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ENGINEERING SCIENCES

Spatial analysis of microclimatic variables in compost-bedded pack barn with evaporative tunnel cooling

RAFAELLA R. ANDRADE, ILDA DE FÁTIMA F. TINÔCO, FLÁVIO A. DAMASCENO, GABRIEL A.S. FERRAZ, LETÍCIA CIBELE S.R. FREITAS, CECÍLIA DE FÁTIMA S. FERREIRA, MATTEO BARBARI & CARLOS G.S. TELES JUNIOR

Abstract: In this study, we aimed to assess the spatial variability of microclimate inside a closed compost-bedded pack barn (CBP) with a negative ventilation system during summer and winter. The research was carried out in a CBP located in the Zona da Mata region, Minas Gerais, Brazil. For each of the stations analyzed, the following environmental mean variables observed inside a CBP were measured: air dry-bulb temperature (t_{db}), air relative humidity (RH), and windspeed, Temperature-Humidity index, and specific enthalpy. The kriging maps showed that the most critical housing conditions in the thermal environment were found, mainly, from the central part of the CBP, close to the exhaust fans. The analyses also pointed out that the system presented temperature gradients along the length, up to 3°C. During the summer afternoon, the entire region of the CBP was in a discomfort situation (t_{db}>26°C; RH>75%). During the winter, the measured environmental data remained within the comfort zone throughout the facility. However, probably due to the lack of thermal insulation of the material used to close the sides of the CBP, it did not allow spatial thermal uniformity for both seasons. It was also inefficient to keep the animals within the comfort zone for lactating cattle during the critical summer period.

Key words: animal welfare, compost barns, dairy cattle, evaporative cooling, heat stress, model-based geostatistics

INTRODUCTION

Dairy cattle, especially high-yielding cattle, are particularly sensitive to heat stress, making the dairy industry one of the livestock sectors most affected by heat (Ouellet et al. 2019). Thus, the inadequate thermal environment can cause changes in the productive and reproductive performance in the health and welfare of cattle, which can make the activity unfeasible (Polsky & von Keyserlingk 2017, Dikmen et al. 2020).

As a way to improve and control the raising environment, there is a growing and continuous interest from producers in the search for more effective management strategies to guarantee increased productivity and milk quality, combined with the rational use of resources (Andrade et al. 2021). In this sense, the compost-bedded pack barn (CBP) indicates to be an interesting management alternative that suggests mitigating the negative effects of thermal stress on dairy cattle, by reducing the thermal magnitude of the environment during the hottest seasons and the hottest hours of the day.

The CBP is usually used successfully in regions with mild weather, such as North America and Europe. The use of the CBP system is relatively new in Brazil, compared to conventional systems, however, it indicates the potential to bring significant benefits to the comfort, welfare, and productive performance of dairy cattle (Radavelli et al. 2020, Andrade et al. 2021, Yameogo et al. 2021).

In the CBP, the animals remain in free circulation inside a covered facility, which contains a large area of collective bedding where cows are distributed. The bed, usually made up of varied organic material, must be frequently stirred to incorporate animal waste and favor microbial activity in the aerobic composting process (Barbeg et al. 2007, Leso et al. 2020).

In Brazil, basically, almost all CBP follow the country's standard construction typology, consisting of open installations on the sides, without thermal insulation on the roofs (Damasceno 2020). They can be ventilated naturally or via forced ventilation by positive pressure. Such an open typology, however, makes the thermal control of the environment vulnerable. Recently some closed CBP facilities with more stringent environmental control systems are being implemented in Brazil, in order to remedy or alleviate this problem (Andrade et al. 2020, Valente et al. 2020, Oliveira et al. 2021).

The fully enclosed confinement system, however, requires special attention as to the way of ventilation, since adequate air renewal inside the CBP is essential to improve the bed drying, the indoor air quality, as well as to maintain the animals thermal comfort environment (Janni et al. 2007, Lobeck et al. 2012).

Therefore, the knowledge of the spatial variability of microclimate attributes allows a spatial visualization which is useful for planning and controlling information in the production environment besides indicating possible stress zones inside the facility (Miragliotta et al. 2006, Faria et al. 2008). Thus, the use and support of mathematical tools and computational techniques, such as the geostatistics use, makes the interpretation of the environmental attributes variability more accurate, helping in the correct handling of confined animals and the more effective control of the ventilation system used (Abreu et al. 2016, Curi et al. 2017, Lopes et al. 2020, Oliveira et al. 2021).

We hypothesized there is spatial variability of the thermal environment inside the CBP, with critical housing conditions for lactating cows. Therefore, the objective of this study aimed to evaluate the dependence and spatial distribution of microclimate conditions, in a CBP with a negative ventilation system, during the summer and winter.

MATERIALS AND METHODS

Characterization and description of the compost-bedded pack barn

The data for this study were collected in a closed compost-bedded pack barn (CBP) for the confinement of dairy cattle in the lactation phase; provided with negative pressure ventilation in tunnel mode, associated with the evaporative cooling system (ECS), with porous plates use during two study periods: December 2018 (summer) and July 2019 (winter), for fifteen days continuous in each season; and during four periods of the day (the dawn, period from 00:00a.m. to 05:00a.m.; morning, from 06:00a.m. to 11:00a.m.; afternoon, from 12:00p.m. to 05:00p.m.; and night, from 06:00p.m. to 11:00p.m.).

The choice to study winter and summer is because these are the most critical climatic seasons for the breeding of dairy cattle of European origin. If, on the one hand, the heat of the tropical summer is a source of great stress to animals, in winter, the biggest problem in the CBP facilities is the high humidity of the bed, which can make the system unfeasible.

The studied CBP is located in the Zona da Mata region, Minas Gerais, Brazil (670 m altitude, coordinates 20° 46' 41" S, and 42° 48' 57" W). The local climate, according to the Köppen classification, is of the Cwa-type, with cold, dry winter and hot and humid summer (Alvares et al. 2013).

The CBP was built in May 2017 has a northwest-southeast orientation, total dimensions of 55.0 m long × 26.4 m wide, a gable roof, corrugated metal roof tiles, a height of 5 m, and eaves of 0.8 m. The internal spatial distribution of the CBP is composed of: a) drive-through alley with a concrete floor with an area of 220 m² (containing a single trough 55 m long), being the region where the tractor circulates for food distribution; b) feeding alley (0.8 m linear^{-1} per animal) with concrete floor with an area of 220 m² (separated from the bed area by a 1.2 m high wall), with four drinking fountains (1.0 m linear^{-1} for each group of 15 animals) in this region; c) 880 m² bedding area; d) management corridor with concrete floor and an area of 132 m² (Figure 1).

The facility roof lining and the lateral closure material (without insulation) are made of polypropylene, in blue color. Five deflectors were installed across the facility (3 m above the floor line, spaced every 11 m, the first deflector was 5.5 m away from the evaporative plate) to direct and increase the animals' airflow. The deflectors extended over the bed area and feeding alley. The CBP was kept closed on the sides by polypropylene curtains, equipped with an automatic opening system, activated in a power outage, thus guaranteeing air renewal. The CBP lighting was carried out using ten 100W LED lamps. In summer, the luminous intensity values registered inside the CBP were 82.7 lx and 20.4 lx, during the day and night, respectively. In winter, the luminous intensity values registered inside the CBP were 69.9 lx and 15.3 lx, during the day and night, respectively.

On the southeast side of the CBP, a series of five porous cellulose plates (total dimensions of 18.0 × 3.5 m) was used in the ECS composition. A sensor positioned inside the CBP, monitored environmental conditions and was programmed to be activated when the air temperature was equal to or higher than 21 °C and relative humidity below 75 %. Thus, the plates were moistened by dripping to allow the adiabatic cooling of the external air that passed through the same suction path (negative pressure), promoted by the exhaust fans located on the opposite end.

At the opposite end (northwest side) of the facility were five large exhaust fans (BigFan®, Caxias do Sul/RS, BR, high-volume low-speed

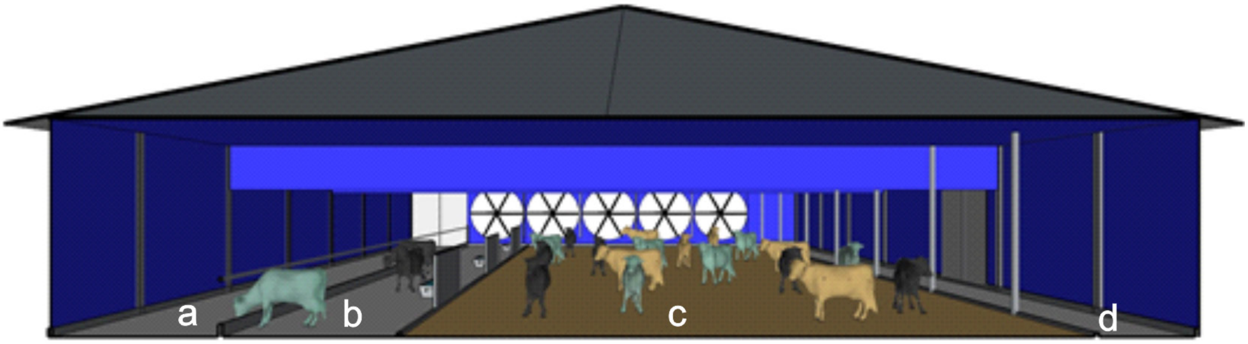

Figure 1. Schematic representation of the experimental facility. (a) drive-through alley; (b) feeding alley; (c) bedding area; (d) management corridor. Source: Andrade et al. (2021).

- HVLS, 3.5 m in diameter, six propellers, an air volume of 150,000 m^3 h^{-1}, and power of 1491.4 W). The five exhaust fans remained on continuously (24 hours day^{-1}).

The superficial washing of the feeding alley floor was performed by the known flushing system and happened once daily, in the morning.

The CBP had a bed made up of a mixture of wood shavings and coffee husks, with an approximately 0.60 m thickness. The bed's stirring was mechanized and happened periodically, twice a day, usually at 6:30a.m. and 12:00p.m., with a depth of 0.20 m. The stirring was carried out through the hybrid implement (chisel with roller) coupled to a tractor (JOHN DEERE® 5078E, 78hp) to incorporate animal waste into the bedding material, promote higher aeration for the composting process, and decompress the bedding.

In the summer experimental period, 80 cows were housed in the CBP, with a space per cow of 11 m^2 cow^{-1}. In the winter period, 88 cows were housed in the CBP, with a space per cow of 10 m^2 cow^{-1}. The cows were Holstein breed, weighing approximately 614.0 ± 58.4kg.

Following the management already practiced on the property, lactating cows were distributed in two Batches inside the CBP, according to the animals' milk production. The animals with the highest production rates were housed in Batch 1 (bed area 38.5 m x 16.0 m), average of 31.0 ± 5.1 kg milk day^{-1}, located close to the evaporative plates. Batch 2 (bed area 16.5 m x 16.0 m), with the lower production animals, average of 19.1 ± 6.8 kg milk day^{-1}, was located close to the exhaust fans. Within the CBP there were primiparous cows with a mean age of 2.7 years and multiparous cows with a mean of 4 lactations.

During the experiment, the property's standard routine was maintained, and milking was performed twice a day (3:00a.m. and 1:00p.m.) in a 2 x 5 herringbone milking parlor attached to the CBP. The average duration of each milking was one hour and thirty minutes. The cows had free access to the feeding trough and drinking fountains, with food provided twice a day.

Environmental instruments and measurements

The microclimatic data collection (temperature and relative humidity of the air) occurred uninterruptedly, 24 hours day^{-1}, at 5-minute intervals, for fifteen days continuous in summer and fifteen days continuous winter, according to methodology adapted from Freitas et al. (2018) and Damasceno et al. (2019). The air dry-bulb temperature (t_{db}, °C) and air relative humidity (RH, %) data were recorded using 54 low-cost sensors (DHT22, model AM2302, Aosong Electronics Co., Ltd., Guangzhou, China, relative humidity measurement range from 0 to 100 %, accuracy of ± 2 %, temperature measurement range from – 40 ° to + 80 °C, an accuracy of ± 0.5 °C) distributed over the region of the bed and the feeding alley, defining a total measurement area of 55 m × 20 m. The internal area of the CBP was divided into a regular mesh of 5.5 x 3.5 m, totaling 54 points $sensors^{-1}$ evenly spaced throughout the facility. Each sensor was positioned at a measurement point, as shown in Figure 2. The sensors were installed at 2.0 m height concerning the bed and the floor of the feeding alley.

The data collected by the sensors were sent every 5 minutes to the main station for processing and storing the data in a micro SD. This station consisted of the Arduino Mega 2560 board, capable of receiving t_{db} and RH data from the air, from 54 DHT22 sensors.

On each Arduino Mega 2560 (https://www.arduino.cc/) board, a real-time clock module was attached to control the time; 16×2 LCD (I2C),

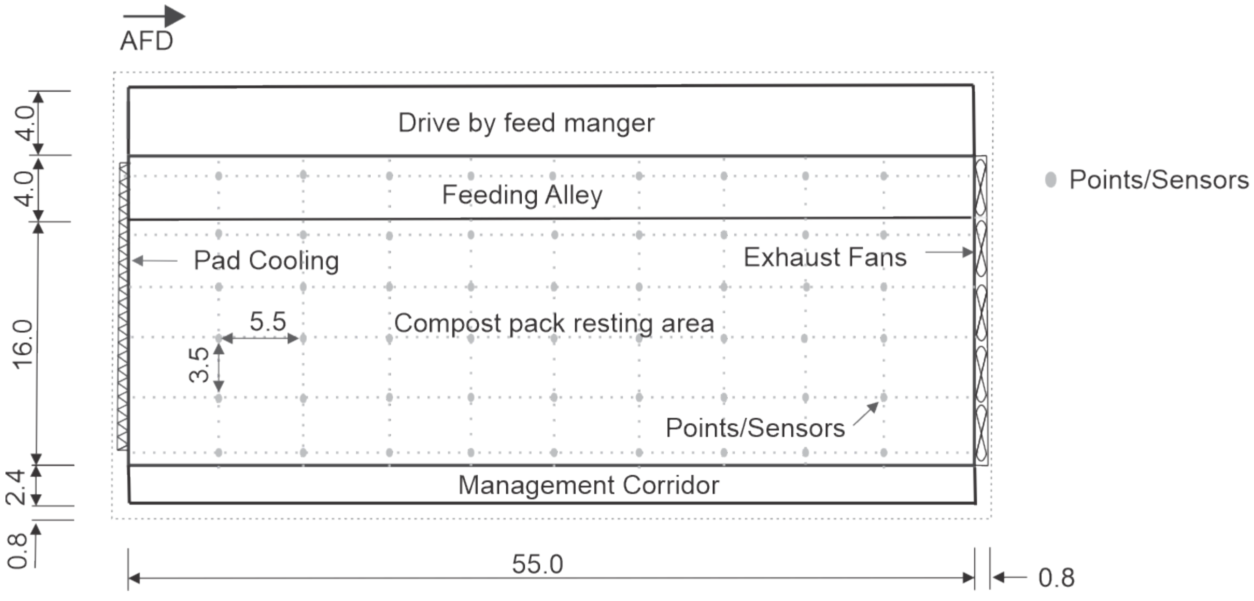

Figure 2. Schematic representation of the collection points inside the compost bedded pack barn (CBP). *AFD – Air flow direction. Dimensions in meters (m). Subtitle: Points/Sensors.

display used to present data measurements, times and dates provided by the RTC (Real Time Clock); Micro SD card module, which allows data to be read and written to the SD card; four DHT22 sensors; according to an adapted methodology by Freitas et al. (2019).

To assess the external environmental conditions, a meteorological shelter was used, in which two t_{db} and RH recorders were placed inside. The data were collected every 5 minutes, 24 hours a day^{-1}. These data were used for the climatic characterization of the region where the CBP was located.

To identify the most critical environmental periods inside the CBP, the average daily values of t_{db} and RH of the air obtained during each experimental period (summer and winter) were divided into four periods. Dawn period (00:00a.m. to 5:00a.m.), morning (6:00a.m. to 11:00a.m.), afternoon (12:00p.m. to 5:00p.m.), and night (6:00p.m. to 11:00p.m.).

Subsequently, in possession of the collected microclimate data and to assess possible conditions of heat stress and the spatial variability of the attributes, the average of Temperature-Humidity Index (THI) and the specific enthalpy (H) were calculated for the four periods of the day investigated.

1) Temperature-Humidity Index (THI), using equation 1 corrected and modified by Mader et al. (2006).

$$THI = 0.8.t_{db} + \mathrm{RH}.\left(\frac{t_{db} - 14.4}{100}\right) + 46.4 \qquad (1)$$

Where: t_{db} = air dry-bulb temperature (°C); RH = air relative humidity (%).

Specific enthalpy (H), according to the model proposed by Rodrigues et al. (2011):

$$H = 1.006.t_{db} + \frac{RH}{PB} 10^{\frac{7.5.t_{db}}{237.3+t_{db}}} \left(71.28 + 0.052.t_{db}\right) \qquad (2)$$

Where: H is the specific enthalpy (kJ kg dry air^{-1}); PB is the barometric pressure (mmHg), equal to 706 mmHg.

The internal air velocity was measured at two different heights, at 1.5 m high, in order to check the air velocity when the animals were standing; and at 0.05 m in height, to check the windspeed when the animals were lying down, as well as to check the windspeed for drying the bed. The measurements were made using a hot wire anemometer (Instrutherm®, model TAFR-180, speed 0.2 to 20.0 m s^{-1}, an accuracy of ± 0.1 m s^{-1}). The average windspeed (V_m, m s^{-1}; the height of 1.5 m) was obtained by positioning the device in the same points as the DHT22 sensors in the region of the bed and feeding alley (totaling 54 points), the windspeed at bed level (V_l, m s^{-1}; the height of 0.05 m) was obtained in the bed region (totaling 45 points). The sensor was positioned at each measurement point by a period of one minute or until the windspeed has stabilized. The windspeeds were measured when all the gates were closed, the exhaust fans were in operation, and the facility was with all the cows. As the five exhaust fans were always on, only one measurement was performed daily during the entire experimental period, always at 10 a.m.

Statistical Analysis

The geostatistics technique was used to verify the spatial distribution of the microclimate within the CBP and the dependence between the collection points. The spatial dependence of environmental variables (t_{db}, HR, THI, H and V_m and V_l) was analyzed using semivariogram adjustments and ordinary kriging interpolation. This method was used to predict the levels of the variables in places not sampled inside the CBP.

To estimate the semivariogram, the Matheron estimator (1962) was used according to equation 3, to quantify the spatial dependence of the variables within the facility.

$$\hat{\gamma}(h)=\frac{1}{2N(h)}\sum_{i=1}^{N(h)}\left[Z(X_i)-Z(X_i+h)\right]^2 \qquad (3)$$

Where: *N (h)* is the number of observation pairs $Z(X_i)$ e $Z(X_i + h)$ separated by a distance *h*.

From the adjustment of a mathematical model $\hat{y}(h)$, the coefficients of the theoretical model were obtained for the semivariogram, called nugget effect (C_0), contribution (C_1), sill ($C_0 + C_1$), and range (a).

The spatial dependence index (SDI) was used to analyze the spatial dependence and calculated from the ratio between the nugget effect (C_0) and the sill ($C_0 + C_1$). To analyze the SDI of the attributes under study, the classification by Cambardella et al. (1994), in which a strong dependence is considered in semivariograms with SDI ≤ 0.25; moderate dependence on semivariograms with 0.25 < SDI ≤ 0.75 and weak dependence on semivariograms with SDI > 0.75.

The semivariogram was adjusted by the Method of Restricted Maximum Likelihood (REML), as suggested by Marchant & Lark (2007). The models tested for the adjustment of the experimental semivariogram were spherical, exponential, and Gaussian, according to Vieira et al. (2010), and through the geoR library (Ribeiro Junior & Diggle 2001) of the software R Development Core Team (2016).

Subsequently, once the semivariogram of the variables was known and spatial dependence occurred, the levels of spatial distribution maps of the microclimate variables were made using the ordinary data kriging technique. This method allows the visualization of data spatialization, through the interpolation of values, without trend and with minimal variance (Vieira 2000). From the interpolated data, maps of the response surface were generated using the Surfer® software, version 13.4.

RESULTS AND DISCUSSION

Analysis of microclimate variables

The average air temperature inside the CBP during summer was similar to the outdoor environment, until the moment when the internal temperature of the air reached 21.0 °C. After that, the automatic spraying of the porous material occurred to promote the evaporative cooling of the incoming air (Figure 3).

Before the activation of the ECS (indoor air temperatures below 21.0 °C), although following similar behavior curves, it was found that the air temperature values inside the CBP were slightly higher than the observed for external temperatures, which can be attributed to the heat produced by the cows and the equipment, by the heat generated in the bed composting process and due to the heat energy from the short-wave solar radiation that passed through roofs and side walls and was retained temporarily inside the CBP.

However, after the activation of the ECS, there was an inversion of the temperature curves, with a reduction in the internal temperatures of the housing, compared to those of the outdoor environment. Those variations in the internal and external averages t_{db} (Figure 3a) show, therefore, that the use of the ECS was able to reduce the t_{db} of the air inside the housing, during the most critical periods of the day, with an average of 4.0 and 3.8 °C below the outdoor environment, during summer and winter, respectively.

Concerning the variable RH, it can be observed, based on Figure 3b, similar behaviors of average hourly values of the indoor air relative humidity over time when compared to the values measured in the outdoor environment. However, in the case of periods with higher temperatures, it was necessary to use the ECS in the hottest hours of the day (temperatures above 21 °C), requiring the activation of the sprinklers on the porous plate, generating an increase in the relative humidity value of the air inside the CBP. The mean RH values observed were high inside the CBP facility, during the two seasons analyzed (predominance of mean RH values above 70%).

Figure 4 shows the hourly average values of the Temperature-Humidity Index (THI), referring to the environment outside and inside the CBP, during the experimental period of summer and winter.

It is verified that, during the summer, the average hourly variation of the THI for both environments (outdoor and indoor) at times of higher air temperature were those that were above the maximum limit recommended by the literature of 74 (Mader et al. 2006) for dairy cattle. During the summer, the maximum average of THI was 76 and 80, in internal and external environment, respectively. During winter, the maximum mean value of THI was 67 and 71, indoors and outdoors, respectively. Demonstrating that in the hottest times of the

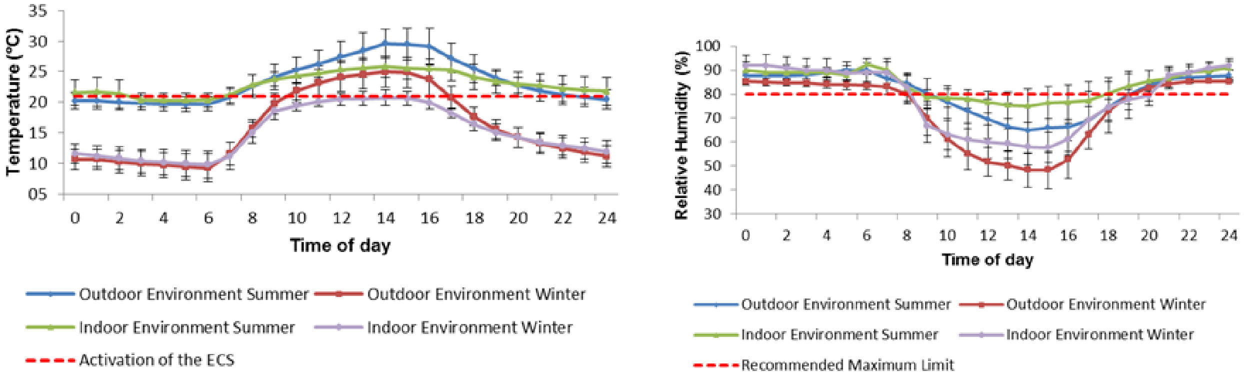

Figure 3. Average variation and standard deviation of the hourly mean values of (a) air temperature (tair) in °C and (b) relative humidity (RH), in %, of the air inside the closed compost-bedded pack barn (CBP), equipped with the EACS - Adiabatic Evaporative Cooling System, and in the external environment, throughout the experimental period of summer and winter.

day, the architectural characteristics of the CBP and the ventilation system adopted were not enough to reduce the THI values.

Therefore, to reduce these high THI values, it would be important to carry out some internal improvements in the CBP, such as using roofing materials and side closures with good insulation and, adapting to this, other construction and ventilation devices that can contribute to the better thermal comfort of the animals. During the winter, the hourly mean values of THI (outdoor and indoor) remained within the thresholds recommended by the literature.

As expected, compared to winter, the summer period was more critical with regard to the thermal comfort of dairy cows, as high values of t_{db}, RH and THI were recorded. That is, they had a longer length of stay in conditions of thermal discomfort due to heat.

Geostatistical analysis

Table I shows the method, model, and estimated parameters of the experimental semivariogram for the mean values of each period for the variable's dry bulb temperature (t_{db}, °C) and air relative humidity (RH, %), in the inside the compost-bedded pack barn (CBP) during the summer and winter trial period.

According to the geostatistical analysis, all the analyzed situations presented spatial variability of the variables (t_{db} and RH) inside the CBP, expressed by the semivariograms. The importance of the nugget effect (C_0) is related to the verification of the semivariogram's discontinuity for distances shorter than the shortest distance between the collected points. Part of this discontinuity may be due to errors that occurred, for example, by analysis errors, errors sampling, among others (Vieira, 2000). As it is impossible to quantify the individual contribution of these errors, the nugget effect can be expressed as a percentage of the threshold, thus facilitating the comparison of the spatial dependence degree of the variables under study (Trangmar et al. 1986).

Thus, the SDI showed that the microclimate attributes showed spatial dependence according to the classification proposed by Cambardella

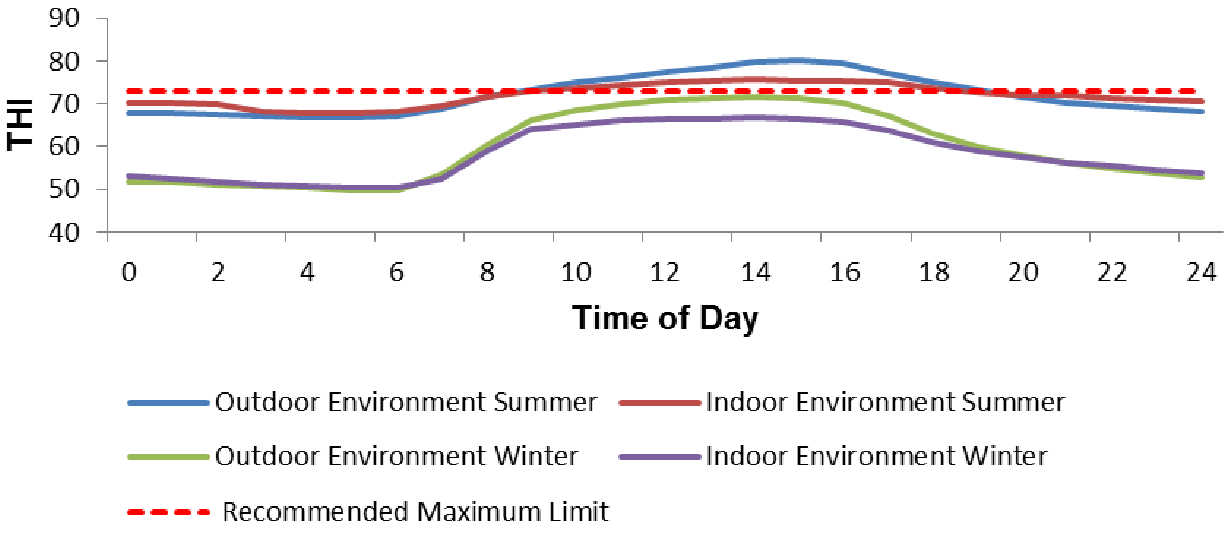

Figure 4. Variation of the hourly mean values of Temperature-Humidity index, inside the closed compostbedded pack barn (CBP), equipped with the EACS - Adiabatic Evaporative Cooling System, and in the external environment, throughout the experimental period of summer and winter.

et al. (1994). The adjusted semivariograms demonstrated that the t_{db} and RH showed a strong and moderate degree of dependence, with the semivariogram being adjusted in the Gaussian model in practically all situations, except for the t_{db} during the night and in the winter, which was adjusted to the spherical model.

The reach values concerning the semivariograms are relevant in determining the spatial dependence limit. They indicate the sampling limit distance in which the collected points are spatially correlated (Ferraz et al. 2016). The highest values of t_{db} range during the summer referred to the dawn period (summer), with a range of 51.035 m, and in the winter during the afternoon, with a range of 34.685 m. For RH, the highest reach values referred to the morning in the summer and during the afternoon and night in the winter, with a reach of 36.141 m, 30.240 m, and 30.240 m, respectively.

Figure 5 illustrates the ordinary kriging interpolation of the variable air dry-bulb temperature (°C), in the dawn, morning, afternoon and night, obtained inside the CBP, during the summer and winter seasons.

It can be seen from Figure 5 that, in all the analyzed situations, the t_{db} increased as it moved away from the evaporative cooling plates. Consequently, the highest temperatures are

Table I. Method, model, and estimated parameters of the experimental semivariogram for the mean values of each period for the variables air dry-bulb temperature (t_{db},°C) and air relative humidity (RH, %) inside the compost-bedded pack barn (CBP) during the winter and summer.

Variables	Method	Model	C_0	C_1	C_0+C_1	a	SDI	ME	SDm	RE	SDR
Summer											
t_{dbDawn}^{1}	REML	Gaussian	0.013	0.242	0.256	51.035	0.052	-0.001	0.130	-0.002	1.011
$t_{dbMorning}$	REML	Gaussian	0.009	0.374	0.383	22.830	0.024	0.007	0.147	0.023	1.032
$t_{dbAfternoon}$	REML	Gaussian	0.003	1.025	1.028	34.619	0.003	-0.001	0.073	-0.002	1.014
$t_{dbNight}$	REML	Gaussian	0.033	0.434	0.467	49.480	0.072	0.001	0.206	0.001	1.014
Winter											
t_{dbDawn}^{1}	REML	Spherical	0.016	0.082	0.098	3.823	0.167	0.000	0.319	0.000	1.009
$t_{dbMorning}$	REML	Gaussian	0.000	0.078	0.078	20.550	0.004	0.001	0.036	0.011	1.003
$t_{dbAfternoon}$	REML	Gaussian	0.024	0.591	0.616	34.685	0.039	-0.001	0.194	-0.003	1.028
$t_{dbNight}$	REML	Spherical	0.016	0.081	0.098	3.890	0.167	0.000	0.318	0.000	1.009
Summer											
RH_{Dawn}^{1}	REML	Gaussian	0.017	4.079	4.096	19.158	0.004	0.002	0.251	0.004	0.956
$RH_{Morning}$	REML	Gaussian	0.131	30.866	30.996	36.141	0.004	-0.011	0.517	-0.009	1.044
$RH_{Afternoon}$	REML	Gaussian	0.221	10.753	10.974	27.857	0.020	0.004	0.562	0.002	0.964
RH_{Night}	REML	Gaussian	0.142	2.374	2.516	30.240	0.057	-0.008	0.543	-0.008	1.190
Winter											
RH_{Dawn}^{1}	REML	Gaussian	0.770	0.679	1.449	25.924	0.531	-0.010	0.968	-0.005	1.007
$RH_{Morning}$	REML	Gaussian	0.092	6.249	6.341	19.036	0.015	0.005	0.573	0.006	1.033
$RH_{Afternoon}$	REML	Gaussian	0.142	2.374	2.516	30.40	0.057	-0.041	0.936	-0.040	1.939
RH_{Night}	REML	Gaussian	0.142	2.374	2.516	30.240	0.057	-0.005	0.441	-0.005	0.988

C_0 – nugget effect; C_1 – contribution; C_0 + C_1 – sill; a – range; SDI – spatial dependence index; ME - Mean error; SDm - Standard deviation of mean error; RE - Reduced error; SDR - Standard deviation of reduced error. REML – Method of Restricted Maximum Likelihood.

found at the opposite end, close to the exhaust fans, due on the cooling system by negative pressure ventilation in tunnel mode which conducts air in the longitudinal direction of the facility. As predicted, during the summer and winter seasons, the temperatures in the morning and night are lower than those recorded in the morning and night due to the natural thermal inversion.

The geostatistical analysis also made it possible to visualize the behavior of spatial thermal conditions in the summer period (Figure 5, a, c, e, g). For this period, in all evaluated situations, the CBP area showed t_{db} within the recommended temperature range for lactating cattle (values below 26 °C, Perissinotto & Moura, 2007), except in the afternoon (Figure 5e).

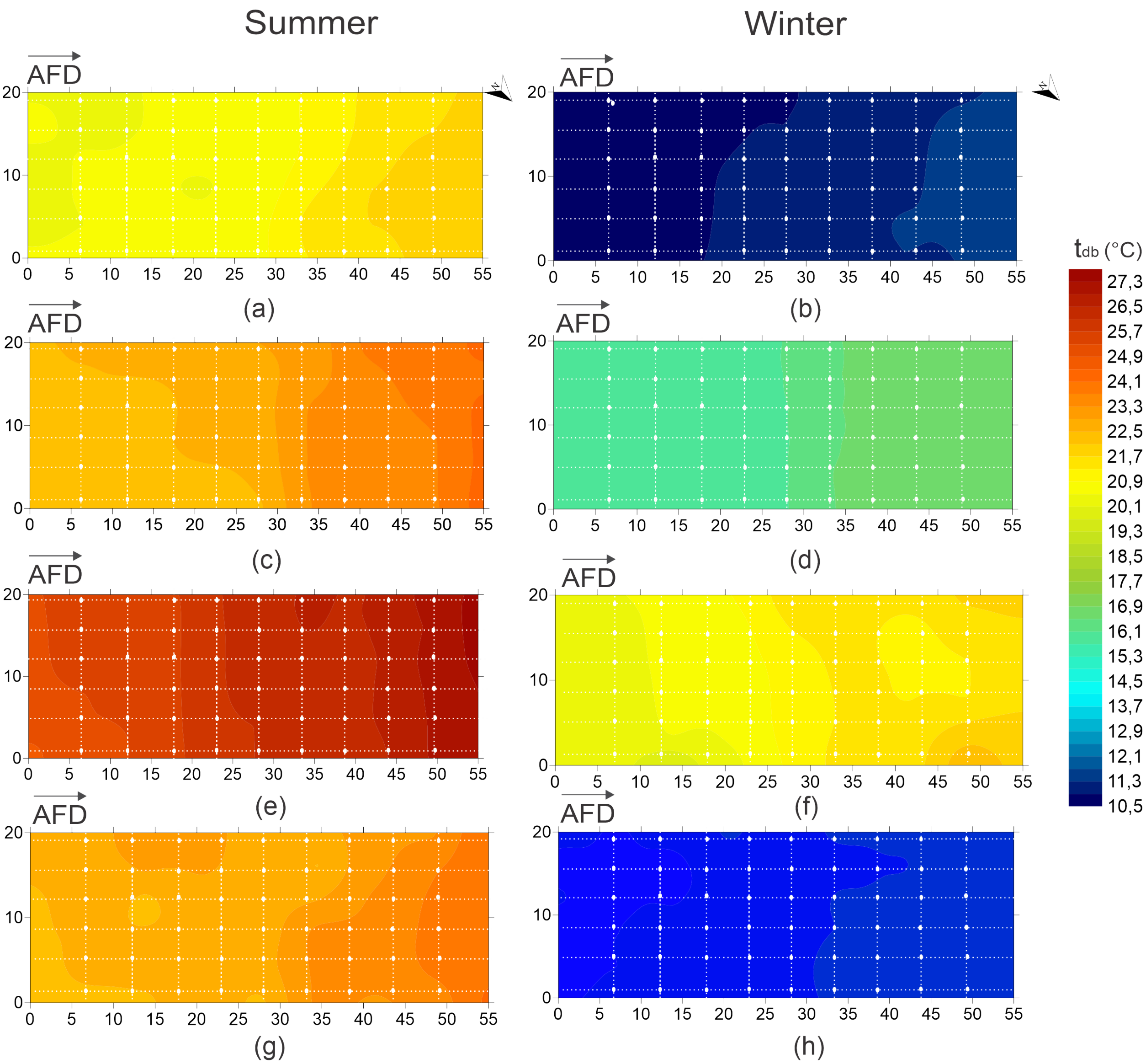

Figure 5. Spatial distribution of the air dry-bulb temperature variable (°C), during the dawn (00:00a.m. to 05:00a.m.), morning (06:00a.m. to 11:00a.m.), afternoon (12:00p.m.-05:00p.m.) and night (06:00p.m. to 11:00p.m.) inside the compost bedded pack barn (CBP), during the summer and winter experimental period. *AFD – Air flow direction.

In the afternoon, in the summer (Figure 5e), the highest difference (almost 3.0 °C) was observed between the recorded minimum and maximum values of the t_{db}, showing the inhomogeneity of this variable at the indoor facility, which may be indicative of spatial dependence among the registered points. Therefore, for this period there was a variation in the t_{db} gradient along with the CBP, in the longitudinal direction. In the direction of the air outlet, the t_{db} increased sharply after 20 m, reaching average maximum values above 27.0 °C (Figure 5e) in the region close to the exhaust fans. Those values exceeded the indicated upper critical temperature between 26 °C for Holstein cows (Perissinotto & Moura 2007), pointing out that part of the region of the facility where Batch 1 was located and the entire region where Batch 2, the animals was under stress due to the heat. The analysis also made it possible to infer that the climate control system used was not efficient in guaranteeing temperatures within the comfort range throughout critical environmental temperatures.

As the air enters and moves longitudinally into the facility, the air temperature rises, which can be justified by the use of the negative ventilation system in tunnel mode. The activation of the exhaust fans moves the incoming air towards the outlet air (where the exhaust fans are located). This longitudinal air flow carries the metabolic heat produced by the confined animals, by composting the bed, by the thermal load generated by the equipment used and originating from the solar radiation transferred through the roof and side closures, as well as promoting the path of air pollutants (humidity, ammonia, dust, etc.) (Teles Júnior 2019, Damasceno 2020).

According to Kadzere et al. (2002), at ambient temperatures above 26 °C, dairy cows can reach a point where their thermoregulatory system can no longer guarantee a satisfactory loss of body heat, and the animal goes into heat stress. The physiological and metabolic adjustments resulting from thermoregulatory responses to thermal stress have negative consequences on dairy cattle productivity and health. The lower productive and reproductive performance is due, largely to the effects of thermal stress in decreasing food intake to reduce the production of metabolic heat and, thus, seeking to maintain the homeothermy (Renaudeau et al. 2012).

The geostatistical analysis made it possible to visualize the behavior of spatial thermal conditions in the winter period (Figure 5, b, d, f, h). In winter, temperatures remained within the comfort range for dairy cows during the entire experimental period; that is, below the interval between 4 to 25 °C mentioned by Roenfeldt (1998) as being comfortable, with a maximum average temperature obtained in the winter afternoon, of 22.2 °C, in the direction the air outlet of the facility (northwest side of the CBP) (Figure 5f). The ventilation system, which always remained in operation, was used to renew the air and dry the bed. The activation of the ECS during the winter was observed only in the afternoon when the indoor air temperature values were above 21°C (Figure 5f).

In the summer, the period that provided the highest uniformity of t_{db} inside the facility was during the night (Figure 5a), with a range of 1.6 °C, a period in which the ECS was off, and only the exhaust fans were in operation. That was also observed during winter (Figures 5, b, d, h), in which the variability was lower for the dawn, morning, and night, with a range of 0.9 °C for the three periods. These periods mentioned were those of lower t_{db} and are within the limit recommended by the literature.

It was also found that the t_{db} values were lower during the morning compared to the afternoon. In the morning, due to the inclination of the sun's rays and the material of the facility's closures is not insulating, the incidence of direct solar radiation is lower, promoting lower air temperature, associated with higher relative humidity, providing better comfort conditions for animals (Silva et al. 2020).

As expected, compared to winter, the highest t_{db} values were found during summer, as the region has well-defined climatic characteristics between the two analyzed seasons, with winter with milder temperatures. The smallest difference between the two seasons was observed during the afternoon, with a difference between the maximum t_{db} of 5°C. Regarding the highest difference in t_{db} between summer and winter, it was observed in the early morning, with a difference between the maximum t_{db} of 10.4 °C.

In Figure 6, the spatial distribution maps of the variable relative humidity (RH, %) are found inside the CBP during different periods of the day in the summer and winter seasons.

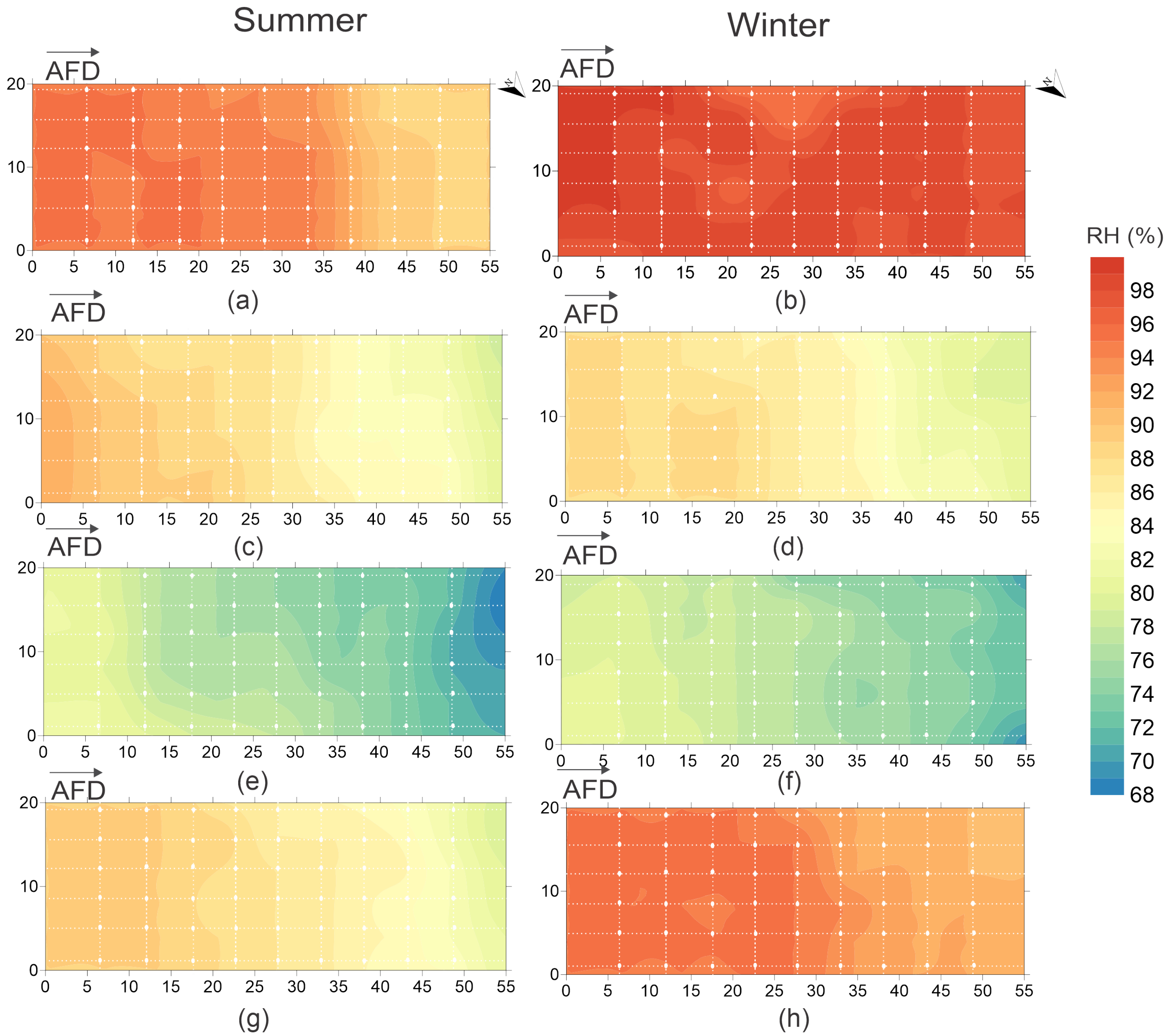

Figure 6. Spatial distribution of the variable air relative humidity (%), during the dawn (00:00a.m. to 05:00a.m.), morning (06:00a.m. to 11:00a.m.), afternoon (12:00a.m. to 05:00 p.m.) and night (06:00p.m. to 11:00p.m.) inside the compost bedded pack barn (CBP) during the summer and winter experimental period.

A different pattern is observed from the one observed for t_{db}. The reduction in relative humidity occurs gradually over the length of the facility. In the regions with the lowest t_{db} values, on the southeastern face of the CBP, the highest RH values in the air were observed; that is, the highest values were close to the porous plates for evaporative cooling, where the average RH levels were predominantly higher than 75%. According to Nääs & Arcaro Jr. (2001), the RH value of 70 % is considered the upper limit to enable the use of ECS to cool the air inside the environment intended for lactating animals through the use of water.

Ward (2013) reports the importance of the relative humidity inside the facility not to exceed 80% when using evaporative cooling plates during hot weather, as it can cause more suffering to animals, making heat dissipation difficult. That premise justifies the relevance of maintaining the correct management of the evaporative cooling system.

In the summer, the period in which the highest RH values were observed inside the CBP was at dawn (Figure 6a), with a low amplitude of 6%. That was also observed during the winter investigation period (Figures 6, b, h), in which the variability was lower for the dawn and night, with a range of 3.0% and 4.7%, respectively. Among the factors responsible for such results, we can mention that, in both periods, the ECS was stirred off and only the exhaust fans were in operation, thus making the RH more homogeneous in that period. During the afternoon, in summer and winter, the highest RH amplitude values were observed, being 12 % for both seasons (Figure 6, e, f).

On the southeastern face of the CBP facility, close to the evaporative plates, up to the central part of the CBP and in the dawn, morning, and night, during summer and winter (Figure 6, a, b, c, d, g, h), high RH values can be observed, which were higher than 85 %. The excessive RH values found for the two seasons can be explained by the high natural humidity of the indoor environment, coming from the bed, the water released by the breathing, and animal waste.

Besides, the high relative humidity inside the CBP is justified by the evaporative cooling system. The evaporative cooling system increases the daytime relative humidity inside the closed facilities with tunnel ventilation (Smith et al. 2006). Thus, when the hot and unsaturated air outside the facility is forced (by the exhaust fans positioned on the opposite end) to pass through the moistened porous plate, simultaneous exchange of heat and mass occurs, with a change in the state of part of the liquid phase water for steam, and relative humidity elevation of the inlet air, with consequent reduction of the temperature of both. In other words, there is a reduction in indoor air temperature, but with an increase in its relative humidity (Baêta & Souza 2010).

The ability to reduce the air temperature through evaporative cooling is higher, the higher the temperature and the lower the relative humidity of the air to be cooled. As the relative humidity increases, the ability to reduce its temperature via evaporative cooling decreases (Harner & Smith 2008).

The use of ECS (regardless of how water is incorporated in the process whether, through evaporative plates, nebulizers, sprinklers, etc.) should not be recommended in environments where the relative humidity is equal to or higher than 75% to 80% due to the increase in humidity associated with these systems (Fournel et al. 2017).

According to Leso et al. (2020), in CBP, especially at high RH conditions, more attention is needed to the handling of the bed. It requires more frequent incorporation of new dry material to reduce the humidity of the bed and keep the rest area dry, healthier, and more comfortable for cows.

The excessive increase in the RH in CBP, besides compromising the health and welfare of the animals, can also influence their hygiene score due to wet bed (Damasceno 2020). According to the same author, a very wet bed compromises the milk quality, hinders the composting process of the bed, besides increasing the deterioration of construction elements, causing warping, and rotting of wood and accelerated oxidation of metal parts present in the CBP.

Table II shows the method, model, and estimated parameters of the experimental

Table II. **Method, model and estimated parameters of the experimental semivariogram for the mean values of each time period for the variables Temperature-Humidity Index (THI), Enthalpy (H, kJ kg dry air^{-1}) and air velocity (V_m and V_l , m s^{-1}), inside the compost-bedded pack barn (CBP) during the winter and summer.**

Variable	Method	Model	C_0	C_1	C_0+C_1	a	SDI	ME	SDm	RE	SDR
Summer											
THI_{Dawn}^{1}	REML	Gaussian	0.010	0.374	0.384	19.488	0.026	-0.001	0.231	-0.003	1.008
$THI_{Morning}$	REML	Gaussian	0.026	0.480	0.506	20.629	0.051	0.009	0.239	0.018	1.030
$THI_{Afternoon}$	REML	Spherical	0.012	0.558	0.570	46.371	0.021	0.000	0.174	-0.001	0.547
THI_{Night}	REML	Gaussian	0.090	0.475	0.566	38.744	0.160	0.000	0.340	0.000	1.013
Winter											
THI_{Dawn}^{1}	REML	Gaussian	0.113	0.761	0.874	16.738	0.129	0.000	0.579	0.000	1.009
$THI_{Morning}$	REML	Gaussian	0.001	0.123	0.124	17.312	0.005	0.002	0.061	0.010	0.995
$THI_{Afternoon}$	REML	Gaussian	0.057	0.756	0.813	28.990	0.070	-0.005	0.304	-0.007	1.033
THI_{Night}	REML	Spherical	0.049	0.243	0.292	3.940	0.167	0.000	0.550	0.000	1.009
Summer											
H_{Dawn}^{1}	REML	Gaussian	0.112	0.654	0.765	15.636	0.146	-0.009	0.500	-0.009	1.026
$H_{Morning}$	REML	Spherical	0.001	0.604	0.605	16.571	0.002	0.011	0.504	0.011	1.024
$H_{Afternoon}$	REML	Spherical	0.000	0.716	0.716	18.709	0.000	0.002	0.474	0.002	0.947
H_{Night}	REML	Spherical	0.188	0.922	1.110	26.520	0.169	-0.006	0.694	-0.004	1.013
Winter											
H_{Dawn}^{1}	REML	Gaussian	0.028	0.384	0.412	16.377	0.068	-0.008	0.247	-0.016	0.975
$H_{Morning}$	REML	Gaussian	0.004	0.124	0.128	11.566	0.029	0.004	0.159	0.010	0.979
$H_{Afternoon}$	REML	Spherical	0.103	1.347	1.451	40.083	0.071	-0.011	0.629	-0.009	1.033
H_{Night}	REML	Spherical	0.090	0.184	0.273	52.405	0.328	0.001	0.363	0.002	1.011
Summer											
V_m	REML	Spherical	0.031	0.059	0.091	23.362	0.345	-0.006	0.239	-0.013	1.015
V_l	REML	Spherical	0.000	0.033	0.033	15.637	0.000	-0.003	0.111	-0.014	0.954
Winter											
V_m	REML	Gaussian	0.018	0.024	0.042	22.498	0.432	-0.003	0.154	-0.011	1.009
V_l	REML	Exponential	0.000	0.023	0.023	16.118	0.000	0.000	0.119	-0.001	0.968

C_0 – nugget effect; C_1 – contribution; C_0 + C_1 – sill; a – range; e SDI – spatial dependence index; ME - Mean error; SDm - Standard deviation of mean error; RE - Reduced error; SDR - Standard deviation of reduced error. REML –Restricted Maximum Likelihood.

semivariogram for the mean values of each period for the variables Temperature-Humidity Index (THI), Specific air enthalpy (H, kJ kg of dry air^{-1}) and air velocity (V_m and V_l, m s^{-1}), inside the closed CBP.

Based on the results of the geostatistical analysis, it appears that the variables THI, H and $V_{m,}$ and V_l showed spatial dependence (Table II). Damasceno et al. (2019) studying the spatial variability of climatic attributes of a CBP in tunnel mode, using the geostatistical tool and making kriging maps, also found spatial dependence for the climatic attributes t_{db}, UR, THI, and V_m.

For the variables THI, H, $V_{m,}$ and V_l, the semivariograms were calculated and adjusted, as shown in Table II. The variables THI, H, and V_l showed high spatial dependence, except for H during the night in winter, which presented moderate dependence space. V_m presented moderate spatial dependence during the summer and winter. The larger the spatial dependence (SDI), the less the nugget effect contributes to the variability of the data and, therefore, kriging is better (Curi et al. 2017).

When analyzing the range, concerning the spatial extent to which the data are correlated, for all periods in which the data were sampled, the points were associated with other points at considerable distances. The highest range values for the THI were in the afternoon (46.371 m) in the summer; for H at night (52.405 m) in winter; a V_m with similar values in winter and summer (22.498 m and 23.362 m, respectively); and V_l also showed similar values during winter and summer (16.118 m and 15.637 m, respectively).

From the semivariogram adjustments for the THI indexes under study, the values of these variables were estimated using ordinary kriging. Therefore, it was possible to build spatial distribution maps for the THI during each study period, as shown in Figure 7. Thermal stress conditions were calculated using the combined effects of t_{db} and RH.

It was possible to observe through the kriging maps of Figure 7 that, for summer and winter, the spatial distribution of the THI was similar to the one of the air temperatures for the analyzed periods. As expected, compared to winter, the highest THI values were found during the summer due to the higher t_{db} and RH values observed during this season.

There was also a similar trend inside the CBP concerning the analyzed periods, indicating that from the central region of the CBP and towards the exhaust fans (northwest side), there was a marked increase in THI.

The THI thresholds that characterize a situation of comfort or discomfort differ among authors. In general, the proposed limits for dairy cattle are THI ≤ 74 thermal comfort condition; 74 < THI < 79 - alert condition for producers; 79 ≤ THI < 84 - danger condition and safety measures must be taken to avoid losses to the squad; and THI ≥ 84 - emergency situation (Mader et al. 2006).

From the data collected in the summer (Figure 7, a, c, e, g), it was observed that, even with the presence of artificial ventilation, the THI values remained above the limits (THI > 74) characterized as comfort situations for animals, except during the early morning. However, there were no conditions of intense thermal stress (THI ≥ 84) during the analyzed periods. The highest value determined for the THI (78) was verified in the afternoon, considered an alert condition for producers, a fact that occurred due to the combination of high values of t_{db} and RH verified for this region.

During the summer, the THI values increased sharply over the last 25 m of the CBP, closer to the exhaust fans, reaching the value of 74, during the morning and night (Figure 7, c, g). Those results indicate that, during the morning and night, the

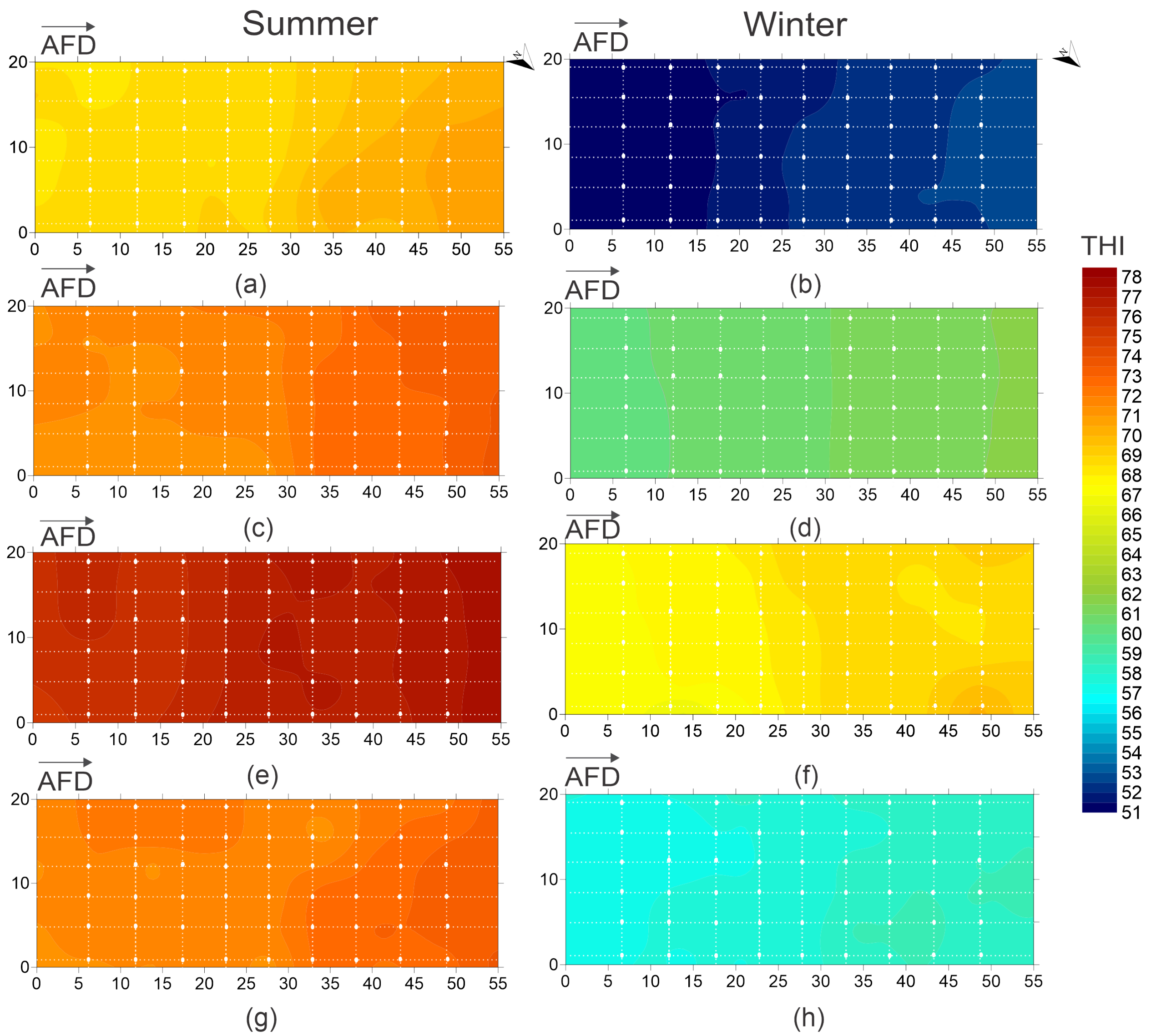

Figure 7. Spatial distribution of the Temperature and Humidity Index (THI) during the dawn (00:00a.m. to 05:00a.m.), morning (06:00a.m. to 11:00a.m.), afternoon (12:00a.m. to 05:00 p.m.) and night (06:00p.m. to 11:00p.m.) inside the compost bedded pack barn (CBP) during the summer and winter experimental period.

animals in Batch 2 were in heat stress condition. During the summer afternoon, the THI values increased sharply over the last 35 m closest to the exhaust fans, reaching a value of 78 (Figure 7e), close to the same ones (northwest face). During that period, the animals in Batch 1 and Batch 2 were in a heat stress condition. This THI behavior profile indicates critical points where the distribution of this variable represented a certain degree of discomfort for the animals.

Based on the above arguments, it appears that the low insulation of the side closure (curtains) and the roof did not guarantee the thermal inertia of the CBP, negatively affecting the thermal uniformity of the facility.

As expected for the climatic region under study, during the winter season, the THI values were within the comfort zone for dairy cows (Figure 7, b, d, f, h). In this season, the highest THI value (71) was recorded close to the exhaust fans (northwest face) during the afternoon (Figure 7f). However, those values are not considered as a discomfort situation for dairy cows in the production phase.

In the summer, the period of the day in which the most uniform THI was observed inside the CBP was at night (Figure 7g), with an amplitude of 2. The other periods presented similar amplitudes, the amplitude of 3 (Figure 7 a, c, g). During the winter, the more homogeneous periods had an amplitude of 1.5 and were found during dawn, morning, and night (Figure 7 b, d, h), when the ECS was not in operation.

Lobeck et al. (2012), evaluating closed Free Stall facilities with a low-profile cross-ventilated system (LPCV), naturally ventilated Free Stall and CBP with mechanical ventilation, in Minnesota, USA, observed that all systems presented, during the most critical periods, THI values above 72, which indicated that the cows were experiencing some thermal stress. Similar to the THI values found in the present study.

Smith et al. (2006) compared a Free Stall with tunnel ventilation, associated with evaporative cooling, with a conventional Free Stall with fans, also associated with evaporative cooling, located in Northern Mississippi. The aim of the study was to evaluate the efficiency of the evaporative cooling system in alleviating heat stress in lactating dairy cows. The authors observed that tunnel-ventilated cooled cows reduced respiration rates by 13.1 ± 0.78 breaths min^{-1} and rectal temperatures by 0.4 ± 0.03 °C compared to conventional Free Stall. In this way, tunnel ventilation cooling dramatically reduced exposure to heat stress and improved the comfort of lactating dairy cows when compared to traditional cooling technologies under present conditions.

Pires et al. (2002) observed that during the summer, lactating Holstein cows kept in a confinement system when subjected to high temperature and relative humidity, reduced the conception rate as a result of the physiological changes commonly observed during the caloric stress process. The authors observed that the conception rate was 45.7% in the summer, compared to 71.2% in the winter.

Figure 8 shows the spatial distribution maps of the variable specific air enthalpy (H), at dawn, morning, afternoon and night, obtained inside the CBP, during the experimental period of summer and winter.

It can be observed that, as expected, compared to winter, the highest values of H were found during the summer. There was a gradient in the H values throughout the facility, with the trend of lower values for all the periods evaluated occurring close to the evaporative cooling plates (southeast face).

According to the obtained results, the average values of the amount of energy present in the air point to H values above the comfort limit of 65.8 kJ kg of dry air^{-1}, obtained from the t_{db} of 26 °C and RH of 70 %. There was a marked increase in H in the afternoon, followed by a decrease in the night. In the afternoon the negative pressure ventilation system in tunnel mode was not efficient to promote sufficient changes in the amount of heat inside the CBP (Figure 8e).

During the summer afternoon, H increased sharply over the last 35 m, reaching a value of 70, close to the exhaust fans (northwest face). During this period, the animals housed in Batch 1 and Batch 2 were in a heat stress condition. This H profile indicates critical points, and the distribution of this variable showed some degree of discomfort for the animals' occupation.

The averages of H observed in this study for the afternoon are close to those obtained by Garcia (2017), who obtained average values of 70.5 kJ kg of dry air-^{1} in the summer in a

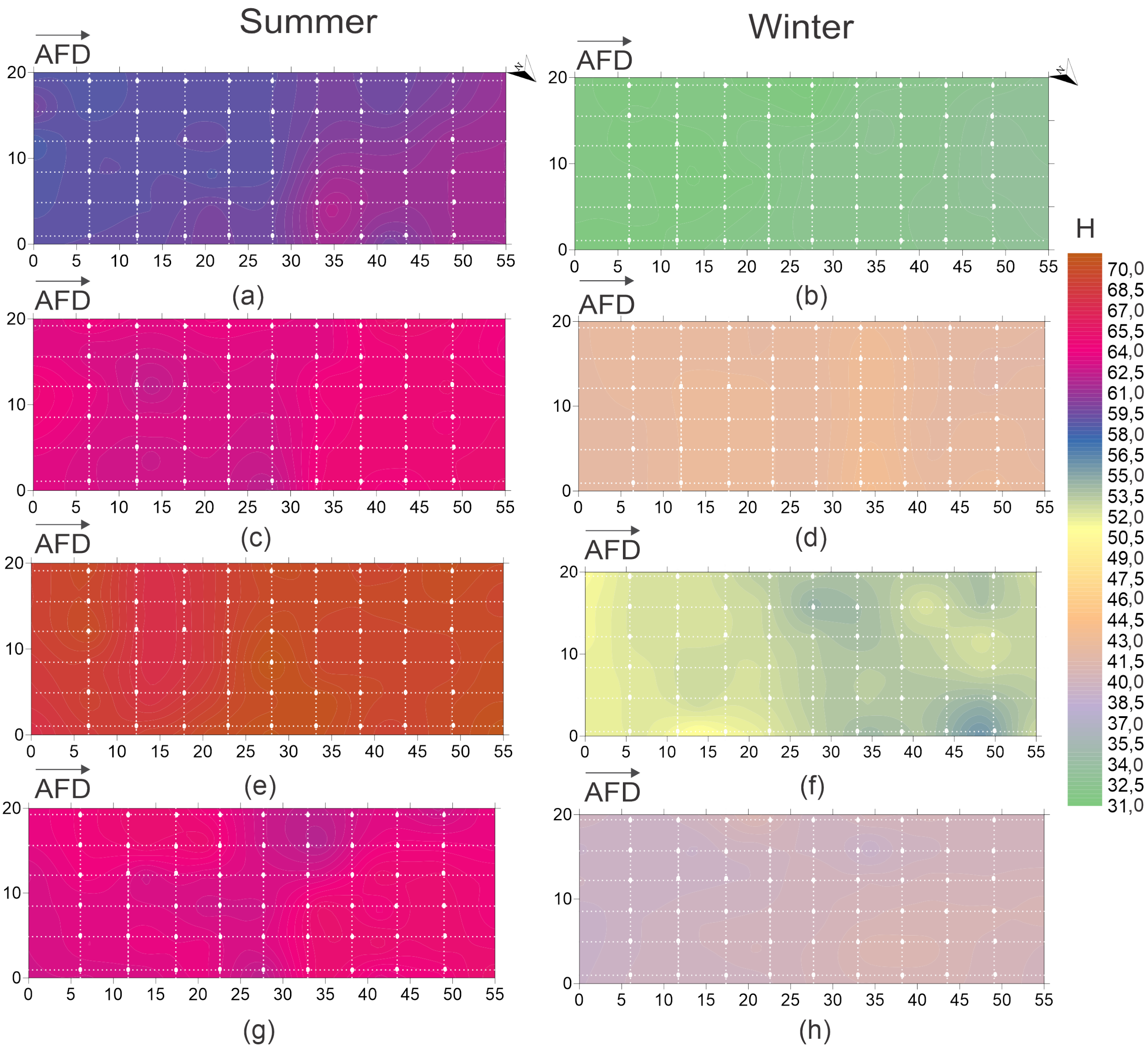

Figure 8. Spatial distribution of Enthalpy (H, kJ kg dry air-1) during the dawn (00:00a.m. to 05:00a.m.), morning (06:00a.m. to 11:00a.m.), afternoon (12:00p.m to 05:00pm) and night (06:00p.m. to 11:00p.m.) inside the compost bedded pack barn (CBP) during the summer and winter experimental period.

free-stall facility of the LPCV located in a region with a hot and humid climate.

Given this, one must pay attention to the conditions of the thermal environment inside the facility in the most critical situations, that is, when they are outside the recommended ideal range, to prevent the performance and productivity of dairy cattle from being compromised.

In the winter, the CBP proved to be suitable for the confinement of dairy cows, with a maximum average of 57 kJ kg of dry air^{-1} obtained in the afternoon, on the northwest face, close to the exhaust fans (Figure 8f).

Figure 9 shows the spatial distribution of the variables mean air velocity (V_m, m s^{-1}) and air velocity at bed level (V_l, m s^{-1}), during the summer and winter, inside the CBP.

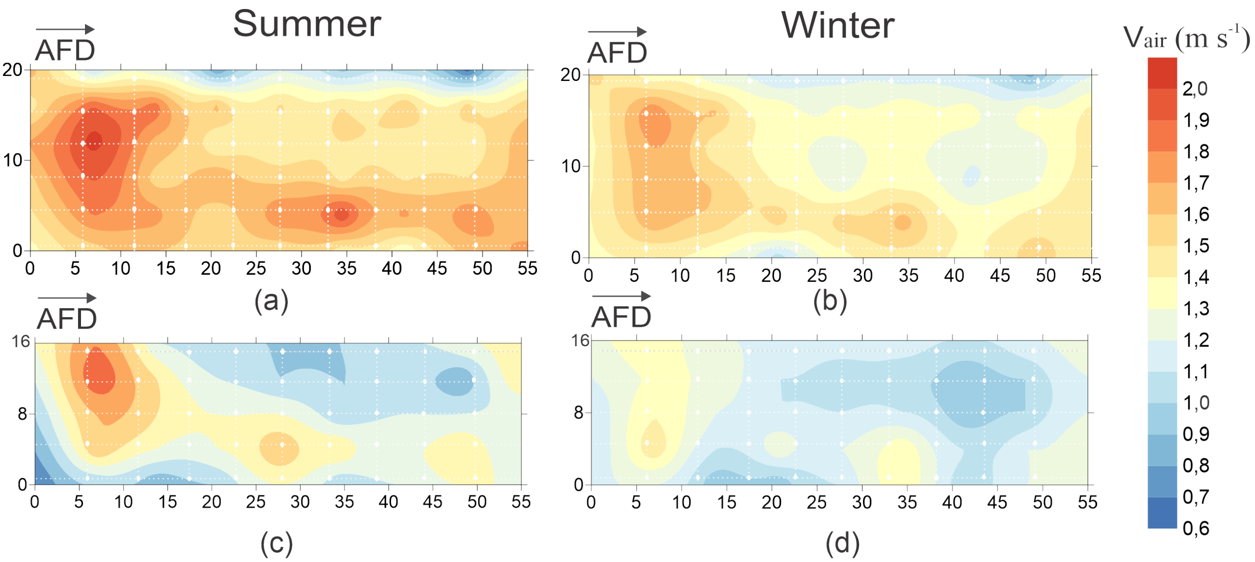

Figure 9. Spatial distribution of variables: a) mean air velocity during the summer (Vm); b) mean air velocity during winter (Vm); c) air velocity at bed level during the summer (Vl); d) air velocity at bed level during winter (Vl), inside the compost bedded pack barn (CBP).

It can be seen that V_m (Figures 9, a, b) showed a high amplitude between the minimum and maximum speeds, with values ranging from 0.6 to 2 m s^{-1} in summer and 0.85 to 1.65 m s^{-1} in winter. There are distinct regions along the length of the CBP. The results indicate that the regions with the highest values were on the southeast face, close to the evaporative panels, with values ranging from 1.65 m s^{-1} and 2 m s^{-1}, in winter and summer, respectively. In the central part of the CBP, there was a higher predominance of V_m, around 1.25 m s-^{1} and 1.4 m s-^{1}, in winter and summer, respectively. Again, a region with higher values, on the northwest side, close to the exhaust fans. V_m values less than 1 m s-^{1} were found in the region of the feeding alley.

The average variability found can be indicative of the existence of the data heterogeneity. According to Faria et al. (2008), the high variability of wind speed can be explained by the fact that this variable is characterized by changing its magnitude and direction constantly in short intervals of time.

The study results were inferior to those obtained by Damasceno et al. (2019), who observed V_m values that reached 3m s^{-1} in CBP in tunnel mode, possibly indicating flaws in the dimensioning of the ventilation system of this present study.

Air velocity at bed level (V_l) (Figures 9, c, d) presented values that varied from 1.1 to 1.9 m s^{-1} in summer and from 0.9 to 1.5 m s^{-1} in winter, presenting lower values when compared to values obtained from V_m. However, it can be seen from the kriging maps that V_m and V_l showed higher values during summer (Figure 9, a, b), when compared to winter (Figure 9, b, d). The V_m during the summer presented higher amplitude when compared to the winter, being of 1.4 and 0.8, in summer and winter, respectively.

The variation in the air velocity values at both heights may be associated with an increase in pressure loss due to the animals, the characteristics of the evaporative panel, and the deflectors present in the facility.

Next to the side curtains (Figures 9 a, b, c, d), there was a marked variation in V_m and V_c, and this possibly occurred due to the infiltration of air through the curtains, through failures of the seal.

The wind speed maps showed that the ventilation system used did not guarantee the homogeneity of this variable within the evaluated CBP. With all exhaust fans in operation, the windspeed in the CBP ventilation system in tunnel mode was uneven and below ideal (values below 2.0 m s^{-1}) for the two heights and analyzed periods. Air velocity between 2.5 to 3.5 m s^{-1} is considered ideal for feedlot Holstein cows (Damasceno 2020). According to the same author in CBP with ventilation in tunnel mode, the capacity of the exhaust fan must be dimensioned to provide minimum ventilation of 2.0 to 4.0 m s^{-1} during the entire period. With these results of air velocity, it was possible to observe the ineffectiveness of the system in maintaining adequate levels of THI and H, especially during the most critical period of summer.

Adequate ventilation in this type of system is important to help cool animals, reduce excess moisture from the air, remove the heat and moisture that the biologically active bed generates, and extend the time between adding more bedding (Janni et al., 2007).

Based on the above study, it appears that the improvement of the facility insulation, quality, and adequate dimensioning of the ventilation system, among other factors, are decisive in the best practice of this activity.

CONCLUSIONS

The geostatistic method show a spatial dependency of the variables t_{db} (air dry-bulb temperature), RH (air relative humidity), THI (Temperature-Humidity Index), H (Specific enthalpy) and V_m (average windspeed) and V_l (windspeed at bed level) and a predominance of strong and moderate spatial dependence. The kriging maps showed that the critical housing conditions of the thermal environment, mainly, from the central part of the CBP, towards the exhaust fans, in summer. The analyses also pointed out that the system presented t_{db} gradients along the length, up to 3 °C.

Were observed high values of RH (predominance of values above 75 %), close to the evaporative plates, during the two evaluated seasons. The THI and H were above the thermal comfort thresholds during the summer, mainly in the afternoon. The V_m and V_l over the entire CBP interior area was not uniform, indicating the possibility of promoting higher ventilation intensification.

Spatial distribution for microclimate variables in CBP can be easily reproduced through the use of Geostatistics technique, reducing the number of field experiments. The developed computational simulation and methodology allow highlighting to determine if management of the thermal environment of confinement facilities for animal production is within the comfort zone.

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RAFAELLA R. ANDRADE[1]
https://orcid.org/0000-0003-3182-0741

ILDA DE FÁTIMA F. TINÔCO[1]
https://orcid.org/0000-0002-8152-0301

FLÁVIO A. DAMASCENO[2]
https://orcid.org/0000-0002-8284-7496

GABRIEL A.S. FERRAZ[2]
https://orcid.org/0000-0001-6403-2210

LETÍCIA CIBELE S.R. FREITAS[3]
https://orcid.org/0000-0002-9607-4092

CECÍLIA DE FÁTIMA S. FERREIRA[1]
https://orcid.org/0000-0003-2059-2755

MATTEO BARBARI[4]
https://orcid.org/0000-0002-0760-8604

CARLOS G.S. TELES JUNIOR[5]
https://orcid.org/0000-0002-3519-0938

[1]Federal University of Viçosa, Agricultural Engineering
Department, Av. Peter Henry Rolfs, s/n, Campus
Universitário, 36570-900 Viçosa, MG, Brazil

[2]Federal University of Lavras, Engineering
Department, Av. Doutor Sylvio Menicucci, 1001,
Aquenta Sol, 37200-000 Lavras, MG, Brazil

[3]State University of Maringá, Department of
Agricultural Engineering, Campus do Arenito,
87820-000 Cidade Gaúcha, PR, Brazil

[4]University of Florence, Department of Agriculture,
Food, Environment and Forestry, Via San
Bonaventura, 13, 50145 Firenze, Italy

[5]Federal Rural University of the Amazon, Institute
of Agricultural Sciences, Av. Perimetral, Terra
Firme, 19702-054 Belém, PA, Brazil

Correspondence to: Rafaella Resende Andrade
E-mail: rafaella.andrade@ufv.br

Author contributions

Rafaella Resende Andrade, Ilda de Fátima Ferreira Tinôco, Flávio Alves Damasceno, Letícia Cibele da Silva Ramos Freitas and Carlos Gutemberg de Souza Teles Junior, conducted the field trials, collect and data analysis, and wrote the manuscript. Cecília de Fátima Souza Ferreira, Gabriel Araújo e Silva Ferraz and Matteo Barbari helped on data analysis and wrote the manuscript.