An Acad Bras Cienc (2023) 95(Suppl. 1): e20220415 DOI 10.1590/0001-3765202320220415
Anais da Academia Brasileira de Ciências | *Annals of the Brazilian Academy of Sciences*
Printed ISSN 0001-3765 I Online ISSN 1678-2690
www.scielo.br/aabc | www.fb.com/aabcjournal

ENGINEERING SCIENCES

Air velocity spatial variability in open Compost-Bedded Pack Barn system with positive pressure ventilation

CARLOS EDUARDO A. OLIVEIRA, ILDA DE FÁTIMA F. TINÔCO,
FLÁVIO A. DAMASCENO, VICTOR C. DE OLIVEIRA, PEDRO HENRIQUE M. RODRIGUES,
GABRIEL A.S. FERRAZ, FERNANDA C. DE SOUSA, RAFAELLA R. ANDRADE,
JOÃO ANTÔNIO C. DO NASCIMENTO & LEONARDO F. DA SILVA

Abstract: In Compost-Bedded Pack Barn (CBP) systems, air velocity is linked with the thermal comfort of housed dairy cattle and bedding quality and, therefore, assessing ventilation efficiency is essential. In this context, the objective of this study was to evaluate and characterize dependence and spatial distribution of air velocity at the 1.5 m height ($v_{air,M}$) and at bedding level ($v_{air,B}$) in an open CBP system with positive pressure ventilation. The study was conducted in 2021, in a facility located in the Zona da Mata region, Minas Gerais, Brazil. The facility area was divided into a mesh composed of 55 equidistant points, where $v_{air,M}$ and $v_{air,B}$ data were collected in the morning (09:00 a.m.) and afternoon (03:00 p.m.) periods, during three weeks in Brazilian winter. Geostatistics techniques were used to assess dependence and spatial distribution. In both periods evaluated, there were a strong occurrence of spatial dependence and non-uniform $v_{air,M}$ and $v_{air,B}$ distributions. The $v_{air,M}$ and $v_{air,B}$ values were lower than recommended (1.8 m·s^{-1}) in more than 65.0% of the area. Adequate ventilation levels were observed only in the first 20.0 m of the facility, from Southeast to Northwest, because of the fan lines present.

Key words: dairy cattle confinement, ventilation efficiency, thermal comfort, geostatistics.

INTRODUCTION

The dairy cattle confinement in partially closed facilities is one of the most used strategies to improve the thermal environment of milk production and, consequently, ensure greater productivity, milk quality, rational use of natural resources and control of greenhouse gas (Perissinotto et al. 2009, Galama et al. 2020, Leso et al. 2020, Mee & Boyle 2020). Among the feedlot systems of dairy cattle used in Brazil, there has been a recent growth in the implementation of the Compost-Bedded Pack Barn (CBP). This system is already consolidated in European and North American countries (Damasceno 2020).

The first CBP systems built in Brazil were designed following North American recommendations but opting for the design of facilities with open sides (Damasceno 2020). In this case, mechanical ventilation systems are usually employed, because it is not possible to ensure, only with the natural ventilation use, adequate conditions of comfort for the housed animals and aeration for the bed composting process (Pilatti & Vieira 2017, Caldato et al. 2020). Normally, mechanical positive pressure ventilation systems are used, using low-volume and high-speed (LVHS) or high-volume and low-speed (HVLS) fans (Leso et al. 2018).

Ventilation systems applied to CBP facilities should ensure that the air velocity (v_{air}) is kept close to 1.80 $m \cdot s^{-1}$ throughout the facility area, making it possible to bedding drying, remove gases and encourage thermal exchanges (Black et al. 2013). In the open facilities case, in which there is no uniform control over ventilation rates, it is essential that ventilation efficiency assessment procedures be performed, to verify whether it is adequate or if there is a need for adjustments in the design and/or management.

In this system type, it is important that the procedures for evaluating ventilation efficiency are performed at different heights, preferably at the 1.5 m height ($v_{air,M}$) and at the bedding level ($v_{air,B}$). At the 1.5 m height (average height of the mass center of dairy cattle), the interest is to evaluate the thermal comfort degree of the animals positioned standing, because the air velocity has a direct influence on the surface temperature and physiological responses of these animals (Almeida et al. 2010, Pilatti et al. 2019). At bedding level, the goal is to measure the air velocity magnitude experienced by the lying animals and available for bedding drying (Black et al. 2013, Damasceno 2020).

Thus, although a ventilation system is still sized in the design phase of a new facility, evaluations should be carried out in the field later, permitting it to make the necessary adjustments and refinements. Therefore, appropriate computational methods and tools should be used, capable of assisting in the diagnosis of the real environment situation and in decision-making to make improvements to it. Among these evaluation processes, highlight the geostatistics techniques use, which allow evaluating dependence and spatial distribution of different variables, as well as analyzing the results based on the natural data structure (Cambardella & Elliott 1992, Medeiros et al. 2014, Oliveira et al. 2021, Andrade et al. 2022).

In view of the above, the objective of this study was to evaluate and characterize dependence and spatial distribution of the variables air velocity at the 1.5 m height and at bedding level in the internal facility area for confinement of dairy cattle in production, in an open Compost-Bedded Pack Barn system with positive pressure ventilation (CBPPV).

MATERIALS AND METHODS

This study was conducted during the three-week period of July 2021, in the Winter, climatic season in which conditions of excessive bedding moisture are observed in CBP systems, a factor considered as a key point for the success of the system and which, therefore, should be controlled. Procedures were performed in accordance with the guidelines recommended by the Ethics Committee in Animal Use of the Federal University of Viçosa (Process 04/2021).

Characterization of the Compost-Bedded Pack Barn system and management practices

Experimental data were collected at a facility for confinement of lactating dairy cattle in an open Compost-Bedded Pack Barn system with positive pressure ventilation (CBPPV). The commercial property where the study was carried out is in the mesoregion of Zona da Mata, in the following coordinates: latitude 20° 46’ 41” S; longitude 42° 48’ 51” W; and altitude 670 m. According to Köppen’s Climatic Classification, the climate of the region is classified as Cwa — subtropical mesothermal, with dry and cold winter, and rainy and hot summer (Sá Júnior et al. 2012).

The CBPPV system was built in July 2019, had Southeast-Northwest orientation, and presented as constructive characteristics: 60.0 m long, 27.6 m wide, 5.0 m right foot, two-water roof, with structure and metal roof, presence of central opening with overlap of 1.0 m, and eaves

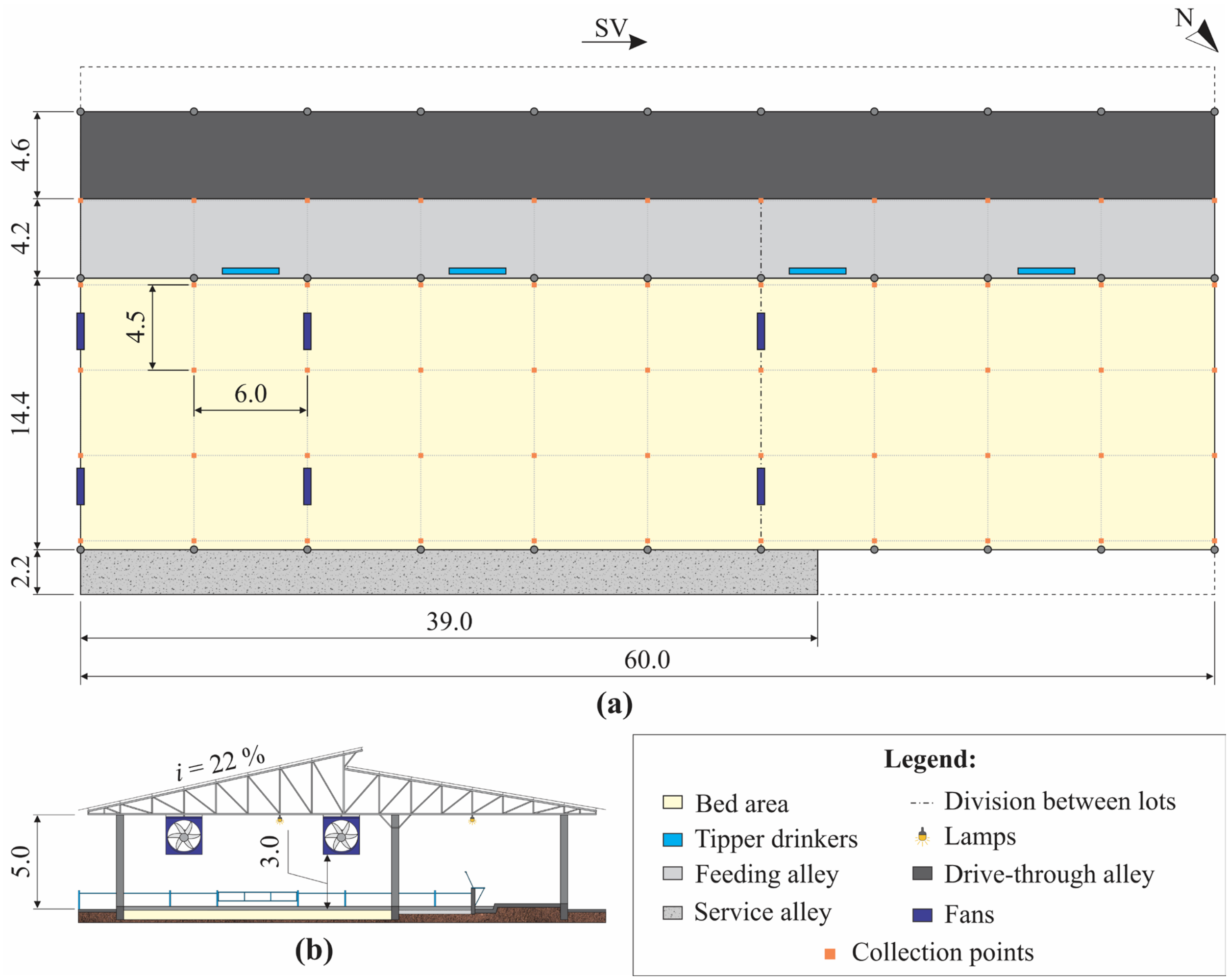

Figure 1. Schematic representation of the Compost-Bedded Pack Barn facility where the experimental data were collected: (a) floor plan with collection points and (b) cross-sectional. *SV — sense of ventilation; *i* — roof slope; N — North indication; dimensions in meters (m).

of 2.2 m. The interior of the system consisted of 864.0 m^2 of bedding area, 252.0 m^2 of feeding alley, where four tipper drinkers (2.0 m long each), 276.0 m^2 of drive-through alley, with a single feeder of 60.0 m in length, and 85.8 m^2 of service alley (Figure 1).

Around the entire bedding facility area, low concrete wall (0.2 m high) was constructed, with functions of avoiding loss of bedding material, material passage to the feeding alley and/or waste from the feeding alley to the bedding area. In the places where tippers drinkers were installed, there were protection walls (1.2 m), to contain the animals, preventing them from having access to water directly from the bedding area, which could wet it. The feeding, service and drive-through alleys had grooved concrete.

The ventilation installed in the barn was positive pressure type, supplied by means of six mechanical fans of low-volume and high-speed: two three-blade fans, 1.52 m in diameter, 1.5 hp of power and 86000 m^3·h^{-1} of air flow, installed on the Southeast facility face; and four six-blade fans, diameter of 1.53 m, 2.0 hp of power and 55000 m^3·h^{-1} of air flow, installed throughout the facility (coordinates 12.0 and 36.0 m, with respect to the Southeast face). The fans were installed at the 3.0 m height, with the 45° inclination in relation to the horizontal, and remained on without interruption (24 h·day^{-1}).

The facility had a lighting system provided by eighteen LED lamps of 100 W, installed at the 4.8 m above the bed, and distributed throughout the facility (nine in the central region of the bedding area and nine in the border region between feeding alley and drive-through alley). The lighting system was activated only during the night period (06:00 p.m. to 06:00 a.m.).

The bed consisted of a mixture of shaving and sawdust, in the form of a mattress about 0.60 m thick, and the approximately time use of four months (in the study beginning — July 2021). For bedding composition, in the initial stage was added a dry sawdust 0.30 m layer, which, together with the feces and urine deposited by the animals, started the semi-composting process. Subsequently, dry materials (shaving and sawdust) were inserted whenever the bedding moisture increased too high, causing increased animal dirtiness, compaction and anaerobiosis bedding situation. During the experimental period, the replacement or dry material addition was performed twice, when it was observed that the bed was over-moisture.

For the bedding material stirring, a hybrid implement (bed rototiller with cultivator, 2.0 m actuation width, 5 rods, 0.50 m maximum depth, 540 rpm maximum rotation, and 0.30 m rotation effective depth) was used, driven by a tractor (light line, 78 hp and 2400 rpm nominal rotation). The revolving operation was performed twice a day (09:00 a.m. and 04:00 p.m.), following standard routine defined in the farm.

The dairy cows housed inside the barn remained distributed in two lots, according to their milk yield and following the routine established in the farm. Animals with higher productivity were housed in Lot 1, which had 518.4 m^2 bedding area (36.0 x 14.4 m) and was located near the Southeast facility face. In turn, the animals with lower productivity remained housed in Lot 2, which had 345.6 m^2 bedding area (24.0 x 14.4 m) and was located near the Northwest facility face. Throughout the experimental period, 80 Holstein cows (Pure of Origin, average weight of 600 kg, lactating) remained housed in the barn, of which 45 were housed in Lot 1 (11.52 m^2·head^{-1}), and 35 remained confined in Lot 2 (9.87 m^2·head^{-1}).

The standard routine of activities in the facility was maintained throughout the experimental period, so milking and feeding were performed twice a day. The milking started at 04:00 a.m. and 04:00 p.m., had an average duration of 02h30min, and were executed in a 2×6 fishbone milking parlour, attached to the facility. The animals' access to the feeding alley, where feed and water were available, was free throughout the day. The floor of the feeding alley was cleaned once a day in the morning, using flushing.

Air velocity data acquisition

To the data collection, the zone occupied by the animals (ZOA), consisting of the bedding and feeding alley, was subdivided by means of a regular mesh (6.0 x 4.5 m), with 55 equidistant points. The points were distributed along the bedding and feeding alley areas, according to the facility characteristics (Figure 1).

Air velocity magnitude data were measured using a hot wire anemometer (Instrutherm®, model TAFR-190, with a scale between 0.1 and 25.0 m·s^{-1} and 5% accuracy). The data were collected at two different heights: 1.50 m above the bedding level ($v_{air,M}$, in m·s^{-1}), to verify air velocity magnitude experienced by the animals positioned standing; and 0.05 m above the bed ($v_{air,B}$, in m·s^{-1}), to simultaneously check the air velocity magnitude experienced by the animals and available for bedding drying. To perform the collections, the hot wire anemometer was positioned at each collection point, in the bedding and feeding alley regions, totaling 55 and 44 collection points of $v_{air,M}$ (ZOA — bedding area + feeding alley) and $v_{air,B}$ (bedding area), respectively. Because it is an open facility, which is influenced by external wind currents, $v_{air,M}$ and $v_{air,B}$ were measured six times during the experimental period, in the morning (09:00 a.m.) and afternoon (03:00 p.m.). All collections were performed with the ventilation system in operation (six fans at maximum velocity) and with the animals' presence inside the facility.

Descriptive statistics and geostatistics analysis

The mean data of $v_{air,M}$ and $v_{air,B}$ were initially evaluated by descriptive statistics. For each variable and in each period (morning and afternoon), values of mean, median, minimum, maximum, standard deviation (SD), coefficient of variation (CV), kurtosis (Kurt.) and asymmetry (Ass.) were obtained. The dispersion assessment of the experimental data was performed using CV classification proposed by Warrick & Nielsen (1980). Data with low dispersion were considered when CV was less than 0.12, moderate dispersion when CV was between 0.12 and 0,24 and, high dispersion when CV was greater than 0.24.

The spatial variability evaluation of the $v_{air,M}$ and $v_{air,B}$ levels inside the facility was performed using geostatistics techniques. The analyses were carried out using the R Development Core Team (2021) computer system, through the ***geoR*** library (Ribeiro Júnior & Diggle 2001).

The spatial dependence of the interesting variables was evaluated by semivariogram adjustments, using the Matheron estimator (1962), according to Equation 1.

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

where $\hat{\gamma}(h)$ is the semivariance, $N(h)$ is the number of experimental observations pairs $Z(X_i)$ and $Z(X_i + h)$ at locations X_i and $X_i + h$, separated by the distance h.

To adjust the experimental semivariograms, the Ordinary Least Squares (OLS) and the Restricted Maximum Likelihood (REML) methods were used. In all cases, Spherical, Exponential and Gaussian models were evaluated (Equations 2, 3 and 4, respectively), as suggested by Vieira et al. (2010a).

$$\hat{\gamma}(h) = C_0 + C_1 \cdot \left[1{,}5 \cdot \left(\tfrac{h}{a}\right) - 0{,}5 \cdot \left(\tfrac{h}{a}\right)^3\right], \text{ if } h \le a$$

$$\hat{\gamma}(h) = C_0 + C_1, \text{ if } h > a \qquad (2)$$

$$\hat{\gamma}(h) = C_0 + C_1 \cdot \left[1 - EXP\left(\frac{-3h}{a}\right)\right] \qquad (3)$$

$$\hat{\gamma}(h) = C_0 + C_1 \cdot \left\{1 - EXP\left[-3\left(\frac{h}{a}\right)^2\right]\right\} \qquad (4)$$

where C_0 is the nugget effect, C_1 is the contribution, and a is the range.

Cross-validation procedures were performed to evaluate and choose the adjustments obtained, and mean error (E_M), mean error standard deviation (SD_M), reduced error (E_R) and reduced error standard deviation (SD_R) were calculated, as described by Ferraz et al. (2020). For each variable, the adjustment in which the closest to zero E_M and E_R were obtained, lower SD_M and SD_R closer to one were chosen, as recommended by Isaaks & Srivastava (1989). From the mathematical models $\hat{\gamma}(h)$ chosen for each variable, coefficients from the theoretical model for the semivariogram were extracted: nugget effect (C_0), contribution (C_1), sill ($C_0 + C_1$), range (a) and practical range (a').

To evaluate spatial dependence, used the Spatial Dependency Index (SDI), obtained through the ratio between the nugget effect (C_0) and the sill ($C_0 + C_1$). The SDI analysis was performed using the classification of Cambardella et al. (1994), which lists spatial dependence as strong (SDI ≤ 0.25), moderate (0.25 < SDI ≤ 0.75) and weak (SDI > 0.75).

Finally, after defining the best-adjusted semivariograms and verifying the spatial dependence occurrence, the ordinary kriging technique was used to estimate the air velocity magnitudes in non-sampled regions. From the interpolated data, spatial distribution maps were generated using the ArqGIS® computer program, version 10.1, with license to use the Department of Agricultural Engineering of the Federal University of Viçosa. For detailed numerical information about the area fractions occupied by each class of the evaluated variables, histograms were generated, as suggested by Oliveira et al. (2023).

RESULTS AND DISCUSSION

Tables I and II list descriptive analysis data and methods, models and parameters estimated from experimental semivariograms adjusted for the variables air velocity at the 1.5 m height ($v_{air,M}$, in m·s^{-1}) and air velocity at bedding level ($v_{air,B}$, in m·s^{-1}), in the CBPPV system internal area (morning and afternoon periods).

It can be observed that in both periods evaluated (morning and afternoon), the mean values recorded for $v_{air,M}$ were close to each other (1.5 ± 0.4 and 1.4 ± 0.3 m·s^{-1}), an indication that this variable had a profile with similar behavior, regardless of the evaluated period (Table I).

Table I. **Descriptive analysis of the mean values of the variables air velocity at the 1.5 m height ($v_{air,M}$, in m·s^{-1}) and air velocity at bedding level ($v_{air,B}$, in m·s^{-1}) inside the open Compost-Bedded Pack Barn system with positive pressure ventilation, during the Winter period.**

Variable	Period	Mean	Median	Minimum	Maximum	SD	CV	Kurt.	Ass.
$v_{air.M}$	Morning	1.5	1.4	0.6	3.3	0.4	0.25	3.41	0.53
	Afternoon	1.4	1.4	0.4	2.6	0.3	0.23	2.50	0.13
$v_{air.B}$	Morning	1.5	1.3	0.2	4.0	0.6	0.41	3.89	1.14
	Afternoon	1.6	1.5	0.2	4.2	0.7	0.44	4.06	1.11

*** SD – standard deviation; CV – coefficient of variation; Kurt – kurtosis; and Ass. – asymmetry.**

Table II. **Methods, models, and parameters estimated from the semivariograms adjusted for the mean values of air velocity at the 1.5 m height ($v_{air,M}$) and air velocity at bedding level ($v_{air,B}$) inside the open Compost-Bedded Pack Barn system with positive pressure ventilation, during the Winter period.**

Variable	Period	Method	Model	C_0	C_1	$C_0 + C_1$	a	a'	SDI	E_M	SD_M	E_R	SD_R
$v_{air.M}$	Morning	REML	Spherical	0.0227	0.2968	0.3195	5.4773	5.4773	0.0710	-0.0005	0.5745	-0.0004	1.0091
	Afternoon	REML	Spherical	0.0157	0.2317	0.2474	5.7163	5.7163	0.0635	-0.0007	0.5049	-0.0007	1.0093
$v_{air.B}$	Morning	REML	Gaussian	0.0000	0.6892	0.6892	6.0831	10.5288	0.0000	-0.0120	0.4273	-0.0116	0.8959
	Afternoon	REML	Gaussian	0.0000	0.8744	0.8744	7.2697	12.5825	0.0000	-0.0146	0.3305	-0.0183	0.9853

***C_0 – nugget effect; C_1 – contribution; $C_0 + C_1$ – sill; *a* – range; *a'* – practical range; SDI – Spatial Dependence Index; E_M – mean error; SD_M – mean error standard deviation; E_R – reduced error; SD_R – reduced error standard deviation; and REML – Restricted Maximum Likelihood.**

Similar behaviors were observed for $v_{air,B}$ (Table I), in which mean values of 1.5 ± 0.6 and 1.6 ± 0.7 $m \cdot s^{-1}$ was recorded in the morning and afternoon periods, respectively. The recording of $v_{air,M}$ and $v_{air,B}$ mean values close to each other is an indication that the mechanical ventilation system used was being effective in maintaining this constant attribute at different heights throughout the facility.

As can be seen from Table I, in both the evaluated periods (morning and afternoon) the mean and median values obtained for the variable's $v_{air,M}$ and $v_{air,B}$ were close to each other. Therefore, it can be inferred that these attributes are close to the normal distribution, according to Little & Hills (1978). According to the classification suggested by Warrick & Nielsen (1980), it was found that the air velocity data showed high variability (CV > 0.24), except for $v_{air,M}$ in the afternoon period, in which the data dispersion was classified as moderate (CV = 0.23). According to Faria et al. (2008), air velocity is an attribute with high spatial and temporal variability, which can undergo abrupt changes in magnitude and direction. Therefore, it is common for this variable data to present high dispersion, even in facilities with the mechanical ventilation use.

Regarding semivariogram adjustments (Table II), the best results were obtained using the Restricted Maximum Likelihood (REML). This method has been used for adjustments of small data clusters, as it results in less biased estimates (Marchant & Lark 2007, Ferraz et al. 2019).

For $v_{air,M}$, the best results were obtained using the Spherical model, while for $v_{air,B}$ were achieved using the Gaussian model (Table II). These two models are appropriate to describe the spatial distribution of the variables under study, because their functions are conditional positive, a condition that ensures that the calculated variances were also positive (McBratney & Webster 1986, Vieira et al. 2010a). Based on the data extracted from cross-validations, it can be concluded that the adjustments were satisfactory, since the E_M and E_R values were close to zero, as well as the SD_R values were close to one, as recommended by Isaaks & Srivastava (1989).

For both variables ($v_{air,M}$ and $v_{air,B}$) and in both periods (morning and afternoon), the values of unexplained variability (C_0) were low when compared to the sill ($C_0 + C_1$) (Table II). Considering the classification suggested by Cambardella et al. (1994), it was found that all values of Spatial Dependency Index (SDI) were low (< 0.25), characterizing the occurrence of strong spatial dependence. The highest value was obtained for the variable $v_{air,M}$ in the afternoon period, in which SDI equal to 0.0710 was obtained. Through these results, it can be concluded that the use of ordinary kriging techniques returned representative results of the variables, since the contribution of the nugget effect to the sill was low (Curi et al. 2017, Oliveira et al. 2023).

According to Andriotti (2003), another important geostatistics parameter is the range (***a***), which is used to determine the spatial dependence limit, separating samples correlated with each other from independent samples. Through Table II, it can be observed that in all cases the ***a*** values were higher than the shortest distance between collection points (4.5 m), reinforcing that the sampled points had correlation with each other and that there was an occurrence of spatial dependence (Andriotti 2003, Vieira 2000). The lowest values were observed for $v_{air,M}$ in the morning, where ***a*** = 5.4773 m. In view of this result, it can be concluded that the distance between collection points was adequate, considering all variables evaluated.

Once the occurrence of strong spatial dependence was observed (Table II), the

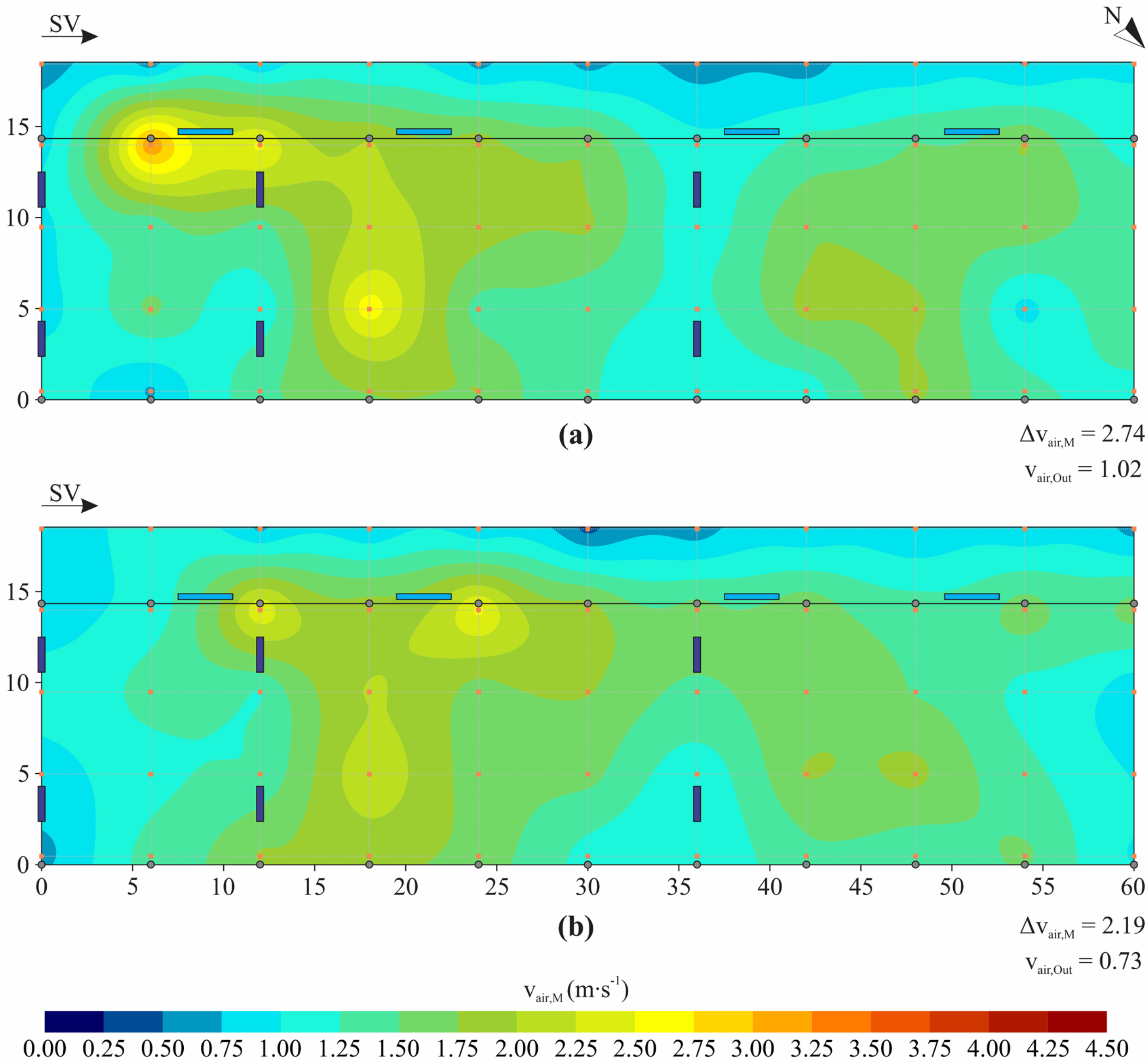

Figure 2. Spatial distribution of air velocity at the 1.5 m height ($v_{air,M}$, in $m \cdot s^{-1}$): (a) morning and (b) afternoon periods. *SV — sense of ventilation; $\Delta v_{ar,M}$ — air velocity variation at the 1.5 m height; $v_{air,Out}$ — average air velocity outside the facility; N — North indication; dimensions in meters (m).

interpolation techniques by ordinary kriging could be used to estimate the data in unsampled locations, allowing the production of spatial distribution maps. These maps were used to identify places with low and/or excessive air speed, to offer solutions for improvements in the environment (Faria et al. 2008, Oliveira et al. 2022). The maps of $v_{air,M}$, in the morning and afternoon periods, are illustrated in Figure 2.

As can be seen through the analysis of Figure 2, the $v_{air,M}$ mean magnitudes presented heterogeneous distributions inside the facility, but were similar between the periods evaluated (morning and afternoon). The mean range of $v_{air,M}$ variation was higher in the morning period ($\Delta v_{air,M}$ = 2.7 $m \cdot s^{-1}$), but the minimum and maximum values were always recorded in the same locations. The $v_{air,M}$ minimum values were observed in peripheral places, especially in regions near the feeding alley, while $v_{air,M}$ higher values were recorded in the bedding area, in the vicinity of tipper drinkers' protection walls (operation zones of the ventilation lines). There was no occurrence of regions with $v_{air,M}$ excessively high (> 5.0 m·s^{-1}).

Through Figure 2, it can be observed that along the feeding alley (Southwest face) average magnitudes of low velocities were recorded (< 1.0 m·s^{-1}). It can be inferred that its occurrence was due to the presence of protection walls between the bedding area and the tipper drinkers' present in the feeding alley (1.2 m height), which, according to Mondaca et al. (2019), act as a physical barrier to air flow, reducing and/or preventing its passage to the feeding alley. If, on the one hand, the presence of these protection walls reduces and/or prevents the passage of air flow currents to the feeding alley, on the other hand it allows the increase of the average magnitudes of air velocity in its vicinity, in the bedding area. For instance, the $v_{air,M}$ highest values (> 3.0 m·s^{-1}) were recorded in the bedding area near a protection wall, in the morning (Figure 2a).

Studies conducted by Berman (2008) and Mondaca et al. (2019) evaluated heat transfer and physiological responses of lactating dairy cattle under thermal stress conditions and observed that air velocity magnitudes greater than 2.0 m·s^{-1} improved the thermal comfort of the housed animals. In CBP systems it is recommended to keep air velocity close to 1.8 m·s^{-1} in the entire zone occupied by the animals (ZOA, below 1.50 m), allowing to ensure the bedding drying, gases removal and favoring thermal exchanges (Black et al. 2013). Admitting the air velocity magnitude recommended by Black et al. (2013) as the minimum air velocity for cooling the animals and bedding drying (MVCDB = 1.8 m·s^{-1}), it was verified that in the morning and afternoon periods there were occurrences of regions with $v_{air,M}$ values lower than recommended (Figure 2). At both times, it was noticed that the highest air velocity magnitudes were recorded in the fans action areas, indicating that they occurred due to the mechanical ventilation presence. However, it was also observed that there were occurrences of zones with low $v_{air,M}$, in which air velocity magnitudes were obtained close to those recorded in the external environment ($v_{air,Out}$ mean equal to 1.0 and 0.7 m·s^{-1}, in the morning and afternoon periods, respectively). These zones were observed in the initial, central, and posterior facility regions, where it can be inferred that the effect of mechanical ventilation was not noticed.

Fagundes et al. (2020) used computational fluid dynamics (CFD) techniques to evaluate the air flow generated by low-volume and high-speed fans (LVHS). The authors verified that in the region directly below the fans first line occurred the formation of a zone with low air velocity magnitude. As the fans were installed at 3.0 m high and with the 45° slope in relation to horizontal, it is estimated that the air flow in the immediately preceding region was suctioned and directed by these equipments, forming an area with low $v_{air,M}$ immediately below them. In fact, through the results shown in Figure 2, it can be inferred that the quantity and arrangement of the equipment present in the facility were not adequate.

Throughout the facility area, the formation of regions with low $v_{air,M}$ also occurred in the central and posterior regions (Northwest) (Figure 2). This occurred because the distance between fan lines was much longer than recommended (12.0 m, according to Damasceno 2020). Therefore, there was no evidence of the continuity occurrence of ventilation air currents, which is necessary to maintain the airflow uniformity.

According to Mondaca et al. (2019), in facilities used for animal confinement, about

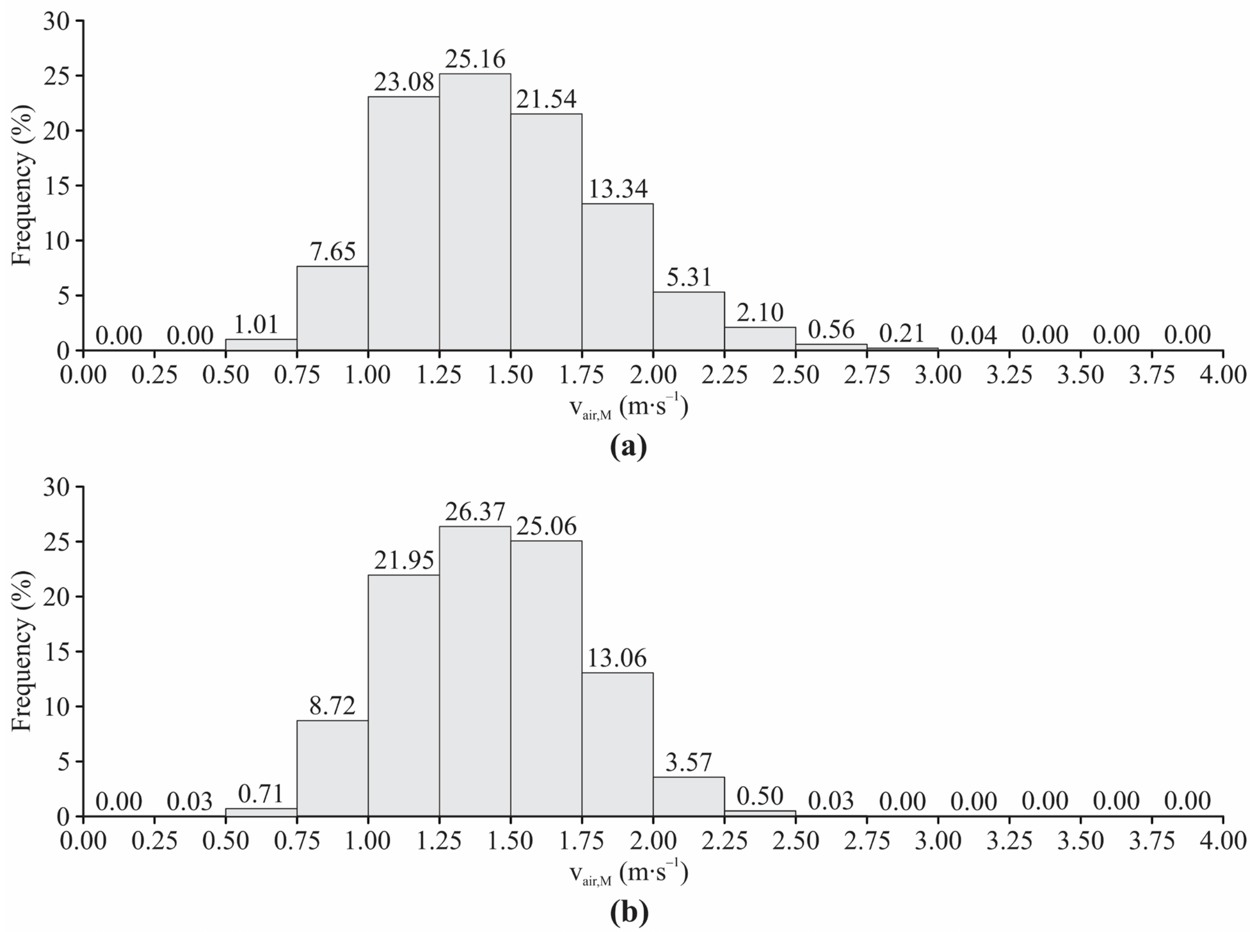

Figure 3. Frequency distribution of air velocity at the 1.5 m height ($v_{air,M}$, in $m \cdot s^{-1}$): (a) morning and (b) afternoon periods.

78.0% of the air flow occurs above or around ZOA. Therefore, through the $v_{air,M}$ results portrayed in this study (Figure 2), it can be inferred that the smallest $v_{air,M}$ magnitudes observed are due to, in part, to the load loss caused by the animals' presence and other obstacles contained in the ZOA, such as protection walls, pillars etc.

In the feeding alley region, where low $v_{air,M}$ magnitudes were recorded (Figure 2), increasing the overall ventilation rate inside the facility would be ineffective in reducing the area with $v_{air,M}$ lower than MVCDB, as stated by Mondaca et al. (2019). To improve the microenvironment in the region, it is recommended to use localized ventilation solutions, through low static pressure ventilation systems associated with evaporative adiabatic cooling, which can be triggered only when identified conditions characterized as thermal discomfort.

To obtain the fractions of area occupied by each class of the variables evaluated, frequency distribution graphs were generated. Figure 3 illustrates the $v_{air,M}$ charts in the morning and afternoon periods.

As can be seen through Figure 3, the $v_{air,M}$ magnitude in the morning and afternoon periods was less than 1.75 $m \cdot s^{-1}$ in about 78.40 and 82.85% of the internal facility area, respectively. Through these numbers, it becomes evident that the mechanical ventilation system present at the site was not able to ensure uniform, constant, and independent conditions of $v_{air,M}$ distribution inside the facility.

As already discussed, the maintenance of $v_{air,M}$ at adequate levels is important for favoring thermal exchanges, because when adequate levels of $v_{air,M}$ are not ensured throughout the entire area of the facility, as observed in this study (Figure 2), temperature gradients can form, as observed by Oliveira et al. (2022). In the hottest period of the day (afternoon), it can be inferred that the regions with low $v_{air,M}$ observed in this study (Figure 2b) were rejected by the animals, as portrayed by Damasceno (2020). If this occurred, the animals tended to group in regions with more mild air temperatures and/or with higher $v_{air,M}$ magnitudes, resulting in increased risk of accidents due to trampling of teat and tail, compaction and worsening of bedding quality.

The spatial distribution maps of air velocity at bedding level ($v_{air,B}$, in $m \cdot s^{-1}$), in the morning and afternoon periods, are illustrated in Figure 4.

As can be seen in Figure 4, the $v_{air,B}$ distribution in the facility was heterogeneous in the two periods evaluated, as can be observed through the high variation amplitudes (morning — $\Delta_{vair,B}$ = 3.8 $m \cdot s^{-1}$; afternoon — $\Delta v_{air,B}$ = 4.0 $m \cdot s^{-1}$). In the two periods evaluated, the $v_{air,B}$ magnitudes presented similar distribution profiles, in evidence that this attribute does not undergo abrupt changes between periods.

According to Oliveira et al. (2019), even in CBP systems with open sides, in which natural air currents are used, the use of mechanical ventilation systems is indispensable. In the present study, it was found that, even with the mechanical ventilation use (LVHS), the $v_{air,B}$ distribution was not uniform inside the facility (Figure 4). In the morning and afternoon periods, only in the first 20.0 m facility length (from Southeast to Northwest) the $v_{air,B}$ was equal to or greater than that recommended for bedding drying, removal of gases and favoring of thermal exchanges (MVCDB). In the entire remainder area, as well as in the initial region of Southeast face, the $v_{air,B}$ magnitude was lower than MVCDB. Regions with excessive $v_{air,B}$ (> 5.0 $m \cdot s^{-1}$) were not recorded.

Through the joint observation of Figures 2 and 4, it can be verified that the places with low $v_{air,M}$ and $v_{air,B}$ in the bedding area are, in parts, coincident (initial regions and from the second half of the facility, from Southeast to Northwest). At the ends of the bedding area, there was a small wall (0.2 m), which functioned as an impediment to air flow currents and, therefore, caused the reduction of the $v_{air,B}$ immediately close. On the other hand, in the second facility half, near the Northwest face, it can be inferred that the record of low $v_{air,B}$ occurred due to the ventilation lines absence, as observed for $v_{air,M}$.

The frequency distribution charts of $v_{air,B}$ are illustrated in Figure 5.

It can be verified that the $v_{air,B}$ magnitude was less than 1.8 $m \cdot s^{-1}$ in about 70.6 and 68.2% of the bedding area, in the morning and afternoon periods, respectively (Figure 5). Although the percentages of area with $v_{air,B}$ lower than MVCDB were lower at the bedding level, it is noted that there was a predominance of sites with low $v_{air,B}$ magnitudes. Through the $v_{air,B}$ numbers presented (Figures 4 and 5), it is evident that the mechanical ventilation system present at the site was not able to ensure uniform, constant, and independent of the climatic conditions inside the facility, as recommended by Damasceno (2020).

Oliveira et al. (2019) analyzed the air velocity spatial variability at bedding level in open CBP systems with several ventilation types (natural, low-volume and high-speed mechanical — LVHS, and high-volume and low-speed mechanical — HVLS) during the Spring period. Inside the LVHS ventilation system (same type of mechanical

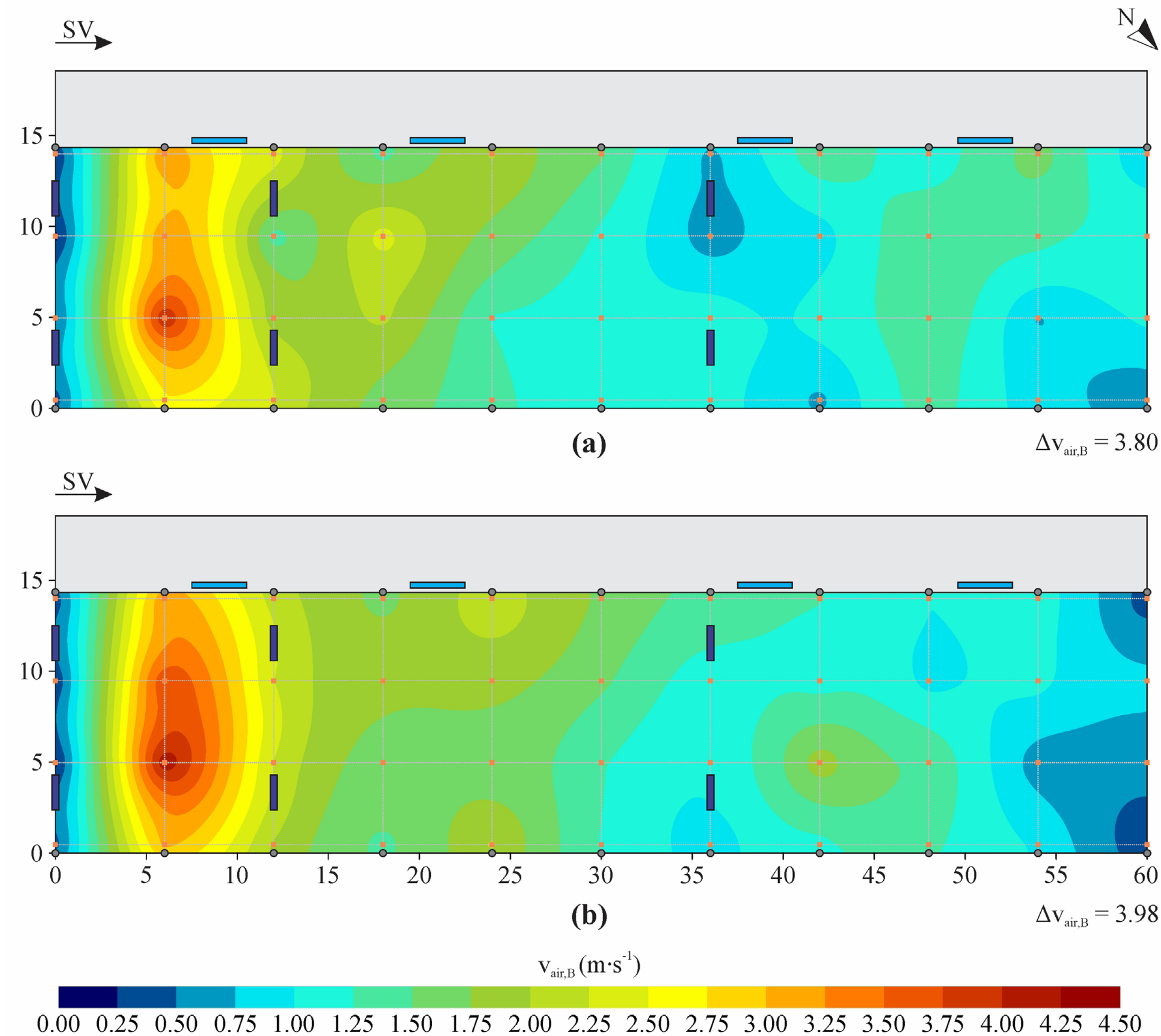

Figure 4. Spatial distribution of air velocity at bedding level ($v_{air,B}$, in m·s^{-1}): (a) morning and (b) afternoon periods. *SV — sense of ventilation; $\Delta v_{air,B}$ — air velocity variation at bedding level; N — North indication; dimensions in meters (m).

ventilation present in the CBP evaluated in this study), the authors observed that $v_{air,B}$ was less than 2.0 m·s^{-1} in about 31.6% of the facility bedding area and concluded that the amount and disposition of the ventilation equipment present were not satisfactory in ensuring homogeneous $v_{air,B}$ conditions.

Andrade et al. (2021) evaluated the spatial distribution of $v_{air,M}$ and $v_{air,B}$ in the internal areas of a closed CBP system with evaporative adiabatic cooling, during the Winter and Summer periods. In the Winter period, the authors observed that the $v_{air,B}$ distribution had high spatial variability (0.9 to 1.5 m·s^{-1}), and $v_{air,B}$ magnitudes below that desired in the internal facility area. The $v_{air,B}$ results portrayed corroborate those achieved in this study, in which $v_{air,B}$ was lower than 1.8 m·s^{-1} (Figures 4 and 5).

In fact, through the results presented (Figures 2, 3, 4 and 5), it can be concluded that the

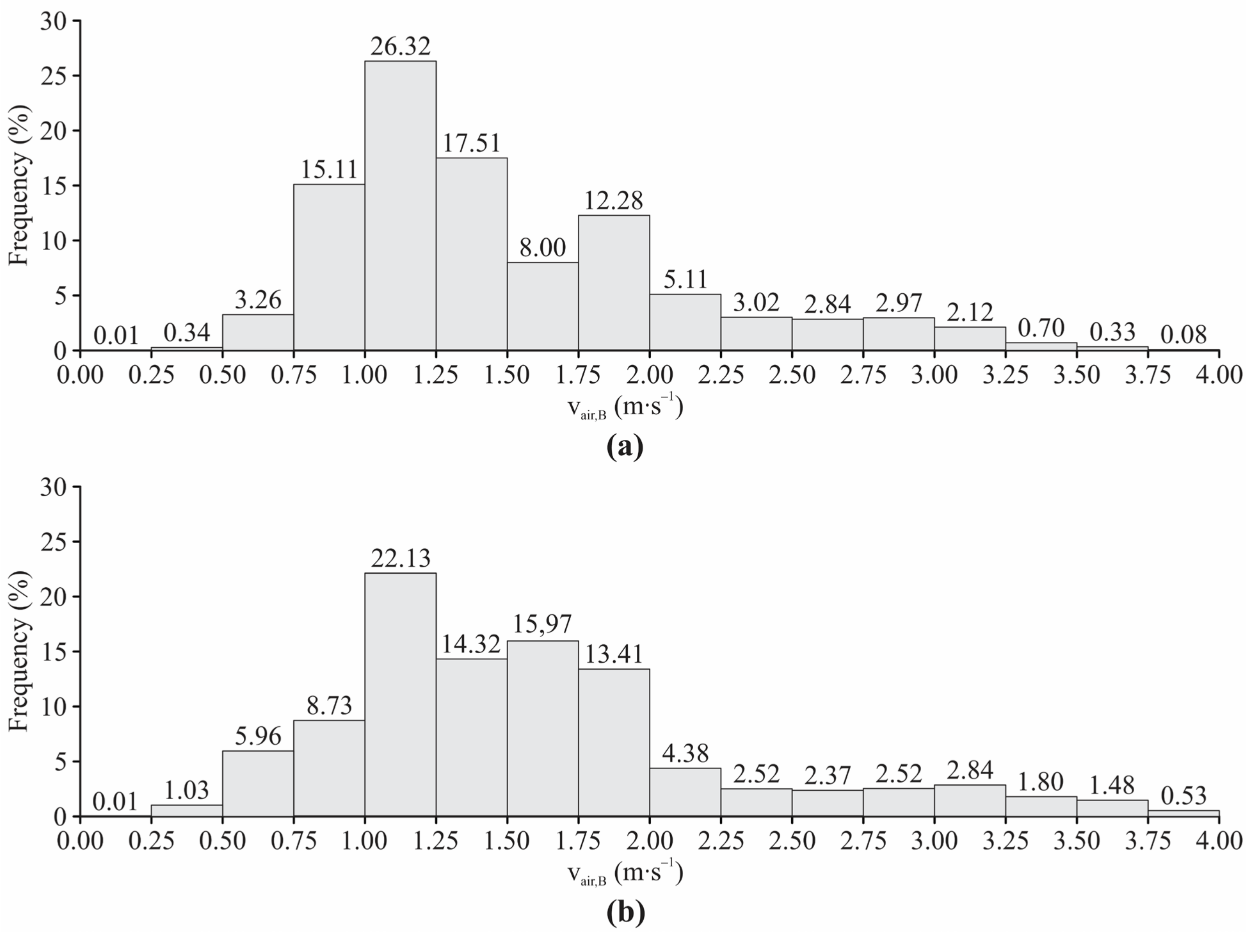

Figure 5. Frequency distribution of air velocity at bedding level ($v_{air,B}$, in m·s^{-1}): (a) morning and (b) afternoon periods.

amount and LVHS fans distribution throughout the CBPPV system did not meet the need for ventilation required in the evaluated facility. Thus, it is recommended that the ventilation system employed be resized, changing the equipment quantity and arrangement throughout the facility area, to promote uniform conditions of $v_{air,M}$ and $v_{air,B}$ distribution, and ensure adequate conditions for bedding drying, removing gases and favoring thermal exchanges.

CONCLUSIONS

The geostatistics techniques application allowed to verify and characterize the spatial dependence occurrence of the variables air velocity at the 1.5 m height ($v_{air,M}$, in m·s^{-1}) and air velocity at bedding level ($v_{air,B}$, in m·s^{-1}) in the internal area of the evaluated system (morning and afternoon periods). In both periods evaluated, a strong spatial dependence was observed, enabling the interpolation techniques application by ordinary kriging and generation of spatial distribution maps.

Through the generated maps, it was observed that the variables presented high spatial variability along the internal facility area. In both times evaluated, the $v_{air,M}$ and $v_{air,B}$ distributions were not uniform, and air velocity magnitudes were recorded between 0.25 and

2.75 $m \cdot s^{-1}$ at the 1.5 m height, and between 0.00 and 4.00 $m \cdot s^{-1}$ at bedding level. At the two times in which data were measured, and at both times evaluated, the $v_{air,M}$ and $v_{air,B}$ magnitudes were lower than that recommended (1.8 $m \cdot s^{-1}$) in more than 65.0% of the internal facility area. Adequate ventilation levels were observed only in the first 20.0 m of the facility, from Southeast to Northwest, because of the fan lines present in this region.

Acknowledgments

The authors would like to thank the Federal University of Viçosa (UFV) and Federal University of Lavras (UFLA), whose support is appreciated. This work was conducted with the support of the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) — Process 422912/2018-2; of the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) — Finance Code 001; and of the Fundação de Amparo à Pesquisa do Estado de Minas Gerais, Brazil (FAPEMIG) — Finance Code 001.

REFERENCES

ALMEIDA GLP, PANDORFI H, GUISELINI C, ALMEIDA GAP & MORRIL WBB. 2010. Investimento em climatização na pré-ordenha de vacas girolando e seus efeitos na produção de leite. Rev Bras Eng Agríc Ambient 14(12): 1337-1344.

ANDRADE RR, TINÔCO IFF, DAMASCENO FA, FERRAZ GAS, FREITAS LCSR, FERREIRA CFS, BARBARI M, BAPTISTA FJF & COELHO DJR. 2021. Spatial distribution of bed variables, animal welfare indicators, and milk production in a closed compost-bedded pack barn with a negative tunnel ventilation system. J Therm Biol 105: 103111.

ANDRADE RR, TINÔCO IFF, DAMASCENO FA, FERRAZ GAS, FREITAS LCSR, FERREIRA CFS, BARBARI M & TELES JUNIOR CGS. 2022. Spatial analysis of microclimatic variables in compost-bedded pack barn with evaporative tunnel cooling. An Acad Bras Cienc 94: e20210226. https://doi.org/10.1590/0001-3765202220210226.

ANDRIOTTI JLS. 2003. Fundamentos de estatística e geoestatística. 1ª ed., São Leopoldo: Editora Unisinos, 166 p.

BERMAN A. 2008. Increasing heat stress relief produced by coupled coat wetting and forced ventilation. J Dairy Sci 91(12): 4571-4578.

BLACK RA, TARABA JL, DAY GB, DAMASCENO FA & BEWLEY JM. 2013. Compost bedded pack dairy barn management, performance, and producer satisfaction. J Dairy Sci 96(12): 8060-8074.

CALDATO EMR, CALDATO A, MARCONDES MI & ROTTA PP. 2020. Manual técnico de construção e manejo de Compost Barn para vacas leiteiras. 1ª ed., Viçosa: Editora UFV, 42 p.

CAMBARDELLA CA & ELLIOTT ET. 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Sci Soc Am J 56(3): 777-783.

CAMBARDELLA CA, MOORMAN TB, NOVAK JM, PARKIN TB, KARLEN DL, TURCO RF & KONOPKA AE. 1994. Field-scale variability of soil properties in Central Iowa soils. Soil Sci Soc Am J 58(5): 1501-1511.

CURI TMRC, CONTI D, VERCELLINO RA, MASSARI JM, MOURA DJ, SOUZA ZM & MONTANARI R. 2017. Positioning of sensors for control of ventilation systems in broiler houses: a case study. Sci Agric 74(2): 101-109.

DAMASCENO FA. 2020. Compost barn como uma alternativa para a pecuária leiteira, 1ª ed. Divinópolis: Adelante, 396 p.

FAGUNDES B, DAMASCENO FA, ANDRADE RR, SARAZ JAO, BARBARI M, VEGA FAO & NASCIMENTO JAC. 2020. Comparison of airflow homogeneity in compost dairy barns with different ventilation systems using the CFD model. Agron Res 18(1): 788-796.

FARIA FF, MOURA DJ, SOUZA ZS & MARATAZZO SV. 2008. Variabilidade espacial do microclima de um galpão utilizado para confinamento de bovinos de leite. Cienc Rural 38(9): 2498-2505.

FERRAZ PFP, FERRAZ GAS, DAMASCENO FA, MOURA RS, SILVA MAJG & RODRIGUES RL. 2019. Spatial variability of enthalpy in rabbit house with and without ridge vent. Rev Bras Eng Agricola Ambient 23(2): 126-132.

FERRAZ PFP, GONZALEZ VC, FERRAZ GAS, DAMASCENO FA, OSORIO JAS & CONTI L. 2020. Assessment of spatial variability of environmental variables of a typical house of laying hens in colombia: Antioquia state case. Agron Res 18(2): 1244-1254.

GALAMA PJ, OUWELTJES W, ENDRES MI, SPRECHER JR, LESO L, KUIPERS A & KLOPČIČ M. 2020. Symposium review: Future of housing for dairy cattle. J Dairy Sci 103: 5759-5772.

ISAAKS EH & SRIVASTAVA RM. 1989. An introduction to applied geostatistics. New York: Oxford University Press, 561p.

LESO L, CONTI L, ROSSI G & BARBARI M. 2018. Criteria of design for deconstruction applied to dairy cows housing: A case study in Italy. Agron Res 16(3): 794-805.

LESO L, BARBARI M, LOPES MA, DAMASCENO FA, GALAMA P, TARABA JL & KUIPERS A. 2020. Invited review: Compost-bedded pack barns for dairy cows. J Dairy Sci 103(2): 1072-1099.

LITTLE TM & HILLS FJ. 1978. Agricultural experimentation: design and analysis. 1st ed., Hoboken: John Wiley & Sons, 368 p.

MARCHANT BP & LARK RM. 2007. Robust estimation of the variogram by residual maximum likelihood. Geoderma 140(1): 62-72.

MATHERON G. 1962. Traité de géostatistique appliquée, n. 14. Paris: Editions Technip, 333 p.

MCBRATNEY AB & WEBSTER R. 1986. Choosing functions for semivariograms of soil properties and fitting them to sampling estimates. J Soil Sci 37(4): 617-639.

MEDEIROS BBL, MOURA DJ, MASSARI JM, CARVALHO TMR & MAIA APA. 2014. Uso de geoestatística na avaliação de variáveis ambientais em galpão de suínos criados em sistema 'wean to finish' na fase de terminação. Eng Agríc 34(5): 800-811.

MEE JF & BOYLE LA. 2020. Assessing whether dairy cow welfare is "better" in pasture-based than in confinement-based management systems. N Z Vet J 68(3): 168-177.

MONDACA MR, CHOI CY & COOK NB. 2019. Understanding microenvironments within tunnel-ventilated dairy cow freestall facilities: Examination using computational fluid dynamics and experimental validation. Biosyst Eng 183: 70-84.

OLIVEIRA CEA, DAMASCENO FA, FERRAZ PFP, NASCIMENTO JAC, FERRAZ GAS & BARBARI M. 2019. Geostatistics applied to evaluation of thermal conditions and noise in compost dairy barns with different ventilation systems. Agron Res 17(3): 783-796.

OLIVEIRA CEA, DAMASCENO FA, FERRAZ GAS, NASCIMENTO JAC, VEGA FAO, TINÔCO IFF & ANDRADE RR. 2021. Assessment of spatial variability of bedding variables in compost bedded pack barns with climate control system. An Acad Bras Cienc 93: e20200384. https://doi.org/10.1590/0001-3765202120200384.

OLIVEIRA CEA, TINÔCO IFF, DAMASCENO FA, OLIVEIRA VC, FERRAZ GAS, SOUSA FC, ANDRADE RR, BARBARI M. 2022. Mapping of the thermal microenvironment for dairy cows in an open compost-bedded pack barn system with positive-pressure ventilation. Animals 12(16): 2055.

OLIVEIRA CEA, TINÔCO IFF, OLIVEIRA VC, RODRIGUES PHM, SILVA LF, DAMASCENO FA, ANDRADE RR, SOUSA FC, BARBARI M & BAMBI G. 2023. Spatial distribution of bedding attributes in open compost-bedded pack barn system with positive pressure ventilation in brazilian winter conditions. Animals 13(5): 786.

PERISSINOTTO M, MOURA DJ, CRUZ VF, SOUZA SRL, LIMA KAO & MENDES AS. 2009. Conforto térmico de bovinos leiteiros confinados em clima subtropical e mediterrâneo pela análise de parâmetros fisiológicos utilizando a teoria dos conjuntos *fuzzy*. Cienc Rural 39(5): 1492-1498.

PILATTI JA & VIEIRA FMC. 2017. Environment, behavior and welfare aspects of dairy cows reared in compost bedded pack barns system. J Anim Behav Biometeorol 15(3): 97-105.

PILATTI JA, VIEIRA FMC, RANKRAPE F & VISMARA ES. 2019. Diurnal behaviors and herd characteristics of dairy cows housed in a compost-bedded pack barn system under hot and humid conditions. Animal 13(2): 399-406.

R DEVELOPMENT CORE TEAM. 2021. R: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing. Available: http://www.R-project.org/. Accessed in 18 October 2021.

RIBEIRO JÚNIOR PJ & DIGGLE PJ. 2001. GeoR: a package for geostatistical analysis. R-News 1(2): 14-18.

SÁ JÚNIOR A, CARVALHO LG, SILVA FF & ALVES MC. 2012. Application of the Köppen classification for climatic zoning in the state of Minas Gerais, Brazil. Theor Appl Climatol 108(1): 1-7.

VIEIRA SR. 2000. Geoestatística em estudos de variabilidade espacial do solo. In: Novais RF, Alvares VH & Schaeffer CEGR (Eds), Tópicos em ciência do solo. Viçosa: Sociedade Brasileira de Ciência do Solo, Viçosa, MG, Brasil, p. 1-53.

VIEIRA SR, CARVALHO JRP, CEDDIA MB & GONZÁLEZ AP. 2010a. Detrending non stationary data for geostatistical applications. Bragantia 69: 01-08.

VIEIRA SR, CARVALHO JRP & GONZÁLEZ AP. 2010b. Jack knifing for semivariogram validation. Bragantia 69: 97-105.

WARRICK WA & NIELSEN DR. 1980. Spatial variability of soil physical properties in the field. In: Hillel D (Ed), Application of soil physics. New York: Academic Press, New York, USA, p. 319-344.

How to cite

OLIVEIRA CEA ET AL. 2023. Air velocity spatial variability in open Compost-Bedded Pack Barn system with positive pressure ventilation. An Acad Bras Cienc 95: e20220415. DOI 10.1590/0001-3765202320220415.

Manuscript received on May 9, 2022;
accepted for publication on February 4, 2023

CARLOS EDUARDO A. OLIVEIRA[1]
https://orcid.org/0000-0002-2104-7428

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

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

VICTOR C. DE OLIVEIRA[1]
https://orcid.org/0000-0003-2719-9972

PEDRO HENRIQUE M. RODRIGUES[1]
https://orcid.org/0000-0002-4697-9678

GABRIEL A.S. FERRAZ[3]
https://orcid.org/0000-0001-6403-2210

FERNANDA C. DE SOUSA[1]
https://orcid.org/0000-0002-5584-728X

RAFAELLA R. ANDRADE[4]
https://orcid.org/0000-0003-3182-0741

JOÃO ANTÔNIO C. DO NASCIMENTO[1]
https://orcid.org/0000-0001-5984-5997

LEONARDO F. DA SILVA[1]
https://orcid.org/0000-0002-9710-8100

[1]Universidade Federal de Viçosa, Departamento de Engenharia Agrícola, Av. Peter Henry Rolfs, s/n, Campus Universitário, 36570-900 Viçosa, MG, Brazil

[2]Universidade Federal de Lavras, Departamento de Engenharia, Av. Doutor Sylvio Menicucci, 1001, Aquenta Sol, 37200-000 Lavras, MG, Brazil

[3]Universidade Federal de Lavras, Departamento de Engenharia Agrícola, Av. Doutor Sylvio Menicucci, 1001, Aquenta Sol, 37200-000 Lavras, MG, Brazil

[4]Universidade Federal de Goiás, Escola de Agronomia, Av. Esperança, s/n, Campus Samambaia, 74690-900 Goiânia, GO, Brazil

Correspondence to: **Carlos Eduardo Alves Oliveira**
E-mail: carloseaoliveira@hotmail.com

Author contributions

Carlos Eduardo Alves Oliveira, Victor Crespo de Oliveira, Pedro Henrique de Moura Rodrigues, João Antônio Costa do Nascimento and Leonardo França da Silva conducted the field trials, collect and data analysis, and wrote the manuscript. Ilda de Fátima Ferreira Tinôco, Flávio Alves Damasceno, Gabriel Araújo e Silva Ferraz, Fernanda Campos de Sousa and Rafaella Resende Andrade helped on data analysis and reviewed the manuscript.