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Bioclimatic assessment of a compost-bedded pack barn system in a highland region during winter

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Abstract. Thermal stress in dairy cattle represents an increasing challenge, even during milder seasons and in high-altitude regions, compromising animal welfare and herd productivity. Confinement systems such as compost-bedded pack barns have been adopted as an alternative to mitigate these effects; however, specific evaluations of their performance are still necessary. In this context, the objective of this study was to evaluate the thermal environment of a compost-bedded pack barn system for dairy cows during the winter season in a highland region. The experiment was conducted during winter in a barn located in the municipality of Diamantina, Minas Gerais, Brazil. Internal and external meteorological variables were monitored, including air temperature, relative humidity, wind speed, black globe temperature, and dry- and wet-bulb temperatures, at three different points inside the barn. Based on these data, the Temperature–Humidity Index (THI), the Black Globe Humidity Index (BGHI), and the Radiant Thermal Load (RTL) were calculated. The results indicated that although the daily mean values of the thermal comfort indices remained within the comfort range for dairy cows, peaks of heat stress occurred at specific times, particularly between 10:00 a.m. and 5:00 p.m., with greater intensity in the central area of the barn. The observed internal thermal heterogeneity highlights the importance of adjustments in management and ventilation strategies. It is concluded that even during winter, environmental control measures are necessary to ensure animal welfare in compost-bedded pack barn systems located in high-altitude regions.

Keywords: Animal environment, bioclimatology, thermal comfort, rural construction.

Avaliação bioclimática de um sistema compost-bedded pack barn em região de altitude durante o inverno

Resumo. O estresse térmico em bovinos leiteiros representa um desafio crescente, mesmo em estações mais amenas e em regiões de altitude, comprometendo o bem-estar animal e a produtividade dos rebanhos. Sistemas de confinamento, como o *compost-bedded pack barn*, têm sido adotados como alternativa para mitigar esses efeitos; entretanto, avaliações específicas de seu desempenho ainda são necessárias. Diante disso, este estudo teve como objetivo avaliar o ambiente térmico de um sistema *compost-bedded pack barn* para vacas leiteiras durante o período de inverno em uma região de altitude. O experimento foi conduzido durante a estação de inverno em um galpão localizado no município de Diamantina, Minas Gerais, Brasil. Foram monitoradas variáveis meteorológicas internas e externas, incluindo temperatura do ar, umidade relativa, velocidade do vento, temperatura de globo negro e temperaturas de bulbo seco e úmido, em três pontos distintos do galpão.

Com base nesses dados, foram calculados o Índice de Temperatura e Umidade (ITU), o Índice de Temperatura de Globo Negro e Umidade (ITGU) e a Carga Térmica Radiante (CTR). Os resultados indicaram que, embora os valores médios diários dos índices de conforto térmico tenham permanecido dentro da faixa considerada adequada para vacas leiteiras, ocorreram picos de estresse térmico em horários específicos, especialmente entre 10 e 17 horas, com maior intensidade na região central do estábulo. A heterogeneidade térmica interna observada destaca a importância de ajustes no manejo e na ventilação. Conclui-se que, mesmo durante o inverno, há necessidade de estratégias de controle ambiental para garantir o bem-estar animal em sistemas *compost-bedded pack barn* situados em regiões de altitude.

Palavras-chave: Ambiência animal, bioclimatologia, conforto térmico, construção rural.

Introduction

Heat stress is a major risk factor in dairy farming, negatively affecting productive efficiency and animal welfare standards in global production systems ([Allen et al., 2015](#); [Atrian & Shahryar, 2012](#); [Maggiolino et al., 2021](#); [Mota et al., 2019](#)). The increasing frequency and intensity of heat waves, within the broader context of climate change ([Baêta & Souza, 2010](#); [Mandú et al., 2021](#); [Rodrigues et al., 2010](#); [Salla et al., 2009](#)), have led to prolonged periods of extreme temperatures, posing a serious threat to agricultural productivity ([Bitencourt et al., 2016](#)).

Confinement systems have emerged as an effective strategy to minimize the impacts of heat stress on lactating cows by improving productivity, milk quality, herd health, and animal welfare while ensuring adequate thermal comfort ([Frigeri et al., 2023](#); [West et al., 1992](#)). By enabling greater control over environmental factors such as temperature, humidity, and nutrition, confinement systems represent a viable alternative for reducing environmental interference in animal performance ([Laurindo et al., 2022](#); [Melo et al., 2016](#); [Mota et al., 2019](#); [Nepomuceno et al., 2023](#)).

Among confined housing systems, the conventional compost-bedded pack barn has gained prominence in Brazil due to its relatively low cost, improved thermal comfort for animals, and capacity to manage waste generated by the herd. However, the absence of a standardized construction model suitable for all regions of the country, given Brazil's vast territorial extent and climatic diversity ([Damasceno, 2012](#); [Guesine et al., 2023](#); [Pilatti & Vieira, 2017](#)), highlights the importance of region-specific studies. Characterizing the internal thermal environment of these facilities is therefore critical for mitigating climatic impacts on animals and ensuring the sustainability of dairy farming.

In this context, and considering the need to better understand the performance of compost pack barn systems, the objective of this study was to conduct a bioclimatic characterization of the internal environment of a compost pack barn for dairy cows during the winter period, aiming to describe the thermal conditions of the facility in high-altitude regions of Brazil.

Material and methods

Location

The present study was conducted during the winter of 2023, from July 1 to September 23, in a compost-bedded pack barn located at the Dairy Cattle Sector of the Department of Animal Science at the Federal University of the Jequitinhonha and Mucuri Valleys (UFVJM), in Diamantina, Minas Gerais, Brazil. The geographical coordinates of the site are 18°10' S latitude, 43°40' W longitude, at an altitude of 1,387 m. The location of the study area is shown in [Figure 1](#).

According to the Köppen climate classification, Diamantina has a Cwb climate, characterized as a subtropical highland climate with dry winters and mild summers. The average annual temperature is 19.2 °C, with an average minimum of 11.2 °C in July and an average maximum of 25.8 °C in February. The total annual precipitation is 1,388.9 mm ([Santos et al., 2024](#)).

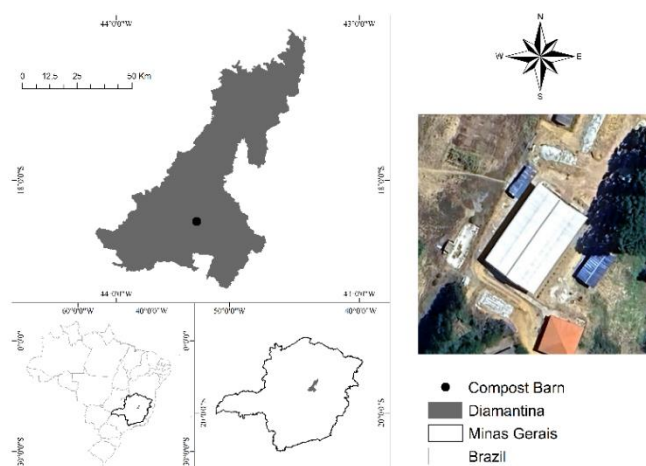


Figure 1. Location map of the compost-bedded pack barn in Diamantina, Minas Gerais

Meteorological data collection

To characterize the internal bioclimatic conditions of the compost-bedded pack barn, the following meteorological variables were monitored: air temperature (T_a), relative humidity (R_h), wind speed (W_s), black globe temperature (T_{bg}), dry-bulb temperature (T_{db}), and wet-bulb temperature (T_{wb}). Measurements were taken at three different locations within the barn: Point 1 (P1 – front), Point 2 (P2 – middle), and Point 3 (P3 – rear), longitudinally distributed to assess environmental heterogeneity.

Air temperature and relative humidity were measured and automatically recorded at 15-minute intervals. Different instruments were used according to availability, with priority given to prior calibration and standardized installation conditions, specifically, placement at 1.5 m above the bedding surface along the central line of the stalls, to ensure data reliability. Two Instrutherm HT-900 dataloggers (accuracy ± 0.5 °C for air temperature and $\pm 3\%$ for relative humidity) were installed at P1 and P2. At P3, a digital thermo-hygrometer (Icel 4010; accuracy ± 1.0 °C for air temperature and $\pm 5\%$ for relative humidity) was used.

Wind speed, black globe temperature, and dry- and wet-bulb temperatures were collected manually every two days at 09:00, 12:00, and 15:00. Wind speed was measured using an Instrutherm TAD-500 thermo-anemometer (range: 0.4 to 30 m s⁻¹; resolution: 0.1 m s⁻¹). Black globe temperature was obtained using an analog black globe thermometer (15 cm diameter matte black-painted copper sphere) and a portable digital globe thermometer (Instrutemp ITWTG 2000; accuracy ± 1.0 °C). Dry- and wet-bulb temperatures were measured with a non-ventilated psychrometer (Incoterm; resolution 0.1 °C).

Additionally, external air temperature and relative humidity data were obtained from the conventional weather station of the UFVJM School of Agricultural Sciences, located approximately 300 m from the compost-bedded pack barn. These hourly data were used as a reference for comparison with the internal environment and for assessing the bioclimatic conditions of the confined space.

Thermal environment assessment

The collected meteorological variables were used to calculate three thermal comfort indices commonly employed in animal environment studies: the Temperature–Humidity Index (THI), the Black Globe Humidity Index (BGHI), and the Radiant Thermal Load (RTL). The indices were calculated using Equations (1), (2), and (3), respectively.

Temperature – Humidity Index (THI), proposed by [Thom \(1959\)](#):

$$THI = 0.72 \times (T_{db} + T_{wb}) + 40.6 \quad (1)$$

Where: T_{db} : Dry-bulb temperature (°C); T_{wb} : Wet-bulb temperature (°C).

Black Globe Humidity Index (BGHI), according to ([Buffington et al., 1981](#)):

$$BGHI = T_{bg} + 0.36 \times T_{dp} + 41.5 \quad (2)$$

Where: T_{bg} = Black globe temperature (°C); T_{dp} = Dew point temperature (°C).

Radiant Thermal Load (RTL), proposed by [Kelly et al. \(1950\)](#):

$$RTL = \sigma \times MRT^4 \quad (3)$$

Where: σ = Stefan–Boltzmann constant ($5.67 \times 10^{-8} \text{ W.m}^{-2}\text{K}^{-4}$); MRT = Mean Radiant Temperature (K).

The THI, BGHI, and RTL were calculated for each day and for each manual data collection time (09:00, 12:00, and 15:00) at each sampling point. Mean values were then obtained for each collection time and sampling location and compared with thermal comfort thresholds reported in the literature for dairy cattle.

For THI, the classification proposed by [Eigenberg et al. \(2007\)](#) was adopted: values ≤ 74 indicate thermal comfort; > 74 and ≤ 78 indicate alert conditions; > 78 and ≤ 83 indicate danger; and values > 83 correspond to an emergency condition.

For BGHI, the ranges established by the National Weather Service were used: values ≤ 74 indicate comfort; 75–78 indicate alert conditions; 79–84 indicate danger; and values > 84 indicate thermal emergency.

In addition to average values, individual measurements were analyzed to detail the temporal variation of the indices throughout the days and collection times.

Discussion

Thermal environment assessment

The bioclimatic characterization of the compost-bedded pack barn during the winter of 2023 revealed significant variations in internal and external air temperature (T_a) and relative humidity (Rh) throughout the evaluated period. The highest internal air temperatures recorded were 29.5 °C at Point 1, 28.8 °C at Point 2, and 36.9 °C at Point 3, occurring predominantly in September, a month marking the transition to spring and an increase in ambient temperature, which reached 29.1 °C externally. The lowest internal air temperatures were 7.3 °C at Point 1 and 7.7 °C at Point 2 on July 5, and 9.0 °C at Point 3 on July 6, while the minimum external temperature reached 6.9 °C on July 5.

[Figure 2](#) illustrates the daily behavior of the thermal variables. On average, the internal temperature of the compost-bedded pack barn exceeded the external temperature between 05:00 and 14:00 for 67% of the time at Point 2 (central region of the barn). This internal heat accumulation, particularly in the central area, may be associated with the composting activity of the bedding, which generates metabolic heat and contributes to an increase in the barn microclimate temperature ([Lesso et al., 2020](#)). In contrast, Point 3 (rear of the barn) maintained lower temperatures than the external environment for a longer period, from 15:00 to 05:00 (63% of the time). This behavior can be explained by the greater exposure of Point 3 to cold northeastern winds during winter, in addition to the prevailing southeastern winds that laterally affect the entire barn structure ([Ferreira et al., 2024](#)).

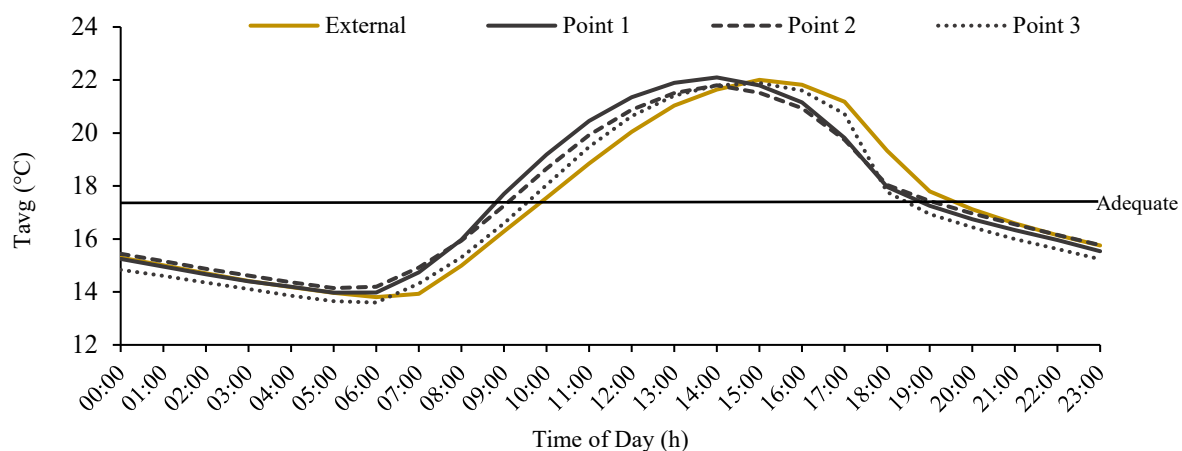


Figure 2. Hourly averages of internal and external air temperature (T_{avg} , °C) in a compost-bedded pack barn during the winter of 2023, in Diamantina, Minas Gerais.

The daily average temperatures for the three points were 17.4 °C (Point 1), 17.4 °C (Point 2), and 17.0 °C (Point 3). Although these values fall within the optimal temperature range for dairy cows (13.0 °C to 18.0 °C ([Manzoor et al., 2019](#))), the hourly analysis revealed that Points 1 and 3 operated outside the thermal comfort zone for 33% of the recorded time, while Point 2 reached 37%. The period between 10:00 a.m. and 5:00 p.m. was the most critical, with temperatures exceeding the ideal range at all three points, indicating a high likelihood of heat stress in the animals.

The thermal heterogeneity observed along the barn, with the central region (Point 2) presenting the most unfavorable conditions, is a critical finding. The lack of uniformity in thermal and ventilation conditions can lead to uneven animal clustering in more comfortable areas, compromising the uniform distribution of feces and urine and, consequently, the quality and composting process of the bedding ([Leso et al., 2020](#)).

Additionally, elevated temperatures directly affect milk yield and composition ([Chen et al., 2023](#)), induce immunosuppression ([Alhussien et al., 2024](#)) and result in hormonal imbalances ([Pakari & Ghani, 2021](#); [Skliarov et al., 2022](#)). The absence of fan operation when internal temperatures exceeded 17 °C (an 11-hour period from 9:00 a.m. to 7:00 p.m., as recommended by [Lobeck et al., 2011](#)) and [Pakari & Ghani \(2021\)](#) likely contributed to heat and moisture retention, negatively impacting barn microclimate and the dissipation of gases and odors ([Barberg et al., 2007](#); [Endres & Barberg, 2007](#)).

Relative humidity (Rh) is a key factor in thermal stress, as it reduces the efficiency of evaporative cooling in animals ([Zhou et al., 2023](#)). The average Rh in the barn during the study period was 76.6%. Mean values at the three points ranged from 58.7% to 94.0% ([Figure 3](#)), frequently exceeding the optimal range for production animals (40% to 80%) ([Manzoor et al., 2019](#)).

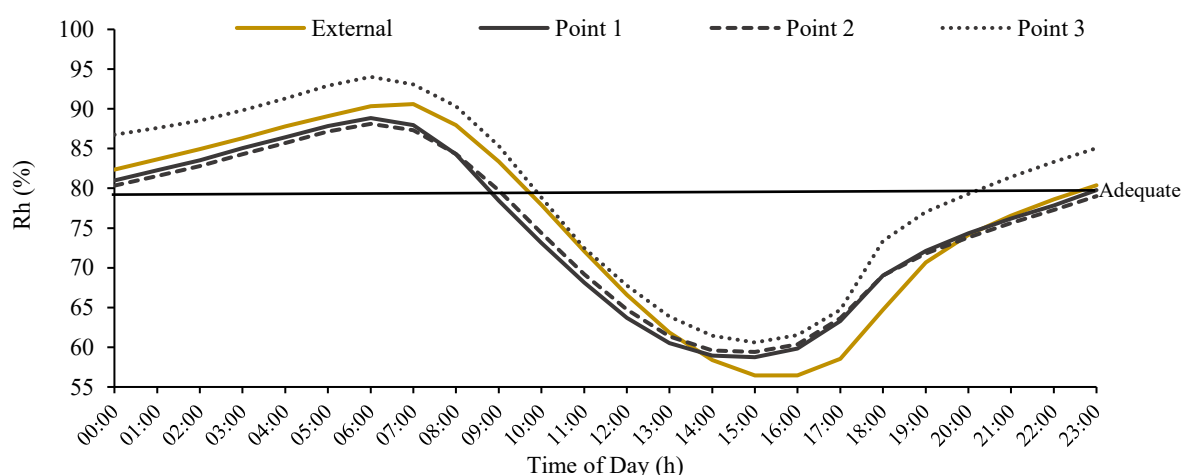


Figure 3. Hourly averages of internal and external relative humidity (Rh, %) in a compost-bedded pack barn during the winter of 2023, in Diamantina, Minas Gerais.

High relative humidity is directly correlated with increased bedding moisture ([Eckelkamp et al., 2016](#)). Bedding moisture levels above 65% impair air movement within the pore spaces, favoring undesirable anaerobic conditions and promoting pathogen development ([Endres & Janni, 2008](#); [Janni et al., 2007](#)). The maintenance of animal hygiene, which is crucial for infection prevention and milk quality, is directly affected by bedding moisture. [Freu et al. \(2023\)](#) identified a positive correlation between bedding moisture content and the incidence of clinical mastitis, while [Fávero et al. \(2015\)](#) reported a 5.7% increase in the probability of environmental clinical mastitis for each additional unit increase in bedding moisture.

The observed THI values ranged from 54.4 to 80.5. The average THI values at the three points remained within the comfort range. However, individual data analysis revealed occurrences of values in the alert range and one value in the “danger” range (80.5), recorded at Point 1 at 3:00 p.m. This maximum value is similar to the maximum THI (81) reported by [Radavelli et al. \(2020\)](#) in different compost-bedded pack barn in the subtropical region of Brazil, and consistent with ([Mota et al., 2019, 2020](#)), who reported average THI values within the comfort range but with peaks in the “danger zone” during winter. The higher average THI at Point 1 is attributed to greater direct solar radiation incidence

on the front area of the barn during the morning and part of the afternoon, leading to an accumulation of energy absorbed by the black globe and, consequently, a higher radiant heat load.

Figures 4 and 5 show an increasing trend in THI and BGHI values throughout the season, especially towards the end of winter. This behavior is critical, as it indicates that during other seasons (spring and summer), the indices may reach higher classifications, compromising the efficiency of the dairy production system due to intensified thermal stress on the animals.

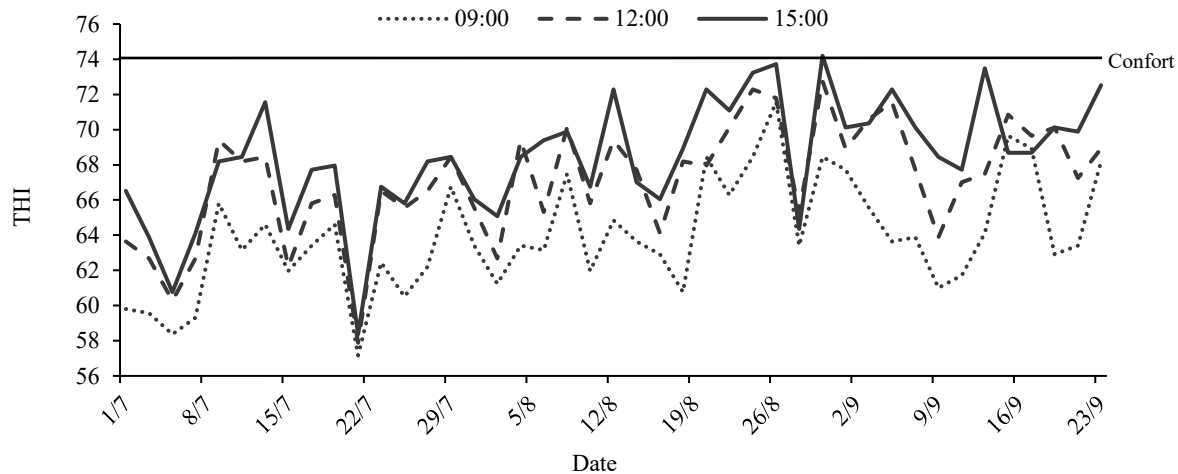


Figure 4. Hourly behavior of the temperature-humidity index (THI) in a compost-bedded pack barn during the winter of 2023, in Diamantina, Minas Gerais.

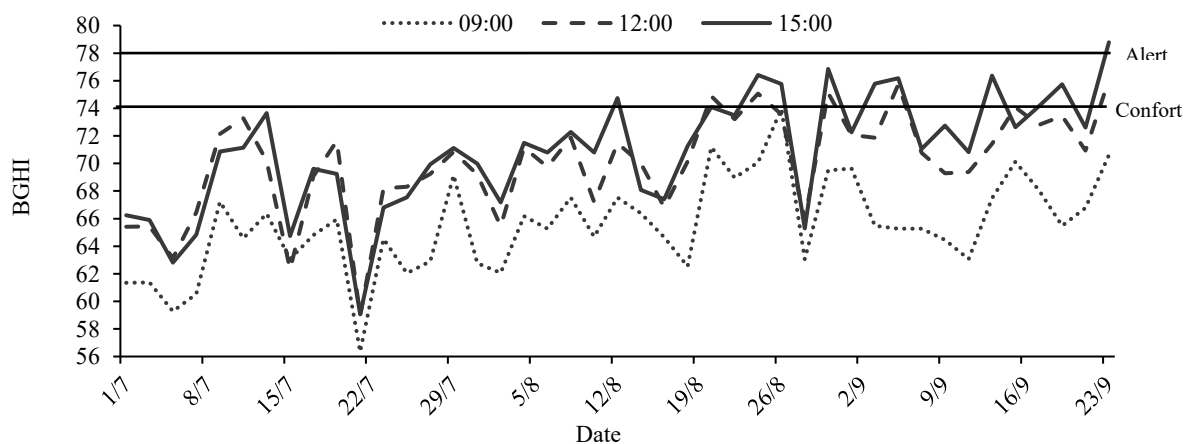


Figure 5. Hourly behavior of the black globe humidity index (BGHI) in a compost-bedded pack barn during the winter of 2023, in Diamantina, Minas Gerais.

The Radiant Thermal Load (RTL) showed average values (Table 1) indicating the highest radiant heat load at Point 1 (mean of $489.18 \text{ W} \cdot \text{m}^{-2}$), confirming that the incident radiation is concentrated with greater intensity in the front area of the compost-bedded pack barn. The overall RTL variation during the study period ranged from $384.41 \text{ W} \cdot \text{m}^{-2}$ to $700.16 \text{ W} \cdot \text{m}^{-2}$, with the highest point value observed at Point 3.

Table 1. Hourly averages and standard deviations of comfort indices in a compost-bedded pack barn during the winter of 2023, in Diamantina, Minas Gerais

Index	Point	Time			Daily average
		09:00 a.m	12:00 p.m	3:00 p.m	
Temperature-humidity index	Point 1	64.23±3.23	67.26±3.26	68.33±3.53	66.60±3.75
	Point 2	63.66±3.46	67.04±3.34	68.23±3.45	66.31±3.91
	Point 3	63.96±3.27	67.12±3.37	68.71±3.33	66.60±3.85
Black globe humidity index	Point 1	66.15±3.57	70.80±3.69	71.13±4.20	69.36±4.43
	Point 2	65.13±3.65	69.81±3.85	70.63±4.33	68.52±4.62
	Point 3	65.28±3.37	69.62±3.85	70.93±4.27	68.61±4.52
Radiant thermal load	Point 1	467.22±43.06	505.73±50.76	494.58±40.52	489.18±47.50
	Point 2	446.79±35.17	485.14±53.61	480.49±42.58	470.81±47.31
	Point 3	442.21±36.53	480.92±41.63	475.99±41.44	466.37±43.22

Figure 6 illustrates that the RTL values throughout the season did not show significant hourly variations, remaining relatively stable across the different times analyzed. It is consistently observed that the lowest RTL values were recorded at 9:00 a.m., which may be related to the typical climatic conditions at this time, with lower incidence of direct solar radiation. In tropical regions, it is desirable to achieve the lowest possible RTL, since radiation represents the main external pathway of heat transfer to the bodies of cattle (Shephard & Maloney, 2023), potentially causing discomfort and heat stress in the animals.

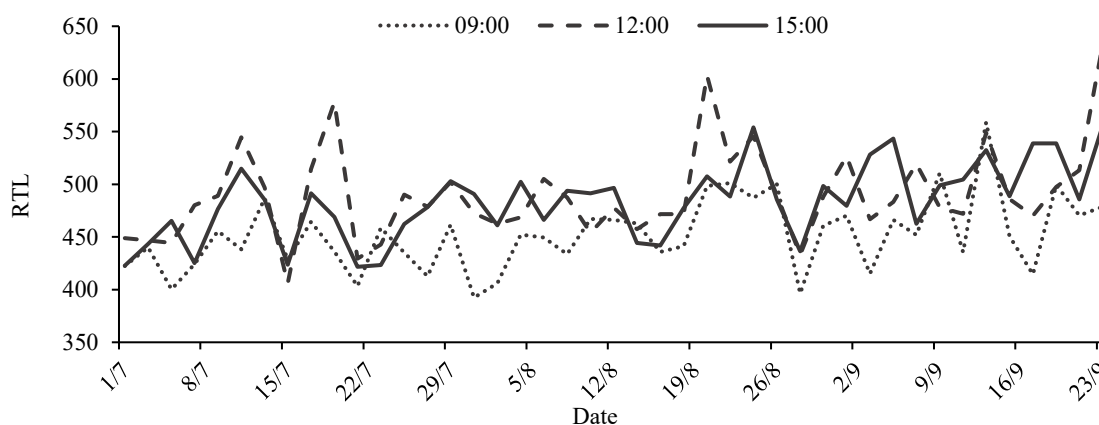


Figure 6. Hourly behavior of radiant thermal load (RTL) in a compost-bedded pack barn during the winter of 2023, in Diamantina, Minas Gerais.

The combined analysis of temperature, humidity, and comfort indices (THI, BGHI, RTL) data at different points within the barn revealed the heterogeneity of the internal thermal environment of the compost-bedded pack barn during winter in a high-altitude region. Although daily averages may suggest comfortable conditions, the occurrence of heat stress peaks and high humidity at specific times and in different barn areas underscores the need for more dynamic and localized management. The limitation imposed by the manual frequency of wind and black globe temperature data collection may have underestimated the actual hourly variability and the occurrence of more acute stress peaks, highlighting the need for continuous monitoring in future studies.

The results of this study, although specific to the winter period and a compost-bedded pack barn in a high-altitude region, provide valuable insights for the design and management of confinement systems in similar climates. Identifying areas and times of greater thermal stress allows optimization of ventilation and cooling systems, as well as animal and bedding management strategies, aiming at the continuous improvement of dairy herd welfare and productivity.

Conclusion

Daily averages of air temperature and thermal comfort indices remained within the thermal comfort zone during the evaluated period. However, critical periods and areas were identified (especially in the center of the barn, and between 10:00 a.m. and 5:00 p.m.) where temperature and relative humidity exceeded ideal ranges, indicating the occurrence of transient heat stress. On the other hand, individual values of the comfort indices at specific times reached “alert” and “danger” levels for thermal stress. This study provides information for improving the design and ventilation strategies aimed at continuously optimizing animal welfare and productivity in compost-bedded pack barns located in high-altitude regions. Future studies should consider continuous monitoring throughout all seasons and the evaluation of physiological and productive responses of the animals.

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