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Thermal stress index for native sheep

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A R T I C L E I N F O

Keywords:
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Ovis aries
Semiarid
Ambient temperature

A B S T R A C T

The first objective of this study was to develop a thermal stress index for sheep based on environmental and animal data collected in a climate chamber under various environmental conditions. The second objective was to compare published indices of thermal comfort and the proposed index, testing them with the data from this study, with the objective of pointing out the most adequate index to be used by breeders when choosing management procedures. A total of 3024 data were obtained for the physiological variables of the sheep exposed to the eight thermal conditions in the climatic chamber and in ambient condition, kept three days in each thermal condition. A principal component analysis summarized the measurements of physiological variables into only one variable (y1). Using SigmaPlot software, multiple regression of y1 with the environmental variables and their combinations produced a number of indices. The equation chosen was the heat stress index for sheep, TSI = 24.153 - (0.0523*A_T) + (0.746*B_{GT}) + (4.104*Vp), with R^2 = 0.668. The correlations presented high values, where these correlation values were assumed to indicate the efficiency of each index as indicators of the animals' response to the environment. Thus, it was assumed that the TSI presents a high efficiency.

1. Introduction

The planet is experiencing serious consequences due to changes in weather patterns, with agricultural and livestock activities being the most sensitive to these changes (Serrano et al., 2022) and, according to projections, tropical and subtropical regions will be the first to be affected (King et al., 2017; Serrano et al., 2021).

The average worldwide surface temperature has risen by around 1°C since the 1880s, and 2018 had the fourth-warmest global land surface temperature since records began (NOAA, 2019). Research has been done to comprehend the physiological strains of animals as well as their productive performance under heat stress conditions in this climate scenario and with frightening future projections regarding global warming (Leite et al., 2021). (Polosky and Keyserling, 2017, Brown -Brandl, 2018).

Environmental factors including temperature, relative humidity, and solar radiation, which can make animals uncomfortable and stressed out, have a significant impact on livestock husbandry (Sejian et al., 2017). As a result of the animal's surrounding thermal environment's complexity (Silva et al., 2007), the exchange of thermal energy between animals and the environment is influenced by both physiological and environmental factors, which are interrelated in a number of intricate and varied ways (Silva et al., 2015; Maia et al., 2016; Sejian et al., 2019; Santos et al., 2021).

Since the different behaviors/responses of the animals regarding their adaptation to different climatic variations have been recognized, there have been numerous attempts to establish an evaluation index for the animal that best fits a specific type of environment, where the goal is

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Table 1
Correlation coefficients between heart rate (H_R), respiratory rate (R_R), rectal temperature (R_T), skin temperature (S_T) and coat surface temperature (C_{ST}).

	H_R	R_R	R_T	S_T	C_{ST}
H_R	1	0.465**	0.360**	0.175**	0.129**
R_R		1	0.540**	0.359**	0.328**
R_T			1	0.499**	0.417**
S_T				1	0.503**
C_{ST}					1

ns: not significant. **p<0.01.

Table 2
Correlation coefficients of five indices with heart rate (H_R), respiratory rate (R_R), rectal temperature (R_T), skin temperature (S_T) and coat surface temperature (C_{ST}) of sheep in climatic chamber.

	THI 1	BGHI	THI 2	TCI	TSI
H_R	0.303**	0.372**	0.301**	0.347**	0.379**
R_R	0.610**	0.682**	0.604**	0.654**	0.686**
R_T	0.750**	0.739**	0.751**	0.754**	0.731**
S_T	0.860**	0.853**	0.863**	0.866**	0.846**
C_{ST}	0.846**	0.831**	0.849**	0.847 **	0.820**

ns: not significant. **p<0.01.

Table 3
Correlation coefficient between the temperature and humidity index - THI 1 (Thom, 1959); black globe temperature and humidity index - BGHI (Buffington et al., 1981), temperature and humidity index - THI 2 (Marai et al., 2007), thermal comfort index for sheep - TCI (Barbosa and Silva, 1995) and heat stress index TSI.

	THI 1	BGHI	THI 2	TCI	TSI
THI 1	1	0.964**	0.986**	0.969**	0.999**
BGHI		1	0.992**	0.962**	0.993**
THI 2			1	0.985**	0.987**
TCI				1	0.964**
TSI					1

ns: not significant. **p<0.01.

to combine the factors that make up the environment and the characteristics of the animals (Marai et al., 2007; Silva et al., 2010).

As for the existing indexes, most are intended to classify the environment, in the evaluation of microclimate, the best known: Thom (1959), Buffington et al. (1981), Baêta et al. (1987), Barbosa e Silva et al. (2015), Moran et al. (2001), Marai et al. (2007), among others, and there are also those that directly evaluate the animals (adaptation indexes). In general, these are indexes that generically evaluate a given location involving local meteorological measurements.

The creation of a mathematical model that calculates the heat loss from the animal to the environment must take into account elements including the animal's breed, species, and surroundings. For animals reared in tropical climates, it is improper to apply equations or indices that are suggested for animals raised in temperate climates (Maia et al., 2005, Fonseca et al., 2016, Fonsêca et al., 2019).

Sheep are homeothermic, and as a result, they maintain a state of body thermal homeokinesis under thermoneutral conditions, when exposed to heat stress situations, however, they are forced to decrease their thermogenic mechanisms and increase their thermolytic processes. (Mitchell et al., 2018, Fonsêca et al., 2019). Silva et al. (2002) developed functions with sheep of the Corriedale breed, but the characteristics of these animals contrast with native animals in semi-arid tropical environment, for example, sheep of the breeds Soinga, Morada Nova and Santa Inês, are animals known to be well adapted to the Brazilian semi-arid (Santos et al., 2011; Costa et al., 2015).

Fonseca et al., 2016 utilizing easily acquired physiological and environmental data, a prediction model of sensible and latent heat transfer in the respiratory tract of Morada Nova sheep was developed under field settings in a semi-arid tropical habitat characteristics, but the model only takes into account the climatic conditions of a single environment, and the specific physiological responses of a single breed.

In general, mathematical models of heat transfer should account for the physiological responses of the animals in relation to the environment to which they are being exposed. This necessitates research that accounts for various thermal environments and employs more than one breed in order to assess how these animals respond to various climatic variations.

The first objective of this study was to develop a thermal stress index for sheep based on environmental and animal data collected in a climate chamber under various environmental conditions. The second objective was to compare published indices of thermal comfort and the proposed index, testing them with the data from this study, with the objective of pointing out the most adequate index to be used by breeders when choosing management procedures.

2. Materials and methods

2.1. General

The procedures performed in this study were approved by the Research Ethics Committee (CEP) of the Federal University of Campina Grande, Paraíba, Brazil, CEP Protocol No. 097.2019.

The study was developed in two phases. The first phase involves obtaining environmental and animal data, whose objective was the construction of a thermal stress index for sheep in a semi-arid region. The second involves the comparison of some published indices of thermal comfort, testing them on the sheep studied, with the objective of pointing out a suitable index for the species, and determining the ranges of comfort and stress of the proposed index.

2.2. Phase 1

Observations were made in the Laboratory of Rural Constructions and Ambience - LaCRA (7° 13′ 51″ South, 35° 52′ 54″ West), of the Federal University of Campina Grande, Paraíba, Brazil, between the months of May and June 2021, in eight thermal environments.

The eight thermal environments used were four air temperatures and four air temperatures + environment modification. The proposed air temperatures were determined based on the thermal comfort zone (TCZ) for sheep that is between 20 and 30 °C, with relative humidity at 60% (Baêta and Souza, 2010; Eustáquio Filho et al., (Baêta and Souza, 2010; Eustáquio Filho et al., 2011), proposing four controlled average temperatures plus environmental modifications, obtaining eight thermal conditions: T20 (20°C, limit temperature between the thermal comfort zone and heat stress by cold); T25 (25°C, thermal comfort zone); T30 (30°C, limit temperature between the thermal comfort zone and heat stress) and T35 (35°C, above the ZCT). An environmental modification was added to each temperature, where at T20 the animals were wetted in order to further reduce the temperature of the environment (T20+AM); at T25, T30 and T35 an extra heat source of heat was added, simulating the heat produced by absorbing solar radiation (T25+FC; T30+FC and T35+FC).

To wet the animals, the water was poured into a container with a sprayer and volumetric identification (1L) to ensure that the amount of water was the same for the three groups and, every 30 min the animals were wet again, preventing them from drying out before the experimentation period of the temperature in question, with an average of 12 L of water applied to each group per day, quantifying 2L/animal. As heat sources, a 250W infrared LED lamp was added to each stall. In all environments, the average wind speed (WS) was 0.5 m s^{-1}.

There was no adaptation period of the animals to the thermal environments, and data collection was performed over a period of three days for each treatment. In the interval between treatments, the animals were

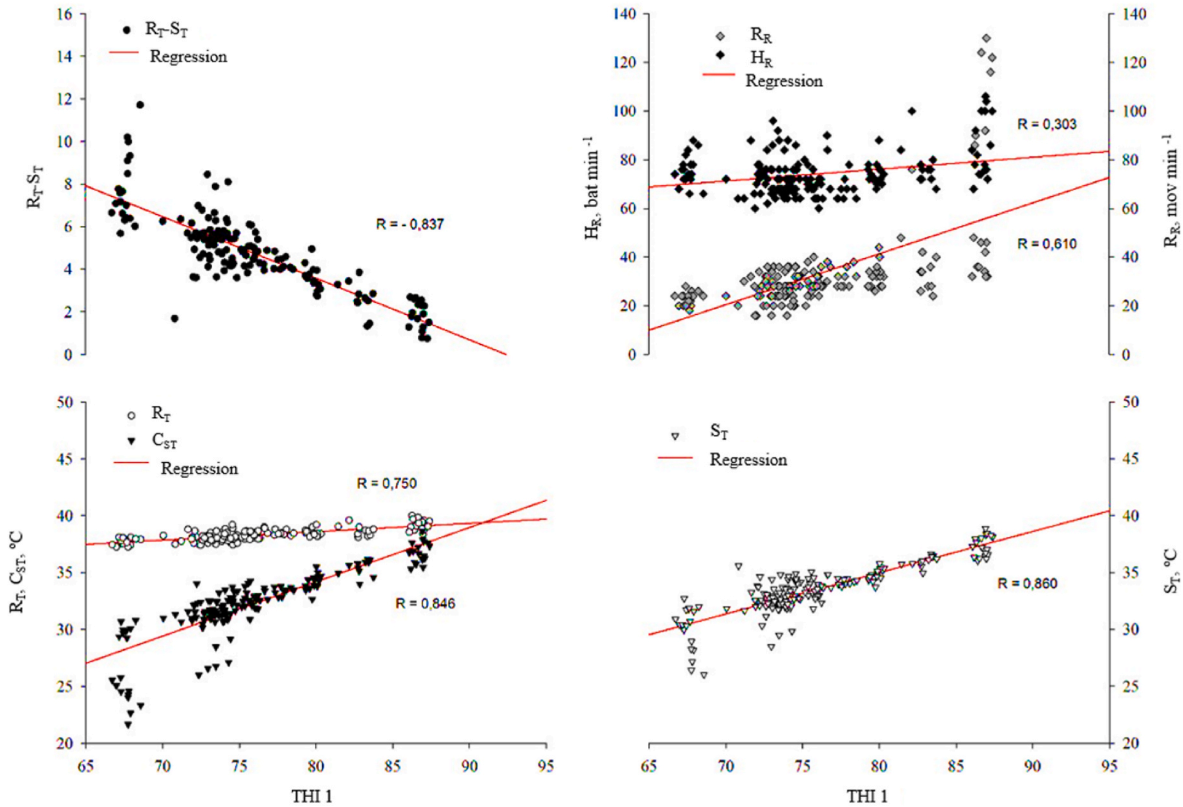

Fig. 1. Regression of the temperature and humidity index (THI - Thom, 1959) on the physiological variables of sheep.

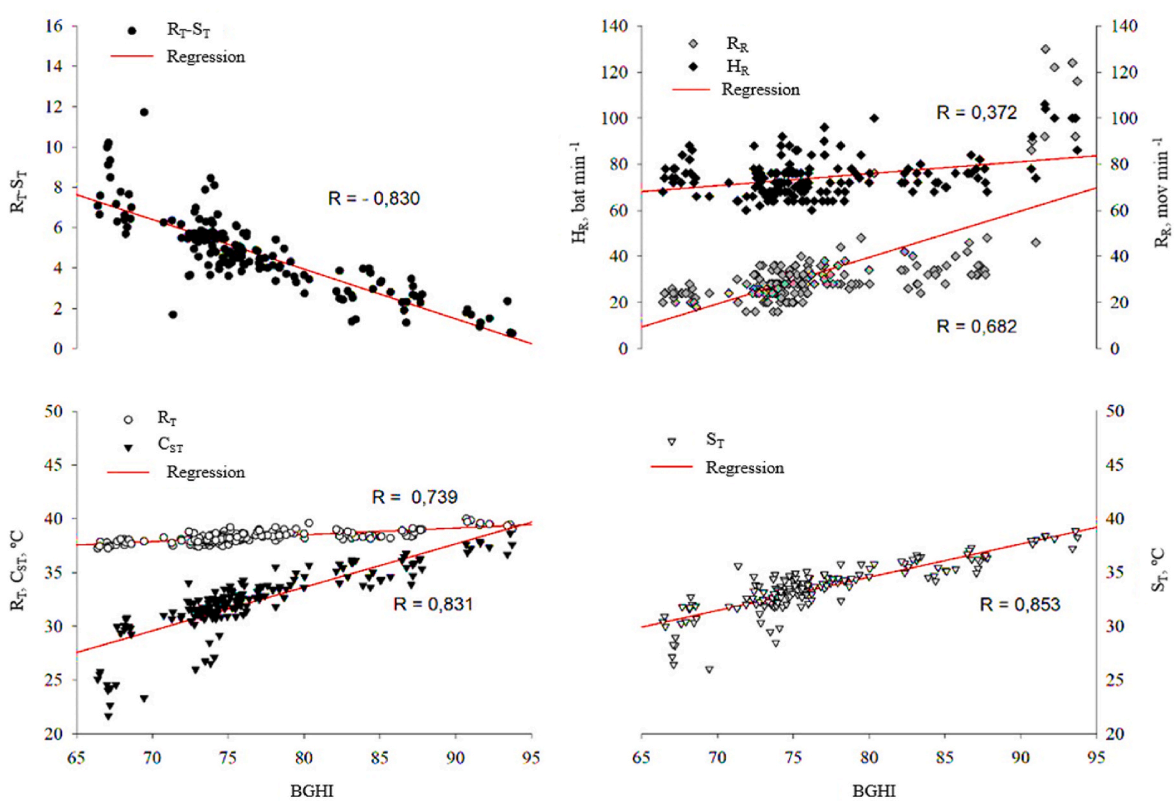

Fig. 2. Regression of the temperature and humidity index (BGHI - Buffington et al., 1981) on the physiological variables of sheep.

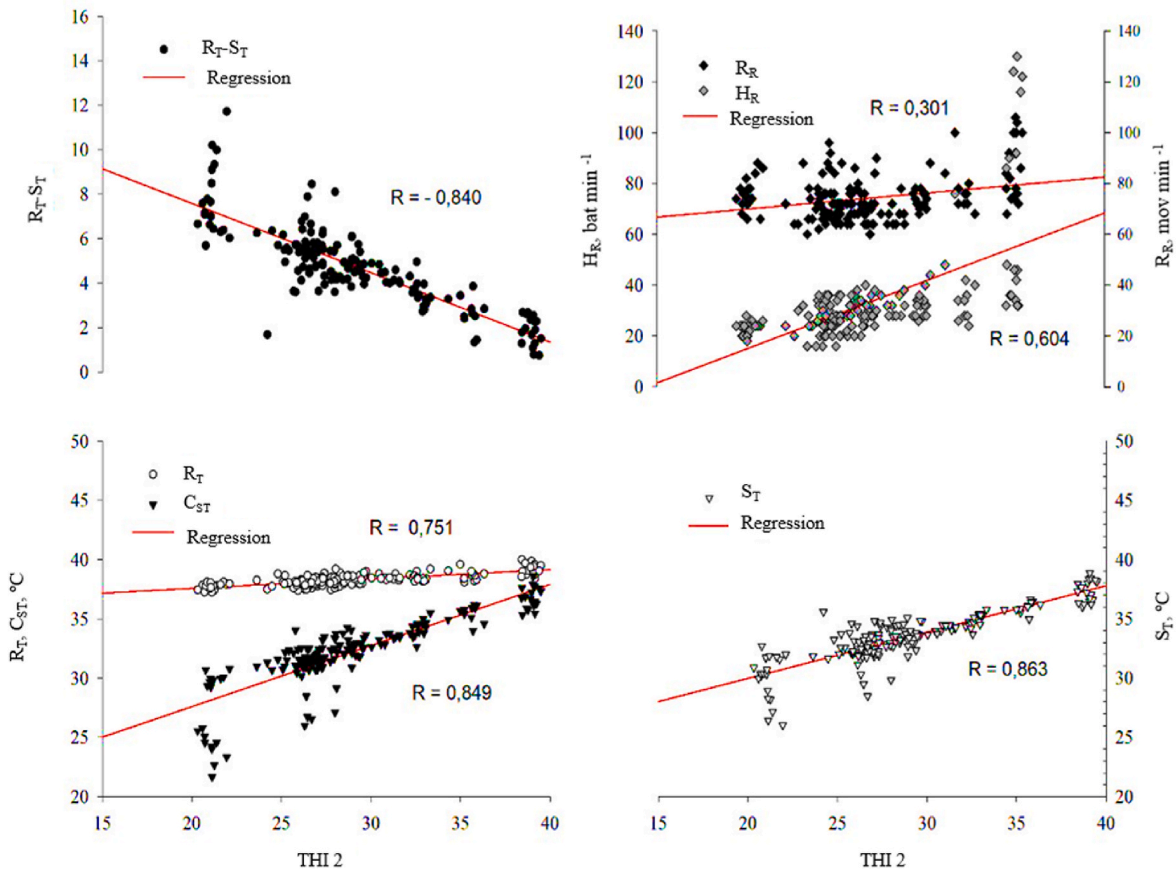

Fig. 3. Regression of the temperature and humidity index (THI 2 – Marai et al., 2007) on the physiological variables of sheep.

exposed to ambient temperature and relative humidity (with the chamber open) to restore their physiological functions for two days. Thus, taking into account the treatment days and the days of restoration of physiological functions, the total duration of the experiment was 38 days.

In each study stage in the climatic chamber, the animals were submitted to a 6/18 h cycle (experimental air temperature/ambient air temperature). The chamber was always turned on at 7 a.m., the first hour was used to stabilize the temperature and relative humidity inside the chamber, and after stabilization, the experimental period began at 8 a.m. and lasted until 2 p.m. On each day, seven measurements of physiological variables were taken at 07h, 10h, 12h, 13h, 14h, 16h, and 18h, where the animals were under the influence of room temperature (7h, 14h, 16h, and 18h) and under the influence of the experimental temperature (10h, 12h, and 13h).

One hundred and sixty-eight determinations of air temperature (A_T, °C), black globe temperature (B_{GT}, °C), dew point temperature (D_{PT}, °C), relative humidity (RH, %), and air partial vapor pressure (Vp, kPa) were used.

The air temperature and relative humidity (A_T, °C and RH, %) were controlled and monitored through a microcomputer with the aid of free software SITRAD® connected to a controller type MT-530 PLUS from Full Gauge Controls®. The controller received the average data of temperature and relative humidity of the air through the sensors, thermistor and humidiostat, respectively, every 15 min, checking and controlling these variables in order to always remain in the desired control range (Setpoint).

Data on air temperature, relative humidity, black globe temperature (B_{GT}, °C), dew point temperature (D_{PT}, °C) were stored in a HOBO U12-012 ONSET Comp® datalogger, with an external and an internal channel coupled to a black globe placed at a height similar to that of the animals (1m from the ground), in each stall. Data were taken and stored daily every 30 min throughout the experimental period. Partial vapor pressure (Vp, kPa) values were also calculated.

Eighteen uncastrated male sheep, six of each breed, Soinga (SOI), Morada Nova (MN) and Santa Inês (STI), with an average age of four months and an average weight of 15 ± 3.60 kg, were considered for the study. They had different colored coats, the SOI with predominantly white coat and black head with a white stripe to the forehead, the MN with red coat and the STI with black coat.

The animals were dewormed at the beginning of the experiment and kept in collective stalls with dimensions of 1.60 × 2.85m in length and width (4.55 m^2 of area), provided with feeders and drinkers, with a floor covered with wood shavings inside the climatic chamber, where each stall housed a group of six animals of each ecotype. The feed was supplied to the animals at two times, 7am and 6:30pm, avoiding the influence of the feed intake: 30h, avoiding the influence of caloric increment in the collections, water was provided ad libitum, and the feed offered to the animals was composed of Tifton hay (Cynodon dactylon, (L) Pers), which constituted 39.94% of the total volume of the feed, ground corn (43.41%), soybean meal (11.15%), urea (0.89%), calcitic limestone (0.89%) and vegetable oil (3.59%), according to the composition indicated by the NRC (2007).

For each thermal condition, on each observation day, each animal was measured for rectal temperature (R_T, °C), respiratory rate (R_R, mov min^{-1}), respiratory rate (H_R, bat min^{-1}), skin temperature (S_T, °C), coat surface temperature (C_{ST}, °C), totaling 3024 observations for each variable.

R_T was recorded by introducing a digital veterinary thermometer into the animal's rectum (at a depth of ~2 cm) with the bulb close to the rectal mucosa, remaining inserted until the reading stabilized. R_R was obtained by indirect auscultation of the heart sounds with the aid of a

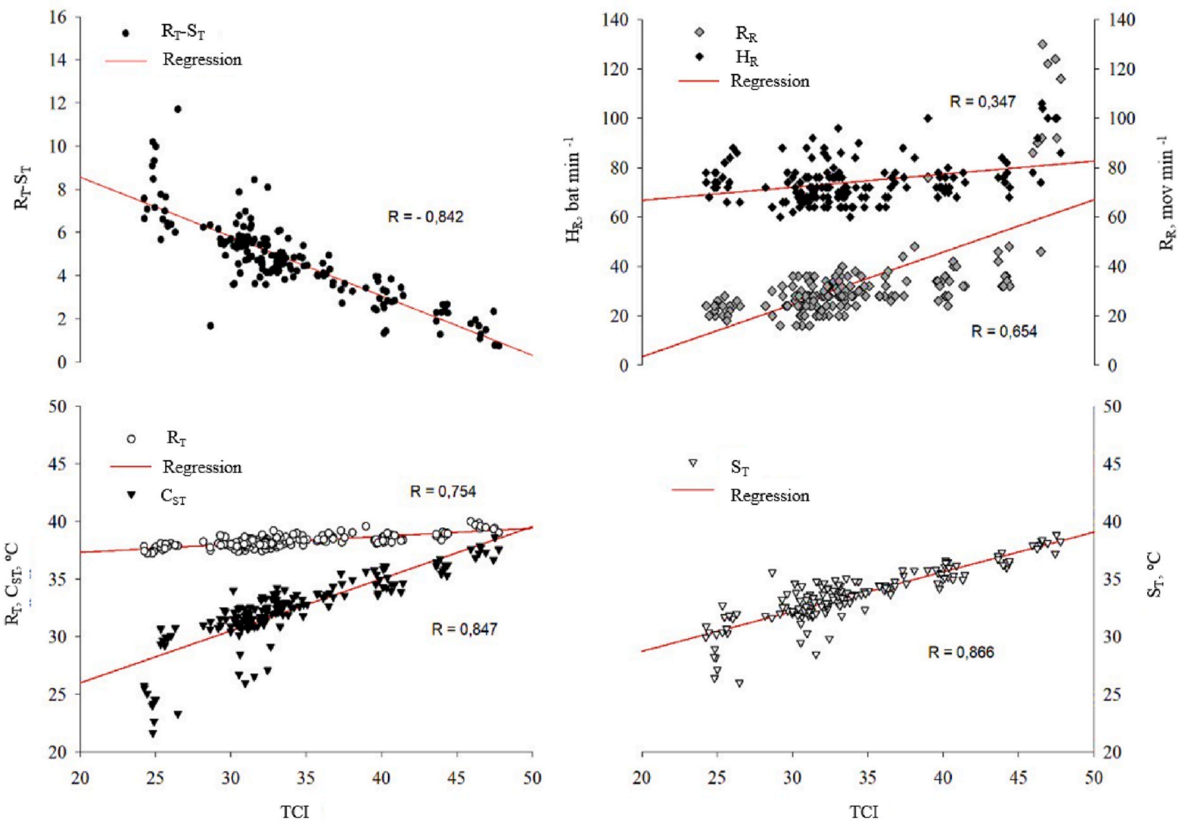

Fig. 4. Regression of the temperature and humidity index (TCI – Barbosa and Silva, 1995) on the physiological variables of sheep.

flexible stethoscope during a 15s period, and extrapolated to 1 min (mov min^{-1}). H_R was obtained by counting the heartbeats with the aid of a flexible stethoscope during a 15s period, and extrapolated to 1 min (bat. min^{-1}). The S_T and C_{ST} were obtained through the arithmetic mean of the temperatures of the cervical, thoracic and gluteal regions of the animals, in areas trichotomized for the S_T, with the aid of a digital infrared thermometer.

To obtain the heat stress index, the six physiological characteristics were summarized in only one variable by means of a principal component analysis, according to procedures described in Rencher (1995). Taking the correlation matrix of the physiological characteristics, RYY', have $\boldsymbol{e}_1^{'}$ [e11 ... e15] as the eigenvector associated with its largest eigenvalue λ1 and whose elements correspond to R_T, R_R, H_R, S_T, and C_{ST}, respectively. Then, the first principal component is the equation:

$$y_1 = e_{11}R_T + e_{12}R_R + e_{13}H_R + e_{14}S_T + e_{15}C_{ST} \quad (1)$$

Several indices were estimated by multiple regression of the principal component y_1 on chosen combinations of the environmental variables, using SigmaPlot software. The best of these was chosen based on the highest R^2 value.

2.3. Phase 2

Subsequently, four thermal indices that already exist in the literature were chosen. The indexes considered were:

a) Temperature and Humidity Index (Thom, 1959):

$$\text{THI 1} = A_T + 0,36 * D_{PT} + 41,5 \quad (2)$$

b) Black Globe Temperature and Humidity Index (Buffington et al., 1981):

$$\text{BGHI} = B_{GT} + 0,36 * D_{PT} + 41,5 \quad (3)$$

c) Temperature and Humidity Index (Marai et al., 2007):

$$\text{THI 2} = (A_T - (0,31 - (0,31 * RH / 100) * (A_T - 14,4) \quad (4)$$

d) Thermal Comfort Index for Sheep (Barbosa and Silva, 1995):

$$\text{TCI} = 0,659A_T + 0,511Vp + 0,550B_{GT} - 0,042WS \quad (5)$$

The above indices were calculated for each combination of environmental variables in the present study and in the proposed index, and their respective correlations with the animals' response (H_R, R_R, R_T, S_T, and C_{ST}) were calculated, as were the correlations between the indices. The values of these correlations were assumed as indicators of the efficiency of each index as indicators of the animals' response to the environment.

3. Results

3.1. Developing the thermal stress index

The first and biggest eigenvalue in the matrix of correlation coefficients between physiological traits, RYY, shown in Table 1, was λ1 = 9.008, which explains 81.88 % of the total variance.

The respective eigenvector was:

$$e_1 = \begin{bmatrix} 0,167 \\ 0,239 \\ 0,299 \\ 0,328 \\ 0,323 \end{bmatrix} \quad (6)$$

which met the assumption that $\boldsymbol{e}_1^{'}\ \boldsymbol{e}_1 = 1$. The principal component,

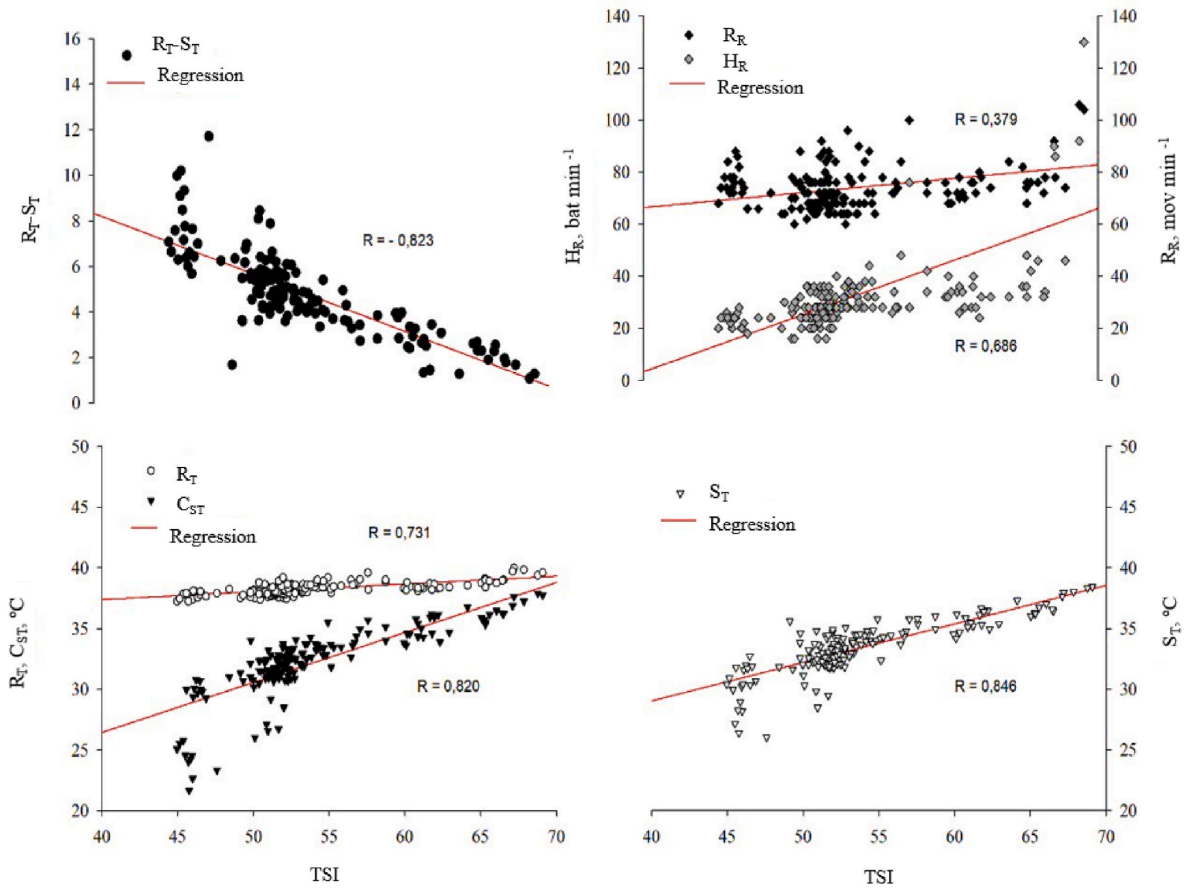

Fig. 5. Regression of the temperature and humidity index (TSI – Author) on the physiological variables of sheep.

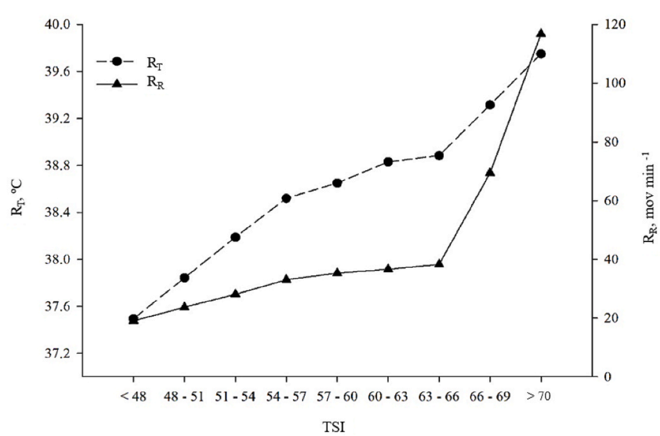

Fig. 6. Mean values of rectal temperature (R_T) and respiratory rate (R_R) of sheep according to the TSI values.

when using the elements of $\boldsymbol{e}_1$ as coefficients for the physiological variables, was:

$$y_1 = 0,167H_R + 0,239R_R + 0,299R_T + 0,328S_T + 0,323C_{ST} \tag{7}$$

The calculated y_1 values were taken as dependent variables and different combinations of the environmental variables as independent variables; then, a series of thermal indices were determined by multiple correlations. After comparing the indices with each other by their R^2 values, the next one, namely the heat stress index for sheep, was chosen:

$$TSI = 24,153 - (0,0523 * A_T) + (0,746 * B_{GT}) + (4,104 * Vp) \tag{8}$$

Table 4
Mean values of heart rate (H_R), respiratory rate (R_R), rectal temperature (R_T), skin temperature (S_T) and coat surface temperature (C_{ST}) according to TSI level.

TSI	H_R (bat min^{-1})	R_R (mov min^{-1})	R_T (°C)	S_T (°C)	C_{ST} (°C)
< 48	63,47	19,05	37,49	29,41	25,99
48,1-51	67,14	23,71	37,84	31,92	30,62
51,1-54	71,86	28,11	38,19	33,26	32,17
54,1-57	76,35	33,06	38,52	34,61	33,71
57,1-60	78,00	35,33	38,65	35,10	34,31
60,1-63	81,73	36,67	38,83	35,81	35,22
63,1-66	83,24	38,29	38,88	36,00	35,47
66,1-69	92,29	69,43	39,31	37,41	36,80
> 70	102,00	116,80	39,75	38,41	37,90

with a coefficient of determination $R^2 = 0.668$.

3.2. Evaluation and validation of the heat stress index

The sheep heat stress index (TSI) values obtained by applying Eq. (8) to the environmental data were correlated with the variables measured on the animals, all 3024 observations, showing highly significant correlation coefficients with R_T and R_R ($p < 0.01$), as presented in Table 2.

For comparison purposes the other thermal indices (THI 1, BGHI, THI 2, TCI) were estimated from the environmental data, and correlated with all 3024 observations. Similar behavior of the four indices was observed for the TSI.

The values of the indices already existing in the literature were correlated with each other and with the proposed thermal index (TSI), showing highly significant correlation coefficients with the TSI ($p < 0.01$), as presented in Table 3.

The TSI presents a high correlation with the other indexes. The values of these correlations were assumed to be indicative of the efficiency of each index as indicators of the animals' response to the environment. Thus, it was assumed that the TSI presents a high efficiency. Furthermore, the respective regression curves were calculated and presented in Figs. 1 to 5.

Table 4 shows the mean values of the physiological variables observed for each of the TSI levels, and Fig. 6 shows the mean values of rectal temperature and respiratory rate observed for each of these TSI levels.

4. Discussion

Buffington et al. (1981) when modifying the THI (Thom, 1959), determined low R^2 values correlating rectal temperature and respiratory rate to THI (0.27 and 0.31, respectively), and to BGHI (0.34 and 0.48), respectively in dairy cows, where the authors considered the BGHI to be more efficient than the THI. Barbosa and Silva (1995), when proposing the TCI for sheep, determined higher R^2 values correlating rectal temperature and respiratory rate to the TCI (0.475 and 0.619, respectively), and to the BGHI (0.444 and 0.584). Thus, high R^2 values were found for rectal temperature and respiratory rate correlated to TSI, 0.731 and 0.686, respectively.(see Fig. 6)

Despite their obvious limitations, the THI (1 and 2) and BGHI indices have been widely used to assess livestock environments in arid and semiarid regions (Maia et al., 2005; Fonsêca et al., 2019). The index's proponents insist that it is correlated with animal production performance, which may be true for temperate zones where it was developed (Silva et al., 2007).

The aforementioned indices are practical tools for determining an area's general climate; they involve local meteorological measurements of air temperature and relative humidity, wind speed, mean radiant temperature, and solar radiation. However, the variables and their coefficients in a specific index must be in accordance with the physiological mechanisms of heat exchange of the animals under consideration.

R_T and R_R are generally assumed to be primary indicators of heat stress in sheep (Sejian et al., 2017), and as the value of TSI increased from <48 to >70, R_T and R_R increased, as expected. Interestingly, in hot environments, R_R assumes increasing relevance as a form of heat loss for the animal.

Four ranges for TSI application can be suggested: ≤63 comfort, ≥63.1 and ≤66 mild to moderate discomfort, ≥66.1 and ≤69 stress, and ≥70 alert, based on the physiological responses of the animals.

When a site's TSI rating is greater than 70, pastures need to have enough tree cover to provide shade and/or shelter. If sheep are raised in a semi-intensive production system, it is best to keep them inside during the hottest part of the day. The area where they are kept should have enough protection from the main sources of thermal radiation and be completely open to the air. If necessary, electric fans and water sprinklers could also be used to further relieve the animals' discomfort.

5. Conclusion

The equation chosen was the heat stress index for sheep, TSI = 24.153 - (0.0523*A_T) + (0.746*B_{GT}) + (4.104*Vp), with $R^2 = 0.668$. The correlations of the TSI with the physiological variables showed high values, as well as the correlations between the already existing indexes and the TSI, where these values of the correlations were assumed as indicative of the efficiency of each index as indicators of the animals' response to the environment. Thus, it was assumed that the TSI presents a high efficiency.

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Authors' contributions

NMHM; VFCF: Conceptualization, Methodology, Data analysis, Formal Analysis, Writing. DAF; BBS; AGO; FTLM: Writing-Review & Editing. AGO; KCD; FTLM: Writing-Review & Editing. DAF; BBS; VFCF: Writing-Review & Editing. NMHM; MRS; LFB: Methodology, Writing-Review & Editing. CVCB; JAPCS; RSS: Conceptualization, Project Supervision, Writing Review & Editing.

Declaration of competing interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the article.

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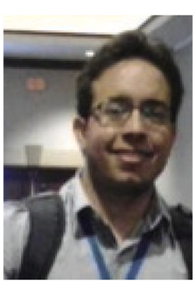

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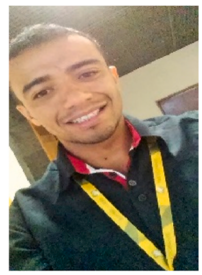

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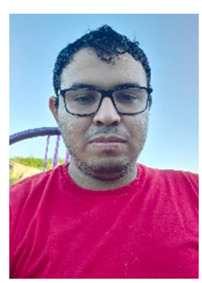

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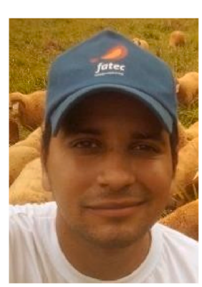

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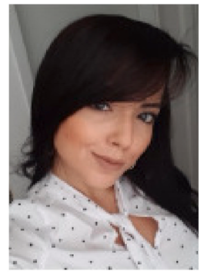

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