



THERMAL COMFORT IN DAIRY CATTLE UNDER TROPICAL CONDITIONS: INSIGHTS FROM TUPÃ-SP (2020–2025)

AValiação DO CONFORTO TéRMICO EM BOVINOS DE LEITE NA REGIÃO DE TUPÃ/SP PARA OS ANOS 2020 A 2025

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ABSTRACT

Dairy cattle farming is very important for Brazilian agribusiness, being responsible for generating income, jobs, and food production. However, weather conditions can directly affect the productivity and well-being of the animals, especially in regions with a tropical climate. In this context, the Temperature and Humidity Index (THI) is widely used to assess the thermal comfort of dairy cows and identify situations of heat stress. This study aimed to evaluate the thermal comfort conditions of dairy cows in the Tupã-SP region from 2020 to 2025 by analyzing meteorological data on temperature and relative humidity. The data were obtained from the National Institute of Meteorology (INMET) and used to calculate the THI, allowing the classification of environmental conditions into thermal comfort, alert, danger, and emergency. The results showed that there were climatic variations over the years analyzed; 2022 showed the most favorable conditions for thermal comfort, while the other years remained mostly in the alert range, with periods of moderate and severe stress. Times of day and seasons with a higher frequency of thermal discomfort were also identified, especially during summer, autumn, and spring. It is concluded that continuous monitoring of weather conditions is essential for adopting management strategies that minimize the effects of thermal stress, promoting animal well-being, productivity, and the sustainability of dairy farming.

Keywords: Dairy cattle; Thermal comfort; Heat stress; THI; Animal environment; Tupã-SP.

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RESUMO

A bovinocultura leiteira possui grande importância para o agronegócio brasileiro, sendo responsável pela geração de renda, empregos e produção de alimentos. Entretanto, as condições climáticas podem influenciar diretamente o desempenho produtivo e o bem-estar dos animais, principalmente em regiões de clima tropical. Nesse contexto, o Índice de Temperatura e Umidade (ITU) é amplamente utilizado para avaliar o conforto térmico de bovinos leiteiros e identificar situações de estresse térmico. O presente estudo teve como objetivo avaliar as condições de conforto térmico de bovinos de leite na região de Tupã-SP, no período de 2020 a 2025, por meio da análise de dados meteorológicos de temperatura e umidade relativa do ar. Os dados foram obtidos junto ao Instituto Nacional de Meteorologia (INMET) e utilizados para o cálculo do ITU, permitindo a classificação das condições ambientais em conforto térmico, alerta, perigo e emergência. Os resultados demonstraram que houve variações climáticas ao longo dos anos analisados, sendo que 2022 apresentou as condições mais favoráveis ao conforto térmico, enquanto os demais anos permaneceram predominantemente na faixa de alerta, com ocorrência de períodos de estresse moderado e severo. Também foram identificados horários e estações do ano com maior frequência de desconforto térmico, principalmente durante o verão, outono e primavera. Conclui-se que o monitoramento contínuo das condições climáticas é fundamental para a adoção de estratégias de manejo que minimizem os efeitos do estresse térmico, promovendo o bem-estar animal, a produtividade e a sustentabilidade da atividade leiteira.

Palavras-chave: Bovinocultura leiteira; Conforto térmico; Estresse térmico; ITU; Ambiência animal; Tupã-SP.

INTRODUCTION

Dairy farming occupies a strategic position in Brazilian agribusiness, contributing to job creation, income generation, and food supply. Brazil has one of the largest cattle herds in the world and is among the leading global milk producers, playing a central role in the national economy. In addition to the production of milk and dairy products, the activity drives sectors such as transportation, animal nutrition, veterinary medicines, and agricultural equipment.

Among the factors that influence the productive performance of cattle, environmental conditions are crucial. Temperature, relative humidity, and solar radiation directly affect thermal comfort, reflecting on the health, behavior, and productivity of the animals. Thermal comfort is characterized by the ability to maintain a balance between heat production and dissipation without compromising physiological functions (Silva, 2008). In tropical regions, such as Tupã-SP, the combination of high temperatures and high humidity favors thermal





stress, which reduces feed intake, compromises milk production, and reproductive efficiency (West, 2003; Kadzere et al., 2002).

The Girolando breed, predominant in the region, combines the hardiness of the Gir breed with the high productivity of the Holstein breed, being adapted to tropical systems. However, even hardy animals can suffer negative impacts during periods of higher thermal intensity. To assess these effects, bioclimatic indices have been widely used. The Temperature and Humidity Index (THI), proposed by Thom (1959), relates ambient temperature and relative humidity, allowing the estimation of levels of thermal stress. Its application helps in identifying risk situations and in adopting management strategies (Buffington et al., 1981).

Given the growing concern about climate change and its impacts on animal production, it is essential to understand the dynamics of meteorological variables and their influence on the well-being of cattle. In this context, this study aimed to evaluate the thermal comfort of dairy cattle in the Tupã-SP region, between 2020 and 2025, using the THI as an analysis tool. The investigation sought to identify critical periods of heat stress and provide support for management strategies that promote well-being, productivity, and sustainability in dairy farming.

General Objective

To evaluate the thermal comfort of dairy cattle in the Tupã-SP region, between 2020 and 2025, through the analysis of meteorological data on temperature and relative humidity, using the Temperature-Humidity Index (THI) to identify environmental conditions that impact the well-being and productivity of the animals.

Specific Objectives

- To collect and organize temperature and relative humidity data from the Tupã-SP region from 2020 to 2025.
- To calculate the values of the Temperature-Humidity Index (THI) throughout the study period.
- To classify the days of thermal comfort (comfort, alert, danger, and emergency).

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- To analyze the frequency and distribution of the different categories of thermal comfort.
- To identify critical periods of thermal stress and relate them to possible impacts on milk production.
- To propose management strategies (shading, ventilation, and nutritional adjustments) to mitigate the effects of thermal stress.

LITERATURE REVIEW

Importance of cattle farming in Brazil

Cattle farming occupies a strategic position in Brazilian agribusiness, being responsible for a large part of meat and milk production, in addition to generating millions of direct and indirect jobs. Brazil has one of the largest cattle herds in the world and leads in meat exports, serving more than 150 countries. This activity contributes significantly to the agribusiness GDP and drives production chains linked to transportation, animal nutrition, veterinary medicines, and agricultural equipment, as well as supplying inputs such as leather, tallow, and collagen to different industries (textile, pharmaceutical, cosmetic, and food).

Thermal comfort in dairy cattle

Thermal comfort is defined as the condition in which the animal maintains a balance between heat production and dissipation without physiological or productive impairment (Silva, 2008). In tropical regions, hot and humid summers favor thermal stress, compromising the homeostasis of animals and reducing their productive efficiency (West, 2003). This imbalance results in metabolic and behavioral changes, as well as a higher incidence of diseases such as mastitis and reduced immunity (Rodrigues et al., 2011).

Evaluation Indices



The Temperature-Humidity Index (THI), proposed by Thom (1959), is widely used to estimate heat stress in cattle, relating ambient temperature and relative humidity. However, because it does not consider solar radiation, it may underestimate discomfort in tropical regions. In this context, the Black Globe Humidity Index (BGHI) emerges as a more accurate alternative, incorporating radiant heat load (Buffington et al., 1981). Recent studies recommend the combined use of indices for greater reliability in microclimate assessment (Martins et al., 2019).

Physiological and Productive Impacts

Heat stress causes an increase in respiratory rate, rectal temperature, and sweating, mechanisms aimed at dissipating heat, but which increase energy expenditure and reduce metabolic efficiency (Rodrigues et al., 2011). In dairy cows, production can drop by up to 20% under severe conditions (Nääs et al., 2010). In addition, there are reproductive losses, such as a reduction in conception rate and an increase in embryonic mortality (West, 2003). These effects highlight the need for management strategies adapted to local conditions.

Management Strategies

Practices such as natural (trees) or artificial (coverings) shading reduce radiant heat load and improve animal comfort (Ferreira, 2015). Ventilation and evaporative cooling systems, such as sprinklers and misting, are also effective in hot climates. In the nutritional field, adjustments to the diet, such as the inclusion of additives and increased energy density, help to compensate for lower dry matter intake (Santos & Prata, 2017). Emerging technologies, such as thermal monitoring sensors, allow for real-time monitoring and more precise decision-making.

Regional Studies and the Context of Tupã-SP

Research conducted in the interior of São Paulo state indicates that cows in pasture-based systems suffer greater heat stress during the summer, especially in areas with high solar





radiation (Martins et al., 2019). The Tupã region, with its tropical climate and hot, humid summers, presents favorable conditions for the occurrence of thermal discomfort. Regional analysis is essential to adapt management recommendations to local specificities, providing support for more effective and sustainable strategies.

Relationship with the Sustainable Development Goals (SDGs)

Practices to mitigate heat stress contribute to greater productive efficiency and sustainability of dairy farming, aligning with SDG 2 (Zero Hunger and Sustainable Agriculture) and SDG 3 (Good Health and Well-being) (UN, 2015). Furthermore, proper management optimizes resources and reduces environmental impacts, aligning with SDG 12 (Responsible Consumption and Production). By adapting livestock farming to local climatic conditions, the study strengthens the resilience of production systems, in line with SDG 13 (Climate Action).

MATERIALS AND METHODS

Study Area

The study was conducted in the Tupã region, in the interior of the state of São Paulo, characterized by a tropical climate, with hot, rainy summers and drier, milder winters. This climatic variability directly influences the thermal comfort of dairy cattle, predominantly herds of the Girolando breed, recognized for its combination of hardiness and high productivity.

Literature Review

The theoretical framework was constructed from consultations in scientific databases (Google Scholar, SciELO, ResearchGate), as well as publications from the Brazilian Agricultural Research Corporation (EMBRAPA) and INMET itself. Studies related to animal





environment, dairy cattle farming, and bioclimatology were prioritized, focusing on tropical regions.

Meteorological Data Collection

Meteorological data on dry-bulb temperature (air temperature) in degrees Celsius (°C) and dew point temperature in degrees Celsius (°C) were obtained from the National Institute of Meteorology (INMET), covering the period from January 2020 to December 2025. Information on dry-bulb temperature and dew point temperature was collected, essential variables for determining the Temperature-Humidity Index (THI). The records were organized in spreadsheets, allowing separation by year, month, season, and time.

Calculation of the Temperature-Humidity Index (THI)

The THI was calculated from the values of air temperature and relative humidity, according to the methodology proposed by Thom (1959). The THI is a widely used indicator in applied climatology and animal welfare studies, as it integrates the effects of air temperature and relative humidity into a single measure. The indicator was calculated using Equation 1:

$$ITU = tbs + 0,36 Tpo + 41,5 \quad \text{Eq.1}$$

Where:

tbs = dry-bulb temperature (air temperature) in degrees Celsius (°C)

Tpo = dew point temperature in degrees Celsius (°C)

The results were classified into four categories of thermal comfort for dairy cattle:

THI ≤ 68: Thermal comfort;

THI 69–72: Alert (mild stress);





THI 73–79: Danger (moderate stress);

THI ≥ 80 : Emergency (severe stress).

This classification allowed for the identification of periods in which the animals were subjected to different levels of thermal discomfort.

Data Analysis

Monthly, maximum, minimum, and annual averages of the THI (Thermal Discomfort Index) were calculated for each year of the study period. The results were organized into tables and graphs, allowing for comparisons between years and the identification of climatic trends. The analysis also considered the temporal distribution of thermal stress events throughout the four seasons, highlighting critical times of occurrence.

RESULTS

Analysis of the Temperature and Humidity Index (THI) between 2020 and 2025 revealed significant variations in the thermal comfort conditions of dairy cattle in the Tupã-SP region. In all years, periods classified in the alert, danger, and emergency categories were observed, confirming the influence of tropical climatic conditions on animal welfare.

Comparison between years

The comparative analysis between 2020 and 2025 revealed a predominance of the alert range, indicating that cattle remained under mild stress for most of the period. Only 2022 presented more favorable conditions, with a greater number of months in thermal comfort, which reinforces the influence of punctual climatic variations on animal welfare. This pattern confirms that, even in years considered moderate, critical episodes of thermal stress occurred, highlighting the need for continuous management.





The results from Tupã-SP align with studies carried out in other tropical regions, such as those by Martins et al. (2019), who also observed a predominance of alert conditions in pasture systems. However, records of prolonged peaks in 2025 suggest that the intensity of discomfort may be more severe locally, amplifying the adaptation challenges. This comparison demonstrates that the analysis of annual averages alone is insufficient to characterize productive risk, and it is essential to consider intra-annual variability and daily peaks.

2020 and 2021: Predominance of the alert range, with annual average THI close to 70. Although they did not present monthly averages in emergence, there were daily peaks above 85, indicating severe risk in certain periods.

2022: Most favorable year, with seven months classified as thermally comfortable and an annual average of 67.1. Despite this, there were occasional records of moderate and severe stress, especially in summer and spring.

2023 and 2024: Intermediate conditions, with annual averages around 69.5 and 70.3, respectively. Both years presented isolated episodes of severe stress, reinforcing the need for continuous management.

2025: Showed a greater range of critical hours, with records of heat stress between 4 am and 8 pm during the summer. The annual average (70.3) remained in the alert range, but the long periods of discomfort indicate a greater challenge for management.

The comparative analysis between the years revealed a predominance of the alert range, with the exception of 2022, which presented a greater number of months with thermal comfort. Table 1 summarizes the annual averages of the THI, highlighting the variation between the years and emphasizing the most critical periods. Based on these data, it was observed that among these six years, only 2022 presented thermal comfort.





Table 1: Annual averages of the Temperature and Humidity Index (THI) in the Tupã-SP region, between 2020 and 2025.

YEAR	ANNUAL AVERAGE (THI)	CONDITION
2020	70,76	Alert (Mild Stress)
2021	69,05	Alert (Mild Stress)
2022	67,17	Thermal Comfort
2023	69,52	Alert (Mild Stress)
2024	70,32	Alert (Mild Stress)
2025	69,10	Alert (Mild Stress)

Source: Authors, 2026.

The alert range predominated in all years, except for 2022, which presented average values compatible with thermal comfort. The horizontal lines indicate the limits of the classification categories: ≤ 68 (comfort), 69–72 (alert), 73–79 (danger), and ≥ 80 (emergency).

Seasonal patterns and critical times

Seasonal analysis demonstrated that summer, autumn, and spring concentrated the highest levels of thermal stress, while winter presented conditions closer to the comfort zone. This pattern confirms the vulnerability of cattle during periods of higher radiation and humidity, reinforcing that the risk is not limited to summer. The critical times, between 10 am and 8 pm, show that the animals remain in discomfort for long periods daily, amplifying the impacts on feed intake and production.

These results align with studies conducted in tropical regions, such as those by Martins et al. (2019), who identified a higher incidence of heat stress in pasture systems during the summer, and Rodrigues et al. (2011), who reported significant physiological changes in dairy cows subjected to high temperatures. However, the prolonged records of discomfort in Tupã-SP, especially in the summer of 2025, suggest that the local intensity may be higher than that observed in other contexts, requiring more rigorous management





strategies. The integrated interpretation of the data reinforces the idea that seasonal and hourly analysis is essential to understand production risks, since annual averages can mask critical situations. Detailing the periods of greatest vulnerability provides support to guide shading, ventilation, and nutritional adjustment practices with more precision and effectiveness.

Table 2 presents the seasonal THI averages between the years 2020 and 2025. It can be observed that summer, autumn, and spring presented higher average values, indicating a greater risk of heat stress, while winter maintained conditions close to the comfort zone. The colors in the horizontal lines represent the limits of the thermal comfort categories: ≤ 68 (comfort-green), 69–72 (alert-yellow), 73–79 (danger-light blue), and ≥ 80 (emergency-red). It is observed that the situation of THI ≥ 80 (emergency-red) did not appear in the five-year averages. Figure 1 presents the graph with the seasonal distribution of THI, reinforcing the need for specific management strategies for each season. Although the annual averages indicate moderate conditions, the daily peaks revealed moments of severe stress, especially in the summer of 2025.

Table 2: Annual averages of the Temperature and Humidity Index (THI) in the Tupã-SP region, between 2020 and 2025, and the seasonal annual averages.

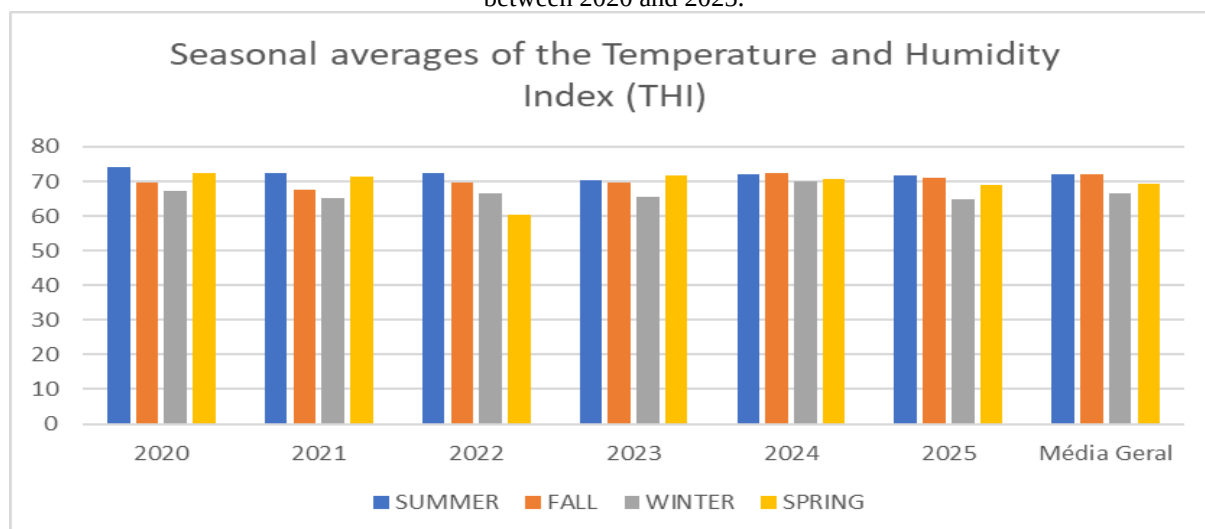
YEAR	SUMMER	FALL	WINTER	SPRING
2020	74,06	69,81	67,30	72,42
2021	72,25	67,54	65,29	71,38
2022	72,35	69,76	66,49	60,44
2023	70,35	69,70	65,55	71,81
2024	72,18	72,35	69,95	70,52
2025	71,61	70,95	64,76	68,83
Overall Average	72,13	72,02	66,56	69,23

Source: Authors, 2026.





Figure 1: Seasonal averages of the Temperature and Humidity Index (THI) in the Tupã-SP region, between 2020 and 2025.



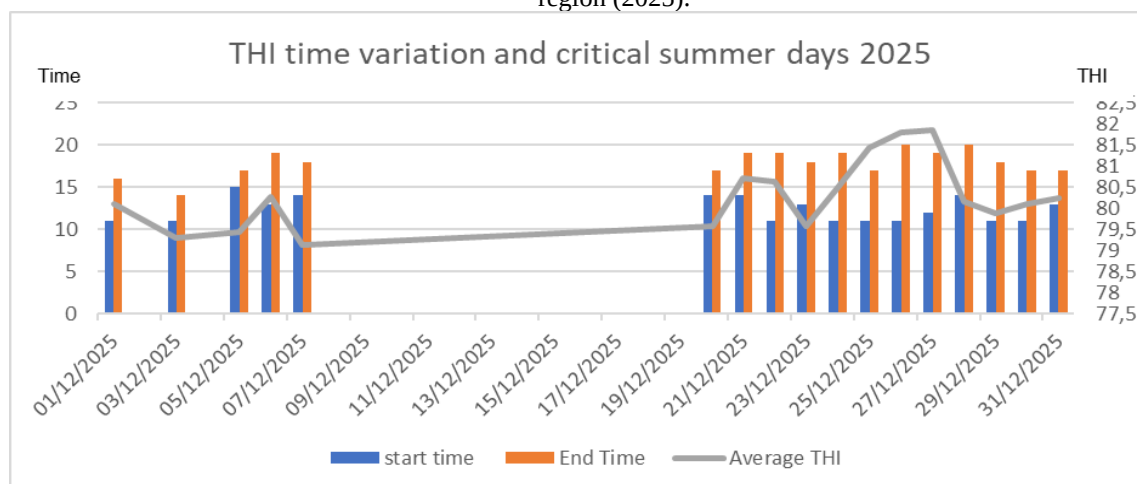
Source: Authors, 2026.

Figure 2 illustrates the hourly variation of the THI on critical days, demonstrating that the animals remained in discomfort for extended periods, which can compromise feed intake and milk production. It can be observed that the values remained above the alert range for much of the day, with peaks exceeding 80 between 12:00 PM and 4:00 PM, characterizing severe heat stress.

The prolonged period of thermal discomfort highlights the direct impact on feed consumption and milk production, reinforcing the need for management strategies such as shading, ventilation, and evaporative cooling.



Figure 2: Hourly variation of the Temperature and Humidity Index (THI) on critical summer days in the Tupã-SP region (2025).



Source: Authors, 2026.

Productive Implications

The results obtained in Tupã-SP confirm that dairy cattle in tropical regions are subject to recurring conditions of thermal discomfort, especially during the summer and spring. This pattern aligns with that observed by Martins et al. (2019) and Rodrigues et al. (2011), who also identified greater vulnerability in pasture-based systems under high temperatures and humidity. However, the prolonged peaks recorded in 2025 suggest that, in the Tupã-SP region, the intensity and duration of thermal stress may be more severe than in other contexts analyzed, increasing the challenges for management.

In addition, national studies such as Nääs et al. (2010) report reductions of up to 20% in milk production under severe thermal stress conditions, which reinforces the practical relevance of the local findings. The occurrence of critical peaks, even in years with apparently favorable annual averages, shows that the analysis of averages alone is not sufficient to assess productive risks. The interpretation of data from Tupã-SP demonstrates that continuous and detailed monitoring is indispensable to anticipate losses and guide mitigation strategies.

Management Strategies

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The results showed that periods of greatest thermal discomfort occurred mainly in summer, autumn, and spring, with emphasis on the prolonged peaks recorded in 2025. Given this scenario, it becomes essential to adopt management practices that act specifically on the critical factors identified:

- Natural or artificial shading, justified by the high radiant heat load observed in the summer and spring months, when the animals remained for long periods under thermal stress.
- Ventilation and evaporative cooling (spraying and misting), recommended for critical times between 10 am and 8 pm, especially as seen in the summer of 2025, when THI values exceeded the danger and emergency range.
- Nutritional adjustments, necessary to compensate for the lower dry matter intake during alert and danger periods, predominant throughout the years analyzed, ensuring maintenance of the diet's energy density.
- Continuous monitoring, using sensors and alert systems, to quickly identify risk situations, is fundamental for anticipating risk situations, since the identified daily peaks demonstrated that annual averages can mask moments of severe stress.

The integration of these practices with the results obtained reinforces that management should be adaptive and directed to the most critical seasonal and hourly conditions, promoting animal welfare and greater productive resilience in the face of climatic variations.

DISCUSSION

The findings of this study corroborate previous research conducted in tropical regions, such as Rodrigues et al. (2011) and Martins et al. (2019), which identified greater vulnerability of cattle in pasture systems during the summer, especially under conditions of high radiation and humidity. The predominance of values in the alert and danger range over the years in Tupã-SP confirms that heat stress is a constant challenge in tropical dairy farming, but the prolonged records of discomfort in 2025 suggest that the local intensity may be higher than that observed in other contexts, increasing production risks.



Compared with national studies, such as Nääs et al. (2010), which report significant reductions in milk production in situations of severe heat stress, the results from Tupã-SP reinforce that even years with apparently moderate annual averages can hide critical peaks capable of compromising productive and reproductive efficiency. This finding highlights the importance of seasonal and hourly analyses, rather than just annual assessments, to fully understand the impacts on animal welfare.

In addition, regional analysis contributes to the formulation of specific management strategies for Tupã-SP, such as shading, ventilation, and nutritional adjustments targeted at the identified critical periods. Such practices not only mitigate the effects of heat stress but also directly address the Sustainable Development Goals (SDGs), especially SDG 2 (Zero Hunger and Sustainable Agriculture), SDG 3 (Good Health and Well-being), and SDG 13 (Climate Action). In this way, the local results strengthen the integration between animal welfare, productivity, and sustainability, offering relevant support for producers and public policymakers.

CONCLUSION

The assessment of the Temperature and Humidity Index (THI) between 2020 and 2025 demonstrated that dairy cattle in the Tupã-SP region were frequently exposed to heat stress conditions, especially during the summer, autumn, and spring seasons. Although 2022 showed a greater predominance of months with thermal comfort, the other years remained mostly in the alert range, confirming that heat stress is a recurring challenge in tropical dairy farming.

The results reinforce that the analysis of annual averages alone is not sufficient to characterize production risks, since the daily peaks revealed prolonged periods of discomfort capable of compromising feed intake, milk production, and reproductive efficiency. This finding highlights the need for continuous and detailed monitoring of meteorological variables, allowing for the anticipation of critical situations and guiding management decisions.





The recommended mitigating measures — such as natural or artificial shading, ventilation and evaporative cooling systems, as well as nutritional adjustments — should be applied in a targeted manner to the most critical periods and times identified. The adoption of these practices contributes not only to reducing the impacts of heat stress, but also to strengthening the sustainability of the activity, in line with the Sustainable Development Goals (SDGs), especially those related to food security, health and climate action.

It is concluded that dairy farming in the Tupã-SP region requires permanent and contextualized adaptive strategies capable of facing the effects of heat stress at different time scales. This study provides relevant subsidies for producers, technicians and researchers, supporting decision-making and promoting more resilient production systems in the face of climate change.

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