JOURNAL OF ANIMAL BEHAVIOUR AND BIOMETEOROLOGY

RESEARCH ARTICLE
Published Online: August 26, 2023
https://doi.org/10.31893/jabb.23027

# Surviving heat: Resilience of Nellore bulls to solar radiation exposure

**Mateus Medeiros dos Santos**[a] | **João Batista Freire Souza-Junior**[a,b] | **Thibério de Souza Castelo**[a] | **João Paulo Araújo Fernandes de Queiroz**[c] | **Leonardo Lelis de Macedo Costa**[a]

[a]ThermoBio - Research Nucleus in Applied Animal Biometeorology, Universidade Federal Rural do SemiÁrido, Mossoró, RN, Brazil.
[b]Department of Animal Science, Universidade Federal do Ceará, Campus do Pici, Fortaleza, CE, Brazil.
[c]Dapartment of Veterinary Medicine, Universidade Federal de Roraima, Boa Vista, RR, Brazil.

**Abstract** We aimed to assess the physiological and biophysical responses of Nellore bulls exposed to solar radiation in semiarid conditions throughout the day. Sixteen Nellore bulls were examined in Tibau city, Northeast Brazil (5°52′ South, 37°20′ West, and 37 m above sea level) over four nonconsecutive days, with data collection taking place at one-hour intervals between 7:00 am and 5:00 pm. Four animals were analyzed each day and kept exposed to the sun for the duration of the study. The average age of the animals was three years, and their average body weight was 650±32 kg. The meteorological station measured air temperature (°C), relative humidity (%), solar radiation ($W.m^{-2}$), and black globe temperatures (°C) every minute, while a digital anemometer thermohygrometer measured wind speed ($m.s^{-1}$) at the same time. Respiratory rate ($breaths.min^{-1}$), expired air temperature (°C), rectal temperature (°C), and body surface temperature (°C) were measured as physiological variables. Biophysical equations were used to estimate the sensible and latent heat transfer mechanisms ($W.m^{-2}$). The air temperature ranged from 28.5 to 32.5°C, and direct solar radiation was between 21 and 891 $W.m-^{2}$. Between 11:00 am and 1:00 pm, the study observed heat gain through longwave radiation, which reached an average of 250 $W.m^{-2}$, with a significant increase ($P < 0.05$) in respiratory rate and body surface temperature during this time. Convection was significant in heat dissipation, particularly when the wind speed was increased from 11:00 am. However, latent heat loss mechanisms were more effective in losing excess body heat under total sun exposure, despite the positive effect of convection. The study findings showed that Nellore bulls maintained their body temperature within a narrow range even when exposed to high solar radiation, thus demonstrating the efficiency of physiological and biophysical mechanisms during times of greater thermal challenge.

**Keywords:** biophysical mechanisms, livestock, physiological responses, thermal challenge, thermoregulation

## 1. Introduction

Livestock worldwide must prepare for the climate changes predicted for the coming decades, which include significant shifts in the annual distribution and volume of rainfall, as well as an increase in land surface temperature by 0.4 to 2.6°C until 2065 (IPCC, 2014; Giannini et al 2017; Samand et al 2020). These changes may negatively impact animal husbandry and production systems due to meteorological variables such as solar radiation, high temperature, wind, and humidity (Mandal et al 2023; Musa et al 2023).

These stressors can lead to physiological imbalances in farm animals (Mylostyva et al 2022), which harm reproduction (Mylostyvyi and Izhboldina, 2021; Đuričić et al 2022), animal health, and nutrient intake (McManus et al 2022), making it challenging for farmers to improve productivity (Das et al 2016; Samand et al 2020). However, Zebu cattle possess several morphophysiological characteristics that make them resistant to extreme thermal challenges, such as light coat color, pigmented epidermis, and well-settled hair (McManus et al 2011). Additionally, they have a high number and activity of sweat glands (Nascimento et al 2019) and a smaller surface area relative to their large body mass (Silva 2000), which contribute to their resilient capacity to tolerate heat without compromising productivity (Costa et al 2015; Sailo et al 2017; Madhusoodan et al 2019; Lima et al 2020).

Despite their inherent resilience, direct solar radiation can still compromise Nellore cattle's thermal balance when raised in pasture systems. Under these conditions, cutaneous evaporation is the most efficient mechanism for maintaining normal physiology at high air temperatures (Costa et al 2018b). However, when exposed to solar radiation throughout the day, sensible heat exchanges become compromised, and animals must use metabolic energy to dissipate excess heat through cutaneous and respiratory evaporation (Costa et al 2018a).

Although zebu cattle's physiological and biophysical responses under shading conditions are well established (Camerro et al 2016; Costa et al 2018a; Costa et al 2018b), little is known about how they respond to the environment when exposed to solar radiation throughout the day. As maintaining normal physiology within narrow limits is crucial for animal survival in adverse environmental conditions, our aim was to evaluate the physiological and biophysical


Received: May 25, 2022 | Accepted: August, 2023

responses of Nellore bulls exposed to solar radiation throughout the day in semiarid climate conditions.

## 2. Material and Methods

### *2.1. Study location and animal management*

The experiment was carried out with sixteen Nellore bulls kept in the environmental conditions of Tibau, RN, Brazil (5°52′ South, 37°20′ West, and 37 m above sea level), an equatorial semiarid region. The animals had an average age of three years and a body weight of 650±32 kg. Data collection was performed during four nonconsecutive days, starting at 7:00 am and ending at 5:00 pm, at one-hour intervals. On each collection day, four animals were kept in an unshaded paddock. All the bulls underwent examination, and no indicators of any diseases were observed among them throughout the study. The bulls were given a specific diet based on age and physiological stage (Supplementary Material I). Feeding took place once a day, and water was provided *ad libitum*.

### *2.2. Meteorological variables*

The air temperature ($T_A$, °C), relative humidity ($R_H$, %), and solar radiation ($R_S$, W.m$^{-2}$) were continuously monitored at regular one-minute intervals using a copper-constant thermosensor connected to a data logger (model CR1000, Campbell Scientific) installed near the paddock. Wind speed ($U$, m/s) was measured with a digital thermohygro anemometer (model THAL 300, Instrutherm). Two black globes (copper hollow spheres 0.15 m in diameter painted matte black) were installed 1.5 m above the ground, with stem thermometers (model ST-9215) inserted into them. One globe was placed in the sun and the other in the shade. Black globe temperatures were used to calculate the mean radiant temperature ($M_{RT}$, °C) using the equation by Da Silva et al. (2010), which was then used to estimate the radiant heat load ($R_{HL}$, W.m$^{-2}$) according to the equation proposed by Da Silva and Maia (2013).

### *2.3. Physiological variables*

Respiratory rate ($R_R$, breaths.min$^{-1}$) was measured by observing the animal's flank movements for one minute. Expired air temperature ($T_{EXP}$, °C) was measured using a K-type thermosensor connected to a digital thermometer (model TH-060, Instrutherm). The thermosensor was fixed inside a facial device developed to facilitate $T_{EXP}$ measurement. This facial device consisted of a plastic tube measuring 12.5×10.5 cm (length × diameter) with a rectal palpation glove fixed to one of its openings (see Supplementary Material II). The palpation glove allowed for air displacement to be noticed during the animal's expiration. Rectal temperature ($T_R$, °C) was measured using a clinical mercury thermometer inserted approximately 10 cm into the animal's rectum. Body surface temperature ($T_S$, °C) was measured in three different body regions (flank, hindquarters, and neck) using a precision infrared thermometer (model 576, Fluke Corporation), and the arithmetic mean was obtained.

### *2.4. Biophysical mechanisms*

#### *2.4.1. Sensible mechanisms*

Based on the Stefan-Boltzmann law, the heat exchange by longwave radiation ($H_R$, W.m$^{-2}$) between the animals' body surface and the environment was calculated using the equation (Da Silva and Maia 2013):

$$\mathrm{H_R} = \mathcal{E}_{\mathrm{S}}\delta\,(T_{\mathrm{S}}^4 - M_{RT}^4),\quad W.m^{-2} \tag{1}$$

where σ = 5.67051×10$^{-8}$ W.m$^{-2}$.K$^{-4}$ is the Stefan-Boltzmann constant, $M_{RT}$ is the mean radiant temperature (°C), $T_S$ is the body surface temperature of the bulls (°C), and $\varepsilon_S$ is the emissivity of biological tissues (0.98).

Based on Newton's Law of Cooling, heat exchange by convection ($H_C$, W.m$^{-2}$) from the body surface to the air was determined by the equation (Da Silva and Maia, 2013):

$$\mathrm{H_C} = \rho c_P (T_S - T_A)\, r_H^{-1},\ \ W.m^{-2} \tag{2}$$

where ρ is the air density (g.m$^{-3}$), cp is the specific heat of air (J.g$^{-1}$.°C$^{-1}$), $T_S$ is the body surface temperature (°C), $T_A$ is the air temperature (°C), and $r_H$ is the boundary layer resistance to convective heat transfer.

$$r_H = \rho c_P d\,(kNu)^{-1} \tag{3}$$

where d is the dimension of the body region (m), K is the thermal conductivity of the air at temperature $T_A$ (W.m$^{-2}$.°C$^{-1}$), and $N_U$ is the Nusselt number.

#### *2.4.2. Evaporative mechanisms*

A 7 cm diameter ventilated capsule coupled to a $CO_2$/$H_2O$ analyzer (Model Li-7000, LI-COR, Nebraska, USA) was used to determine cutaneous evaporation (EC, W.m-²). This analyzer was connected to a computer that provided measurements of atmospheric pressure ($P_{ATM}$, kPa), partial pressure of air vapor ($P_{AIR}$, kPa), and partial pressure of air vapor passing through the capsule ($P_{CAP}$, kPa). To standardize estimates of water loss through the skin, the airflow from the ventilated capsule was kept constant at 1.8 L min-¹, making the $T_S$ inside and outside the capsule equal (Maia et al 2005b). Three distinct body regions (hindquarters, flank, and neck) were evaluated. The values for $E_C$ were obtained through the equation:

$$\mathrm{E_C} = A^{-1}\lambda\Phi(\Psi_S - \Psi_A) \tag{4}$$

where A$^{-1}$ represents the skin surface area under the capsule (m²), λ is the latent heat of water vaporization (J g$^{-1}$), Φ is the airflow rate through the capsule (m³.s$^{-1}$), and ΨS and ΨA are the absolute humidity of the air at the capsule outlet and in the atmosphere, respectively (g.m$^{-3}$) (Maia et al 2005a). Respiratory evaporation ($E_R$, W.m$^{-2}$) was estimated by the equation proposed by Maia et al. (2005a):

$$E_R = \lambda\,\dot{\mathrm{m}}\,\rho^{-1}\,(\Psi_{EXP} - \Psi_A) \tag{5}$$

where ρ is the density of air (g.m$^{-3}$), λ is the latent heat of vaporization (J.g$^{-1}$), ṁ is the mass flow rate (kg$^{-1}$), $\Psi_{EXP}$ is the absolute humidity of the expired air (g.m$^{-3}$), and $\Psi_A$ is the absolute humidity of the atmosphere (g.m$^{-3}$).

*2.6. Statistical analysis*

Physiological and biophysical responses were assessed using repeated measures analysis of variance (ANOVA) with the mixed models procedure (PROC MIXED) in the Statistical Analysis System (SAS version 8.0, SAS Institute Inc., Cary, NC, USA). In this analysis, the animal was included as a random effect in the model, and the time of day was included as a fixed effect. Tukey's test was used for multiple comparisons to verify differences between means ($P < 0.05$) after observing significant differences using ANOVA F test ($P < 0.05$). Boxplot-type graphs were used to demonstrate the obtained data.

**3. Results**

*3.1. Environmental variables*

The meteorological conditions during the study are shown in Figure 1. $U$ ranged from 1.0 to 5.0 m s-1, and $R_{H\ ranged}$ from 52 to 68%. The TA ranged from 28.5 to 32.5°C, with the highest values between 10:00 and 13:00. $M_{RT}$ during the daytime ranged from 58 to 71°C, with high values between 10:00 and 13:00. $S_R$ also followed the same behavior due to the intense direct solar radiation in the geographical region of the study, ranging from 21 to 891 W.m$^{-2}$.

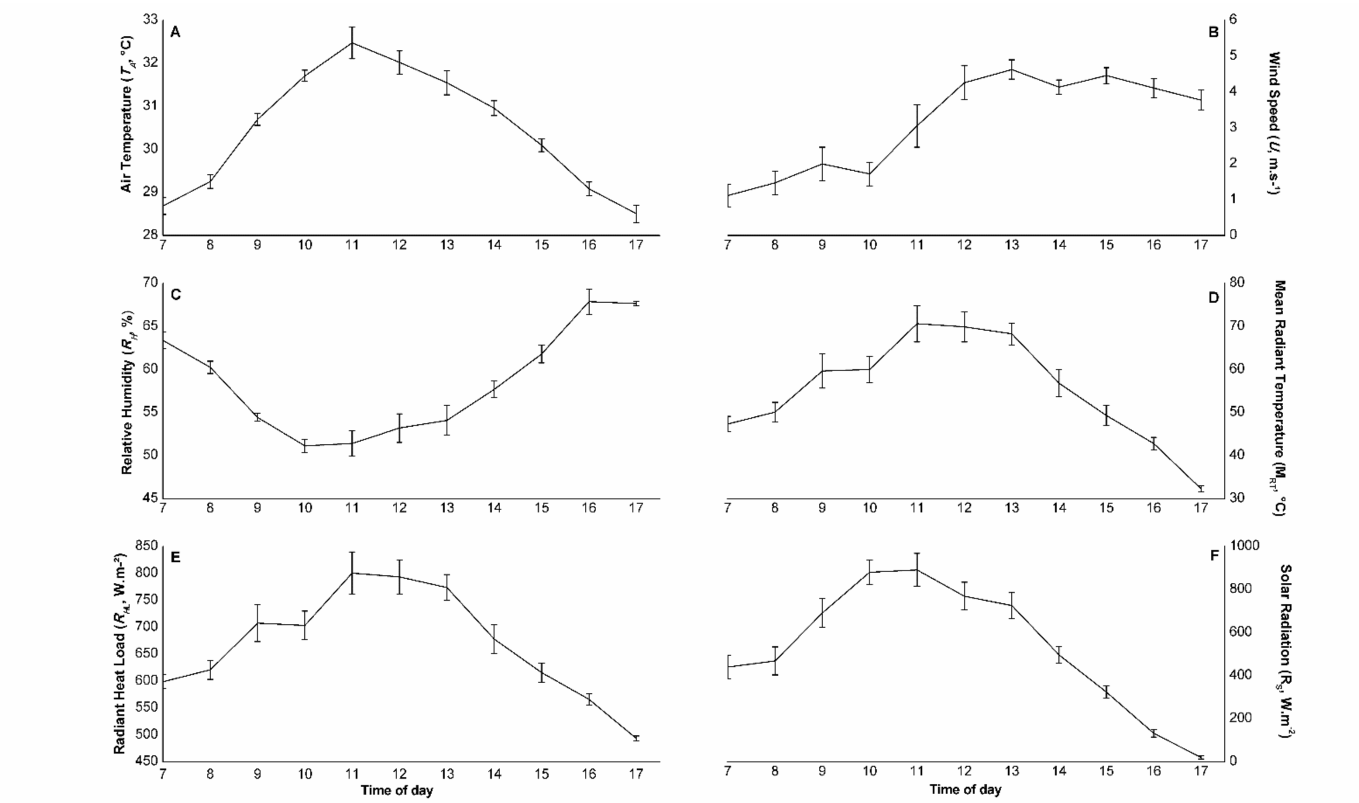


**Figure 1** Environmental variables throughout the day: air temperature (A), wind speed (B), relative humidity (C), mean radiant temperature (D), radiant heat load (E), and direct solar radiation (F).

*3.3. Physiological responses*

Figure 2 shows that there was no significant variation in $T_R$ during the diurnal period ($P > 0.05$), remaining close to 38.5°C. However, an amplitude of approximately 2.5°C in the $T_R$ of the observed animals was observed between 7:00 and 8:00 (37.6 to 39.8°C). This amplitude decreased during the daytime period.

The respiratory rate ($R_R$) varied significantly ($P < 0.05$) throughout the day. In the early morning, the average $R_R$ was 29.82 breaths.min$^{-1}$, reaching 36 breaths.min$^{-1}$ (range from 25 to 56 breaths.min$^{-1}$) between 11:00-13:00 (Figure 3), which was the most thermally stressful period of the day for the animals. There was a significant difference in the body surface temperature ($T_S$) between the times of the day ($P < 0.05$). This physiological variable followed the variation observed in the ambient temperature ($T_A$). The bulls showed an average $T_S$ of 35.5°C in the early morning and 37.8°C at 11:00-13:00, the highest average value recorded (Figure 4).

*3.4. Sensible mechanisms*

The average values of $H_R$ (Figure 5) differed significantly between observation times ($P < 0.05$). Furthermore, the negative means indicate that this mechanism acted as a heat gain pathway, especially during the 11:00-13:00 period (average $H_R$ of -250 W.m$^{-2}$). Unlike $H_R$, $H_C$ behaved as a heat loss mechanism throughout the observation period (Figure 6). The average $H_C$ was significantly lower ($P < 0.05$) in the morning, at 36 and 40 W.m$^{-2}$ during the 7:00-8:00 and 9:00-10:00 periods, respectively. A large variation in $H_C$ (8 to 120 W.m$^{-2}$) was observed during 11:00-13:00, which was not seen during other times. During 14:00-15:00, $H_C$ reached its maximum average of 78 W.m$^{-2}$, which did not differ significantly from the averages recorded during the 11:00-13:00 and 16:00-17:00 periods.

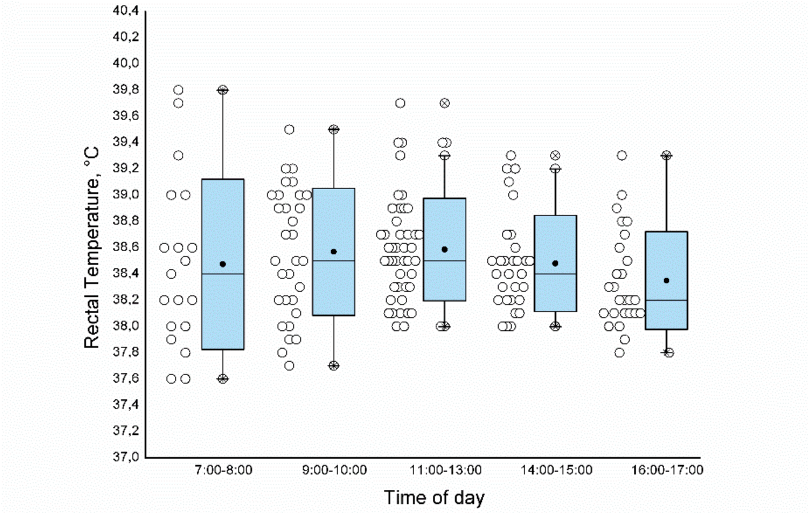


**Figure 2** Rectal temperature (°C) of Nellore bulls throughout the day. (●) Indicate the averages in each hour. (○) indicates all observed data. (ʘ) indicate the outliers.

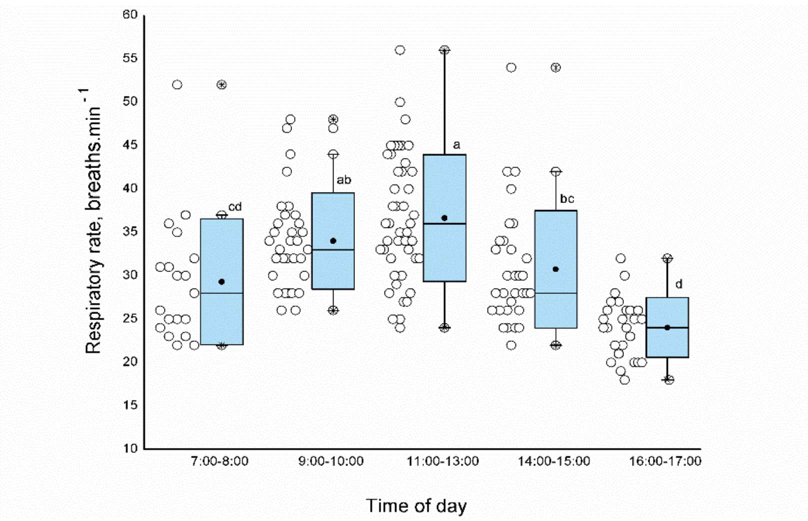


**Figure 3** Respiratory rate (resp.min-$^{1}$) of Nellore bulls throughout the day. (●) Indicate the averages in each hour. (○) indicates all observed data. (ʘ) indicate the outliers. Different letters indicate significant differences between hours (Tukey test; $P < 0.05$).

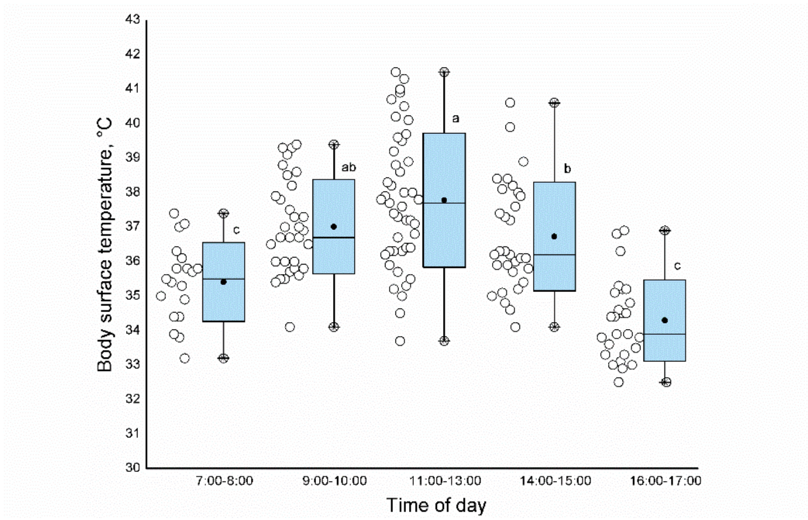


**Figure 4** Body surface temperature (°C) of Nellore bulls throughout the day. (●) Indicate the averages in each hour. (○) indicates all observed data. Different letters indicate significant differences between hours (Tukey test; $P < 0.05$).

*3.4. Evaporative mechanisms*

A significant daily variation was observed for $E_C$ and $E_R$ (Figures 7 and 8; $P < 0.05$), with the highest average values observed during 11:00-13:00 (67 and 42 W.m$^{-2}$, respectively). $E_C$ and $E_R$ were responsible for 59.45 and 40.55% of the total evaporative heat loss in Nellore bulls exposed to the sun.

**4. Discussion**

The climate changes predicted for the coming years are related to rainfall and temperature changes, causing an increase in the planet's surface temperature between 0.4°C and 2.6°C by 2065 (IPCC 2014; Gianinni et al 2017). These environmental variations can have negative effects on the production, reproduction, and health of cattle (Matsoukis et al 2022; Assatbayeva et al 2022; Chawicha and Mummed 2022), leading to a drop in the productivity of meat production systems and becoming a concern for world food production (Rojas-Downing et al 2016; Rojas-Downing et al 2017; Samand et al 2020; Habib et al 2021). For an adult *Bos indicus* cattle to maintain its minimum metabolic rate, the air temperature must be between 10 and 27°C (Hafez 1973; Mount 1979; Curtis 1983). However, the air temperature during the daytime under the present study conditions was outside the thermal comfort range for *Bos indicus* adult cattle recommended by Hafez (1973), Mount (1979), and Curtis (1983). This thermal challenge led Nellore cattle to activate physiological mechanisms to dissipate excess body heat.

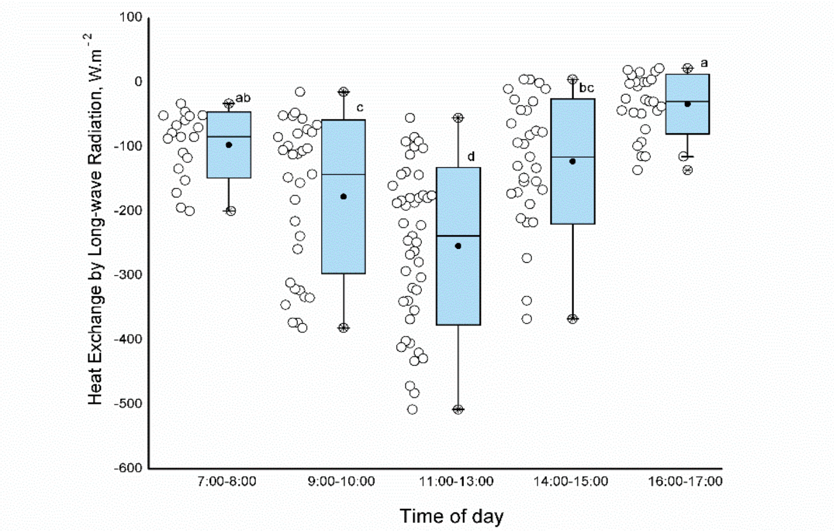


**Figure 5** Heat exchange by longwave radiation (W.m$^{-2}$) in Nellore bulls throughout the day. (●) Indicate the averages in each hour. (○) indicates all observed data. (Θ) indicate the outliers. Different letters indicate significant differences between hours (Tukey test; $P < 0.05$).

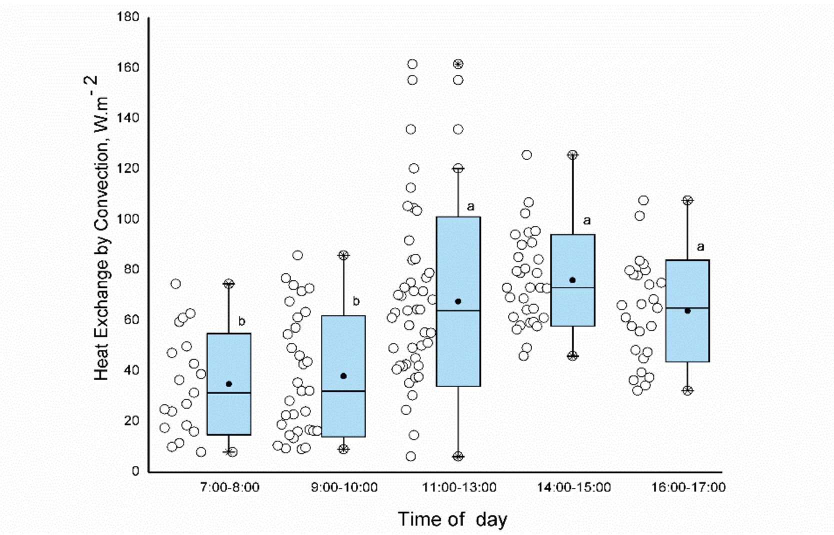


**Figure 6** Heat exchange by convection (W.m$^{-2}$) of Nellore bulls throughout the day. (●) Indicate the averages in each hour. (○) indicates all observed data. (Θ) indicate the outliers. Different letters indicate significant differences between hours (Tukey test; $P < 0.05$).

According to Collier and Gebremedhin (2015), in environments with high air temperatures and high levels of direct solar radiation, the sensible heat loss mechanisms - radiation, convection, and conduction - can become heat gain pathways. These mechanisms depend on a temperature gradient between the animal and the environment. In this study, during the hottest times (between 11:00 and 13:00), the surface temperature ($T_S$) and mean radiant temperature ($M_{RT}$) were recorded at 38 and 70°C, respectively. This thermal gradient between the $T_S$ and $M_{RT}$ made it impossible to lose sensible heat by longwave radiation and turned this mechanism into a heat gain pathway. We observed that at all times of the day, there was heat gain by radiation, with an average gain of 250 W.m-² between 11:00 and 13:00. It is important to highlight a significant dispersion of the $H_R$ data at each time of day; some animals gained more heat by longwave radiation than others within the same time frame. The presence of clouds can explain this variation during data collection, reducing the direct solar radiation that reaches the animals' body surface (Silva and Maia 2013). In studies by Costa et al (2018b) with Nellore cattle in an environment protected from direct solar radiation, the heat exchange by longwave radiation showed positive values throughout the circadian evaluation, with an average of 40 W.m-² between 10:00 and 14:00. This sensible heat loss was possibly favored by the positive thermal gradient between $T_S$ and $M_{RT}$, as the $T_S$ was higher than the $M_{RT}$ inside the facilities.

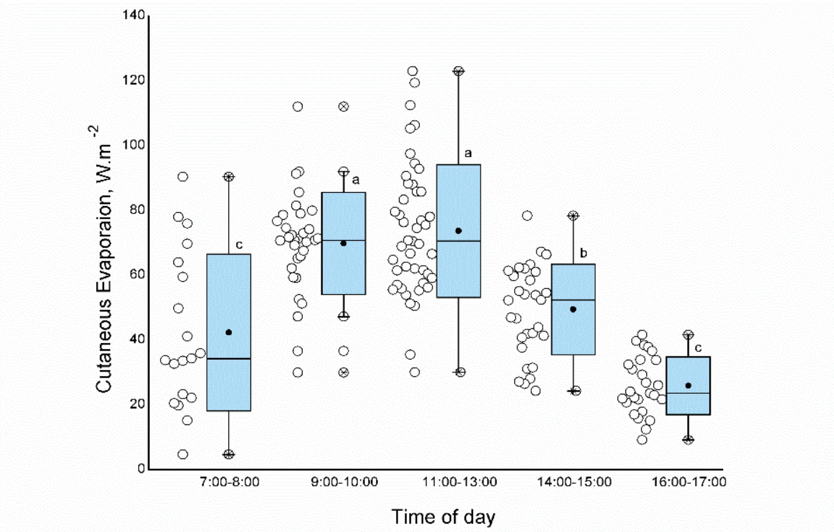


**Figure 7** Heat loss by cutaneous evaporation (W.m-²) of Nellore bulls throughout the day. (●) Indicate the averages in each hour. (○) indicates all observed data. (ʘ) indicate the outliers. Different letters indicate significant differences between hours (Tukey test; $P < 0.05$).

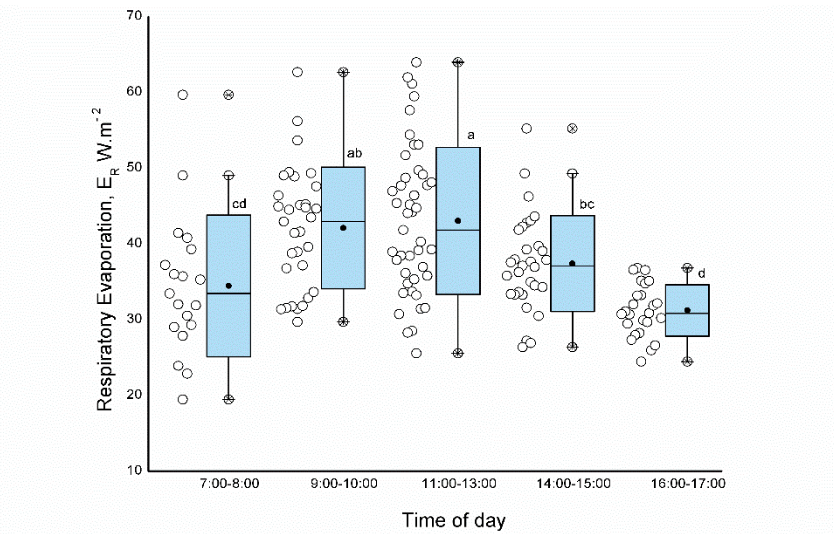


**Figure 8** Heat loss by respiratory evaporation (W.m-²) of Nellore bulls throughout the day. (●) Indicate the averages in each hour. (○) indicates all observed data. (ʘ) indicate the outliers. Different letters indicate significant differences between hours (Tukey test; $P < 0.05$).

Although there was excessive heat gain through longwave radiation ($H_R$) and an increase in ambient temperature ($T_A$) throughout the day, the rectal temperature ($R_T$) remained unchanged, with an average of 38.5°C. Lima et al (2020) reported an average $R_T$ of 39.2°C in Nellore cattle exposed to sunlight in the morning. Costa et al (2018a), who studied the heat balance of Nellore cattle protected from the sun, found mean $R_T$ values ranging from 38.6 to 38.9°C during the daytime. When working with the Guzerat breed in an environment protected from solar radiation, Camerro et al (2016) observed an average $R_T$ ranging from 38.9 to 39.5°C during the daytime. Our study showed an amplitude of approximately 2.5°C in the animals' $R_T$ when analyzing all the data at each hour and during the entire period. However, this variation decreased and remained close to the average by the end of the day. $R_T$ recordings during the early hours of the day were approximately 1°C higher than the average, with an ambient temperature of 28.5°C and solar radiation of 400 W.m$^{-2}$. However, as the $T_A$ and $R_S$ increased, the variation in

$R_T$ decreased, revealing the resilient capacity of Nellore breed animals to a hot and dry environment.

Nellore breed cattle were able to maintain their $R_T$ within narrow limits, indicating that their physiological and biophysical mechanisms were efficient in allowing them to thermoregulate with the environment. As $T_S$ remained higher than $T_A$ during the daytime, the thermal gradient favored sensible heat exchange by convection. Despite the decrease in the gradient between $T_S$ and $T_A$ during the most critical time of day, the exchange of sensible heat by convection (Figure 6) was enhanced by $U$ (Figure 1B), favoring the dissipation of excess heat without energy expenditure by Nellore bulls exposed to the challenge of $R_S$. Costa et al (2018b) recorded a convection heat exchange ($H_C$) of 20 to 40 $W.m^{-2}$ and observed that as the gradient between $T_S$ and $T_A$ decreased, $H_C$ became less efficient.

The present study found that $H_C$ alone was insufficient for the animals to dissipate all the excess body heat from direct solar radiation exposure. Therefore, the animals had to rely on evaporative mechanisms to dissipate this thermal excess. Although the respiratory rate ($R_R$) increased (Figure 3), the observed variation was only 7 $breaths.min^{-1}$, which did not have deleterious effects on the rectal temperature ($R_T$) of Bos indicus animals. The average $R_T$ (Figure 2) remained within normal limits during the daytime, demonstrating the high thermoregulatory capacity of Nellore bulls in semiarid environmental conditions. Although the average variation in $R_R$ during the daytime was within normal limits for adult zebu cattle, it is important to note that there were some animals within the same herd that did not have a significant increase in $R_R$ and $R_T$ compared to the average, suggesting greater tolerance to thermal challenges in specific individuals.

Direct exposure to solar radiation during the day challenges animals to maintain thermal balance with the environment. Although heat loss by convection contributes to dissipating excess heat from longwave radiation, other thermoregulatory mechanisms, such as $E_C$ and $E_R$, were activated to help Nellore cattle tolerate environments with intense solar radiation. $E_C$ is influenced by skin temperature ($T_S$) and atmospheric conditions that allow for water vapor reception. As it does not depend on a temperature gradient between $T_S$ and ambient temperature ($T_A$), $E_C$ is the main means of heat loss in Nellore cattle in high-temperature environments protected from solar radiation (Costa et al 2018b). In high-temperature environments, $E_C$ is responsible for 85% of the total heat loss (Maia et al 2005b). According to Silva and Maia (2011), $E_C$ remains unchanged until $T_S$ reaches values of 31°C. In the present study, all animals already had a $T_S$ above 33°C, requiring heat loss by $E_C$ at all times of the day with the highest values between 9:00 and 13:00, as at this time, animals were already receiving high amounts of solar radiation (21 to 891 $W.m^{-2}$), and $T_S$ and $T_A$ were elevated.

The ability of *Bos indicus* animals to maintain thermal equilibrium may be linked to their efficiency in latent heat loss without causing deleterious effects on their physiology. This characteristic may be related to the morphology and quantity of sweat glands in zebu animals, which enhances sweat activity and heat loss through $E_C$ (Nascimento et al 2019). Pereira et al (2014) observed that in *Bos taurus*, $R_T$ and $R_R$ were positively related to the sweating rate, as the $R_T$ varied from 38.0°C to 40.0°C and $R_R$ from 25 to 150 breaths/min, there was an increase in the sweating rate from 50 to 210 $g/m^2.h$ in an attempt to dissipate excess body heat. Jian et al (2015) observed that *Bos indicus* animals showed higher sweating rate efficiency (595 $g/m^2.h$) and maintained the $R_R$ within normal limits, which occurred in contrast to taurine animals. Thus, we can observe that the characteristics of sweat glands and, consequently, greater sweating capacity in *Bos indicus* animals provide them with greater heat loss efficiency through $E_C$, making them more tolerant to thermal stress than *Bos taurus* animals.

Respiratory evaporative heat loss ($E_R$) depends on the quantity and airflow in the respiratory system, where the higher the respiratory rate ($R_R$) is, the greater the airflow, leading animals to lose more heat by this mechanism. Panting is a physiological response of animals to thermal stress to lose heat by evaporation in the respiratory system, observed by an increase in $R_R$, a decrease in tidal volume, and an increase in ventilation in the respiratory tract (Renaudeau et al 2012; Collier and Gebremedhin 2015). Zebu cattle in shaded environments do not appear to activate $E_R$ significantly (Camerro et al 2016; Costa et al 2018a; Costa et al 2018b). In tropical environments, the $E_R$ of Holstein cows can reach 56.51 $W/m^2$ when the air temperature ($T_A$) is 35°C and the $R_R$ is 80 breaths/min, becoming an important pathway for heat loss (Maia et al 2005b). The contribution of the respiratory system to total latent heat loss in a semiarid equatorial environment can reach 27.3% (Silva et al 2012). However, the relevance of $E_R$ for Nellore bulls exposed to the sun is observed during the most critical moments of the day, where the heat loss by this mechanism is on average 42 $W/m^2$, representing 40.55% of the total latent heat loss during the day. The maintenance of $R_R$ and body temperature ($B_T$) within the normal range confirms the efficiency of sensible (conductive and convective) and latent (evaporative and respiratory) heat loss mechanisms in an environment without shade, minimizing the risks of alveolar hyperventilation and, consequently, marked respiratory alkalosis resulting from increased $R_R$ (Renaudeau et al 2012).

The physiological and biophysical mechanisms were fundamental in dissipating the excess heat gained through exposure to solar radiation practically throughout the day (Figure 9). The physiological responses were kept within the limits of homeothermy. However, there was variation between these responses during the daytime period. When evaluating all 16 Nellore bulls, some animals showed lower $R_T$, $R_R$, and $T_S$ compared to the mean, suggesting that there are animals more tolerant to thermal challenges than other animals of the same breed and herd.

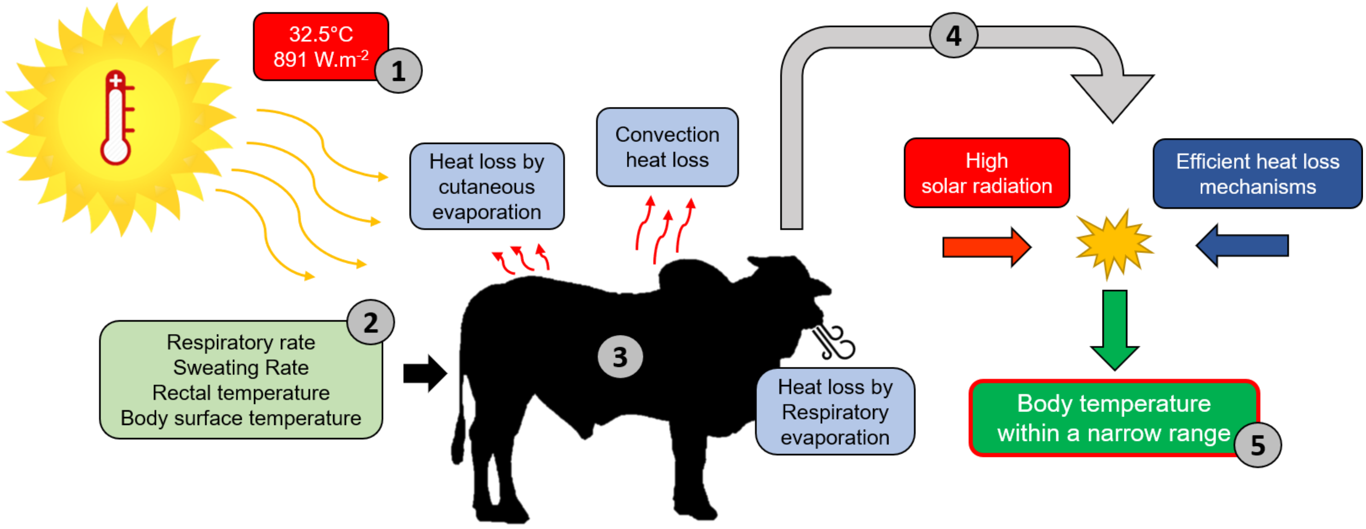


**Figure 9** Remarkable heat stress resilience of Nellore bulls in withstanding adverse environmental conditions, owing to the efficient functioning of their physiological and biophysical mechanisms. 1: Maximum air temperature and solar radiation. 2: Physiological variables. 3: Heat loss mechanisms. 4: Stress caused by high solar radiation *vs* heat dissipation mechanisms. 5: Animal's thermoregulatory efficiency in maintaining its relatively constant body temperature, despite the significant thermal challenge.

## 5. Conclusions

Nellore bulls maintain body temperature within the homeothermy range even when exposed to high solar radiation. This evidence indicates that these animals have morphophysiological attributes that make the biophysical mechanisms of thermolysis more efficient, emphasizing $H_C$, $E_C$, and $E_R$ at times of day with a more significant thermal challenge. However, there is individual variation in the responses evaluated, leading to the understanding that there are animals that are more efficient in losing heat within the same group considered when they are exposed to thermally stressful environments.

## Ethics considerations

During data collection, handling care and experimental procedures followed the Brazilian guidelines and the Ethics Committee on the Use of Animals of the Federal Rural University of Semi-Arid.

## Conflict of Interest

The authors declare that there is no conflict of interest with this work.


## Funding

This research did not receive any financial support.


## References


Assatbayeva G, Issabekova S, Uskenov R, Karymsakov T, Abdrakhmanov T (2022) Influence of microclimate on ketosis, mastitis and diseases of cow reproductive organs. Journal of Animal Behaviour and Biometeorology 10:2230. DOI: 10.31893/jabb.22030

Camerro LZ, Maia ASC, Neto MC, Costa CCM, Castro PA (2016) Thermal equilibrium responses in Guzerat cattle raised under tropical conditions. Journal of Thermal Biology 60:213-221.

Chawicha TG, Mummed YY (2022) An overview of how heat stress impacts dairy cattle fertility. Multidisciplinary Reviews 5:e2022014. DOI: 10.31893/multirev.2022014

Collier RJ, Gebremedhin KG (2015) Thermal Biology of Domestic Animals. Annual Review of Animal Biosciences 3:1-10. DOI: 10.1146/annurev-animal-022114-110659

Costa ANL, Feitosa JV, Montezuma Jr PA, De Souza PT, Araújo AA (2015) Rectal temperatures, respiratory rates, production, and reproduction performances of crossbred Girolando cows under heat stress in northeastern Brazil. International Journal of Biometeorology 59:1647-1653. DOI: 10.1007/s00484-015-0971-4

Costa CCM, Maia ASC, Nascimento ST, Nascimento CC, Neto MC, Fonsêca VFC (2018a) Thermal balance of Nellore cattle. Brazil. International Journal of Biometeorology 62:723-731. DOI: 10.1007/s00484-017-1349-6

Costa CCM, Maia ASC, Brown-brandl TM, Neto MC, Fonsêca VFC (2018b) Thermal equilibrium of Nellore cattle in tropical conditions: an investigation of circadian pattern. Journal of Thermal Biology 74:317-324. DOI: 10.1007/s00484-017-1349-6

Curtis SE (1983) Environmental management in animal agriculture. Ames: The Iowa State University.

Da Silva RG, Maia ASC (2013) Principles of animal biometeorology. Springer, New York Ed. 1.

Das R, Sailo L, Verma N, Bharti P, Imtiwati J, Kumar R (2016) Impact of heat stress on health and performance of dairy animals: A review. Veterinary World 9:260-268. DOI: 10.14202/vetworld.2016.260-268

Đuričić D, Dobos A, Grbavac J, Stiles C, Bacan I, Vidas Ž, Marković F, Kočila P, Samardžija M (2022) Climate impacts on reproductive performance of Romanov sheep in the moderate climate. Journal of Animal Behaviour and Biometeorology 10:2201. DOI: 10.31893/jabb.22001

Giannini TC, Costa WF, Cordeiro GD, Imperatriz-Fonseca VL, Saraiva AM, Biesmeijer J, Garibaldi LA (2017) Projected climate change threatens pollinators and crop production in Brazil. PLoS One. DOI: 10.1371/journal.pone.0182274

Habib HN, Saleh WMM, Gheni QJ, Karomy AS (2021) The effect of Hsp90 gene polymorphism on beef cattle production: a review paper. Multidisciplinary Reviews 4:e2021020. DOI: 10.29327/multi.2021020

Hafez ESE (1973) Adaptacion de los animales domésticos. Barcelona: Labor.

IPCC (2014) Climate Change. Synthesis report. In Core Writing Team, Pachauri RK, Meyer LA (eds), Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 151.

Jian W, Ke Y, Cheng L (2015) Physiological Responses and Lactation to Cutaneous Evaporative Heat Loss in Bos indicus, Bos taurus, and Their Crossbreds. Asian-Australasian Journal of Animal Sciences 28:1558-1564. DOI: 10.5713/ajas.14.0526

Jian W, Duangjinda M, Vajrabukka C, Katawatin S (2014) Differences of skin morphology in Bos indicus, Bos taurus, and their crossbreds. International Journal of Biometeorology 58:1087-1094. DOI: 10.1007/s00484-013-0700-9

Lima SB, G.P.N.P, Stafuzza NB, Pires BV, Bonilha SFM, Cyrillo JNSG, Negrão JA, Paz CCP (2020) Effect of high temperature on physiological parameters of Nelore (*Bos taurus indicus*) and Caracu (*Bos taurus taurus*) cattle breeds. Tropical Animal Health and Production. DOI: 10.1007/s11250-020-02249-y

Madhusoodan AP, Sejian V, Rashamol VP, Savitha ST, Bagath M, Krishnan G, Bhatta R (2019) Resilient capacity of cattle to environmental challenges – An updated review. Journal of Animal Behaviour and Biometeorology 7:104-118. DOI: 10.31893/2318-1265jabb.v7n3p104-118

Maia ASC, Da Silva RG, Battiston Loureiro CM (2005a) Sensible and latent heat loss from the body surface of Holstein cows in a tropical environment. International Journal of Biometeorology 50:17–22. DOI: 10.1007/s00484-005-0267-1

Mandal DK, Kumar M, Tyagi S (2023) Impact of seasons and management factors on seminal attributes and frozen semen doses production in Holstein Friesian crossbred dairy bulls. Applied Veterinary Research 2:e2023004. DOI: 10.31893/avr.2023004

Matsoukis A, Chronopoulou-Sereli A, Stratakos G (2022) Effect of seasonally changing aerial environment on testosterone in Karagouniko and Chios sheep. Journal of Animal Behaviour and Biometeorology 10:2105. DOI: 10.31893/jabb.22005

McManus C, Castanheira M, Paiva SR, Louvandini H, Fioravanti MCS, Paludo GR, Bianchini E, Corrêa PS (2011) Use of multivariate analyses for determining heat tolerance in Brazilian cattle. Tropical Animal Health and Production 43:623-630. DOI: 10.1007/s11250-010-9742-8

McManus C, Louvandini H, Hermuche P, Guimarães R, de Carvalho Junior OA, Pimentel F, Pimentel D, Paiva S, Peripolli V (2022) Genetic and geographical integration for ruminant production under climate change with particular emphasis on Brazil. Applied Veterinary Research 1:e2022009. DOI: 10.31893/avr.2022009

Mount LE (1979) Adaptation to Thermal Environment: Man and His Productive Animals. Baltimore: University Park Press.

Musa HH, Mwacharo JM, Adam SY, Cai D, Ahmed AA (2023) Climate change, nutrigenomics, immune function and diseases and production in dairy cattle: a comprehensive review. Applied Veterinary Research 2:e2023010. DOI: 10.31893/avr.2023010

Mylostyva D, Prudnikov V, Kolisnyk O, Lykhach A, Begma N, Kalinichenko O, Khmeleva O, Sanzhara R, Izhboldina O, Mylostyvyi R (2022) Biochemical changes during heat stress in productive animals with an emphasis on the antioxidant defense system. Journal of Animal Behaviour and Biometeorology 10:2209. DOI: 10.31893/jabb.22009

Mylostyvyi R, Izhboldina O (2021) Problems of livestock reproduction with a focus on climate change. Multidisciplinary Reviews 4:e2021011. DOI: 10.29327/multi.2021011

Nascimento CCN, Fonseca VFC, Fuller A, Costa CCM, Beletti ME, Nascimento MRBM (2019) Can *Bos indicus* cattle breeds be discriminated by differences in the changes of their sweat gland traits across summer and winter seasons? Journal of Thermal Biology 86:102443. DOI: 10.1016/j.jtherbio.2019.102443

Pereira AMF, Titto EL, Infante P, Titto CG, Geraldo AM, Alves A, Leme TM, Baccari Jr F, Almeida JA (2014) Evaporative heat loss in *Bos taurus*: Do different cattle breeds cope with heat stress in the same way? Journal of Thermal Biology 45:87-95. DOI: 10.1016/J.JTHERBIO.2014.08.004

Renaudeau D, Collin A, Yahav S, De Basilio V, Gourdine JL, Collier RJ (2012) Adaptation to hot climate and strategies to alleviate heat stress in livestock production. Animal 6:707–728. DOI: 10.1017/S1751731111002448

Rojas-Downing MM, Nejadhashemi AP, Harrigan T, Woznicki SA (2017) Climate change and livestock: Impacts, adaptation, and mitigation. Climate Risk Management 16:145-163. DOI: 10.1016/j.crm.2017.02.001

Sammad A, Wang YJ, Umer S, Lirong H, Khan I, Khan A, Ahmad B, Wang Y (2020) Nutritional Physiology and Biochemistry of Dairy Cattle under the Influence of Heat Stress: Consequences and Opportunities. Animals 10:793. DOI: 10.3390/ani10050793

Sailo L, Gupta ID, Das R, Chaudhari MV (2017) Physiological Response to Thermal Stress in Sahiwal and Karan Fries Cows. International Journal of Livestock Research 7:275-283. DOI: 10.5455/ijlr.20170226092339

SAS (1999) User's guide, version 8. SAS Institute, Cary.

Silva RG (2000) Introdução à bioclimatologia animal. São Paulo: Nobel. 286p.

Silva RG, Guilhermino MM, Morais DAEF (2010) Thermal radiation absorbed by dairy cows in pasture. International Journal Biometeorology 54:5–11. DOI: 10.1007/s00484-009-0244-1

Silva RG, Maia ASC (2011) Evaporative cooling and cutaneous surface temperature of Holstein cows in tropical conditions. Revista Brasileira de Zootecnia 40:1143-1147. DOI: 10.1590/S1516-35982011000500028