=sci_arttext>. Accessed: Jul. 07, 2020. doi: 10.1590/1807-1929/agriambi.v23n3p203-208.

COUMOU, D.; ROBINSON, A. Historic and future increase in the global land area affected by monthly heat extremes. **Environmental Research Letters**, v.8, n.3, 2013. Available from: <https://iopscience.iop.org/article/10.1088/1748-9326/8/3/034018/pdf>. Accessed: Jul. 07, 2020. doi: 10.1088/1748-9326/8/3/034018.

CURI, T. M. R. D. C. et al. Geostatistic to evaluete the environmental control in different ventilation systems in broiler houses. **Engenharia Agrícola**, v.46, n.6, p.1062–1074, 2014. Available from: <https://www.scielo.br/scielo.php?pid=S0100-69162014000600004&script=sci_arttext&tlng=pt>. Accessed: Jul. 07, 2020. doi: 10.1590/S0100-69162014000600004.

DAĞTEKIN, M. et al. Performance characteristics of a pad evaporative cooling system in a broiler house in a Mediterranean climate. **Biosystems Engineering**, v.103, n.1, p.100–104, 2009. Available from: <https://www.sciencedirect.com/science/article/abs/pii/S1537511009000609>. Accessed: Jul. 07, 2020. doi: 10.1016/j.biosystemseng.2009.02.011.

GABRIEL FILHO, L. R. A. et al. Method of numerical correction of errors occasioned by delay of records during the monitoring of environmental variables of interest for animal production. **Engenharia Agrícola**, v.31, n.5, p.835–846, 2011. Available from: <https://www.scielo.br/scielo.php?pid=S0100-69162011000500001&script=sci_arttext>. Accessed: Jul. 07, 2020. doi: 10.1590/S0100-69162011000500001.

GHANIMA, M. M. A. et al. Impact of different rearing systems on growth, carcass traits, oxidative stress biomarkers and humoral immunity of broilers exposed to heat stress. **Poultry Science**, v.99, n.6, p.3070-3078, 2020. Available from: <https://www.sciencedirect.com/science/article/pii/S0032579120301711>. Accessed: Jul. 07, 2020. doi: 10.1016/j.psj.2020.03.011.

GOLDEN SOFTWARE INC. **Surfer for windows**: realese 7.0, contouring and 3D surface mapping for scientist's engineers user's guide. New York: Golden software, 619 p., 1999.

IPCC. **Climate Change 2001**: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, and C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881p., 2001. Available from: <https://www.ipcc.ch/site/assets/uploads/2018/03/WGI_TAR_full_report.pdf>. Accessed: jul 07, 2020.

IPCC. **Climate Change 2007**: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A.(eds.)]. IPCC, Geneva, Switzerland, 104 p., 2007. Available from: <https://www.ipcc.ch/site/assets/uploads/2018/02/ar4_syr_full_report.pdf>. Accessed: jul 07, 2020.

IPCC. **Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation**. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C. B., V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, K. J. Mach, G.-K. Plattner, S. K. Allen, M. Tignor, and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 582p., 2012. Available from: <https://www.ipcc.ch/site/assets/uploads/2018/03/SREX_Full_Report-1.pdf>. Accessed: Jul. 07, 2020
.

JHA, K. et al. A comprehensive review on automation in agriculture using artificial intelligence. **Artificial Intelligence in Agriculture**, v.2, p.1–12, 2019. Available from: <https://www.sciencedirect.com/science/article/pii/S2589721719300182>. Accessed: Jul. 07, 2020. doi: 10.1016/j.aiia.2019.05.004.

LEE, I.-B. et al. Study of internal climate of naturally and mechanically ventilated broiler houses. **American Society of Agricultural and Biological Engineers Annual Meeting**, p.1–10, 2003. Available from: <https://elibrary.asabe.org/abstract.asp?aid=13871>. Accessed: Jul. 07, 2020. doi: 10.13031/2013.13871.

LIAO, C. M.; CHIU, K. H. Wind tunnel modeling the system performance of alternative evaporative cooling pads in Taiwan region. **Building and Environment**, v.37, n.2, p.177–187, 2002. Available from: <https://www.sciencedirect.com/science/article/abs/pii/S0360132300000986>. Accessed: Jul. 07, 2020. doi: 10.1016/S0360-1323(00)00098-6.

LOURENÇONI, D. et al. Productive responses from broiler chickens raised in different commercial production systems – Part I: *Fuzzy* modeling. **Engenharia Agrícola**, v.39, n.1, p.1–10, 2019. Available from: <https://www.scielo.br/pdf/eagri/v39n1/1809-4430-eagri-39-01-0001.pdf>. Accessed: Jul. 07, 2020. doi: 10.1590/1809-4430-eng.agric.v39n1p1-510/2019.

MARCHINI, C. F. P. et al. Freqüência respiratória e temperatura cloacal em frangos de corte submetidos à temperatura ambiente cíclica elevada. **Archives of Veterinary Science**, v.12, n.1, p.41–46, 2007. Available from: <https://revistas.ufpr.br/veterinary/article/viewFile/9227/6453>. Accessed: Jul. 07, 2020.

MARTO, N. Ondas de calor: impacto sobre a saúde. **Acta Medica Portuguesa**, v.18, p.467–474, 2005. Available from: <http://repositorio.chlc.min-saude.pt/bitstream/10400.17/284/1/AMP%202005%20467.pdf>. Accessed: Jul. 07, 2020.

MAZDIYASNI, O. et al. Heat wave intensity duration frequency curve: a multivariate approach for hazard and attribution analysis. **Scientific Reports**, v.9, n.1, p.1–8, 2019. Available from: <https://www.nature.com/articles/s41598-019-50643-w>. Accessed: Jul. 07, 2020. doi: 10.1038/s41598-019-50643-w.

MEDA, B. et al. MOLDAVI: A model to predict environmental and economic performances of broiler farming systems. In: **10th European IFSA symposium–producing and reproducing farming systems**: new modes of organization for sustainable food systems of tomorrow, Aarhus, Denmark, p.1-4, 2012. Available from: <https://www.researchgate.net/profile/Bertrand_Meda2/publication/282864344_MOLDAVI_A_model_to_predict_environmental_and_economic_performances_of_broiler_farming_systems/links/5624902b08ae93a5c92cbc5f.pdf>. Accessed: Jul. 07, 2020.

MIRAGLIOTTA, M. Y. et al. Spatial analysis of stress conditions inside broiler house under tunnel ventilation. **Scientia Agricola**, v.63, n.5, p.426–432, 2006. Available from: <https://www.scielo.br/scielo.php?pid=S0103-90162006000500002&script=sci_arttext>. Accessed: Jul. 07, 2020. doi: 10.1590/S0103-90162006000500002.

MOURA, D. J. et al. Strategies and facilities in order to improve animal welfare. **Revista Brasileira de Zootecnia**, v.39, n.1, p.311–316, 2010. Available from: <https://www.scielo.br/scielo.php?pid=S1516-35982010001300034&script=sci_arttext>. Accessed: Jul. 07, 2020. doi: 10.1590/S151635982010001300034.

NAWAB, A. et al. Heat stress in poultry production: mitigation strategies to overcome the future challenges facing the global poultry industry. **Journal of Thermal Biology**, v.78, p.131–139, 2018. Available from: <https://www.sciencedirect.com/science/article/abs/pii/S030645651830130X>. Accessed: Jul. 07, 2020. doi: 10.1016/j.jtherbio.2018.08.010.

NAWALANY, G. et al. Effect of floor heating and cooling of bedding on thermal conditions in the living area of broiler chickens. **Archiv fur Geflugelkunde**, v.74, n.2, p.98–101, 2010. Available from: <https://www.researchgate.net/profile/Grzegorz_Nawalany/publication/279525651_Effect_of_floor_heating_and_cooling_of_bedding_on_thermal_conditions_in_the_living_area_of_broiler_chickens/links/5594f22008ae21086d1efc56/Effect-of-floor-heating-and-cooling-of-bedding-on-thermal-conditions-in-the-living-area-of-broiler-chickens.pdf>. Accessed: Jul. 07, 2020. doi: 10.1590/s1415-43662009000600020.

NAZARENO, A. C. et al. Evaluation of thermal comfort and performance of broiler chickens under different housing systems. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v.13, n.6, p.802–808, 2009. Available from: <https://www.scielo.br/scielo.php?pid=S1415-43662009000600020&script=sci_arttext>. Accessed: Jul. 07, 2020. doi: 10.1590/S1415- 43662009000600020.

OLIVEIRA, L. P.; GAI, V. F. Broiler performance in conventional poultry and poultry dark house. **Revista Cultivando o Saber**, v.9, p.93–101, 2016. Available from: <https://www.fag.edu.br/upload/revista/cultivando_o_saber/57056110de972.pdf>. Accessed: Jul. 07, 2020.

OSORIO, R. et al. Thermal environment in two broiler barns during the first three weeks of age. **Revista Brasileira de Engenharia Agricola e Ambiental**, 2016. v.20, n.3, p.256–262, 2016. Available from: <https://www.scielo.br/scielo.php?pid=S1415-43662016000300256&script=sci_arttext>. Accessed: Jul. 07, 2020. doi: 10.1590/1807-1929/agriambi.v20n3p256-262.

PEREIRA, D. F. et al. Estimating mortality in laying hens as the environmental temperature increases. **Revista Brasileira de Ciencia Avicola**, v.12, n.4, p.265–271, 2010. Available from: <https://www.scielo.br/scielo.php?pid=S1516-

635X2010000400008&script=sci_arttext>. Accessed: Jul. 07, 2020. doi: 10.1590/S1516-635X2010000400008.

PERKINS, S. E. et al. Increasing frequency, intensity and duration of observed global heatwaves and warm spells. **Geophysical Research Letters**, v.39, n.20, p.1–5, 2012. Available from: <https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2012GL053361>. Accessed: Jul. 07, 2020. doi: 10.1029/2012GL053361.

ROCHA, H. P. et al. Bioclimatic and production parameters in different poultry houses in the semiarid region of Paraiba State. **Revista Brasileira de Engenharia Agrícola e Ambiental**, v.14, n.12, p.1330–1336, 2010. Available from: <https://www.scielo.br/scielo.php?pid=S1415-43662010001200012&script=sci_arttext&tlng=pt>. Accessed: Jul. 07, 2020. doi: 10.1590/S1415-43662010001200012.

SALAS, R. C. et al. Productivity and financial viability of commercial broiler farm using climate controlled system: the case in a state-owned University in Nueva Ecija, Philippine. **CLSU International Journal of Science & Technology**, v.1, n.1, p.32-45, 2016. Available from: <https://www.clsu-ijst.org/index.php/ijst1/article/view/19>. Accessed: Jul. 07, 2020. doi: 10.22137/ijst.2016.v1n1.04.

SANTOS, M. P. et al. Heat stress in broilers and the need of climatization systems. **Brazilian Journal of Biosystems Engineering**, v.11, n.3, p.265–272, 2017. Available from: <http://seer.tupa.unesp.br/index.php/BIOENG/article/view/549/338>. Accessed: Jul. 07, 2020. doi: 10.18011/bioeng2017v11n3p265-272.

SARAZ, J. A. O. et al. Validation of a CFD model for prediction of the efficiency of evaporative cooling in porous panel. **Revista U.D.C.A. Actualidad & Divulgacion Cientifica**, v.15, n.1, p.209–217, 2012. Available from: <http://www.scielo.org.co/scielo.php?pid=S0123-42262012000100022&script=sci_arttext&tlng=en>. Accessed: Jul. 07, 2020.

SHARIF, A. et al. Management of heat stress in poultry flocks during summer season. **Gomal University Journal of Research**, v.35, n.1, p.35–43, 2019. Available from: <http://www.gujr.com.pk/index.php/GUJR/article/download/28/183>. Accessed: Jul. 07, 2020.

SILVA, E. G. et al. Spatial variability of the environmental characteristics and weight of broilers in shed negative ventilation. **Revista Brasileira de Saude e Producao Animal**, v.14, n.1, p.132–141, 2013. Available from: <https://www.scielo.br/scielo.php?pid=S1519-99402013000100014&script=sci_arttext>. Accessed: Jul. 07, 2020. doi: 10.1590/S1519-99402013000100014.

STULL, R. Wet-bulb temperature from relative humidity and air temperature. **Journal of Applied Meteorology and Climatology**, v.50, n.11, p.2267–2269, 2011. Available from: <https://journals.ametsoc.org/jamc/article/50/11/2267/13533>. Accessed: Jul. 07, 2020. doi: 10.1175/JAMC-D-11-0143.1.

VALE, M. M. et al. Characterization of heat waves affecting mortality rates of broilers between 29 days and market age. **Revista Brasileira de Ciencia Avicola**, v.12, n.4, p.279–285, 2010. Available from: <https://www.scielo.br/pdf/rbca/v12n4/a10v12n4.pdf>. Accessed: Jul. 07, 2020. doi: 10.1590/S1516-635X2010000400010.

VALE, M. M. et al. Data mining to estimate broiler mortality when exposed to heat wave. **Scientia Agricola**, v.65, n.3,