International Journal of Biometeorology (2024) 68:45–56
https://doi.org/10.1007/s00484-023-02569-2

ORIGINAL PAPER

Psychrometry in the thermal comfort diagnosis of production animals: a combination of the systematic review and methodological proposal

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Received: 2 April 2023 / Revised: 16 September 2023 / Accepted: 23 September 2023 / Published online: 26 October 2023

Abstract

Animal welfare and productive performance are compromised when animals are housed in environments which place them outside their thermal comfort zone. However, the identification of thermal stress, when based on air properties, suggests the use of outdated and generic indices. The objective of this work was to develop and validate a methodology for classifying and diagnosing heat stress in production animals based on psychrometric air relations. The model was created for broilers, pigs, dairy cattle, and laying birds, categorized into a total of 21 breeding phases. For each phase, a bibliographic search was carried out for the psychrometric parameters of the air—dry bulb temperature (AT) and relative humidity (RH)—that satisfied the animals' critical and ideal thermoneutral zones. Adding the local atmospheric pressure (AP), the parameters were used to calculate the enthalpy (h), resulting in five comfort ranges. Based on this, a decision tree was elaborated, consisting of three attributes (AT, RH, and h) and seven diagnostic classes, based on the psychrometric principles of air. The proposed methodology was used in a case study, with a database extracted from an individual shelter for calves. For the evaluation of the decision tree, two induction algorithms, ID3 and c4.5, were compared, both of which presented high accuracy and proposed simpler tree models than the one theoretically developed for the methodology. In conclusion, the methodology represents a great potential to characterize the thermal comfort of the animals, diagnose the causes of stress, and recommend possible corrective actions. The study revealed that decision trees can be adapted and simplified for each creation phase.

Keywords Decision tree · Specific enthalpy of air · Thermal stress · Thermoneutrality

Introduction

Heat stress stands out for its negative influence on the productive performance and well-being of farm animals, since they need to allocate energy resources to maintain thermoregulation (He et al. 2019; Polsky and Von Keyserlingk 2017). Heat stress represents a significant contributor to economic losses within the livestock farming industry, exerting adverse impacts on various aspects such as meat production, milk yield, physiological functions, reproductive outcomes, and animal survival rates and overall health (Abdelnour et al. 2019; Bin-Jumah et al. 2020; de Castro Júnior and Silva 2021; Theusme et al. 2023). For instance, Silveira et al. (2021) showcased how the thermal conditions significantly affect the performance of Brahman bulls. This issue becomes critical in animals housed in tropical climate regions, which represent most of the Brazilian territory.

The success of a production depends, among other factors, on the physical properties of the housing environment, such as air temperature, relative humidity, solar radiation, and wind speed, which will directly influence the thermal exchanges between the animal and the environment (Aziz et al. 2016; Bin-Jumah et al. 2020).

Over time, different combinations of air properties were proposed, categorizing thermal stress based on obtaining comfort indexes, such as the Temperature Humidity Index (THI), by Thom (1959); the Buffington Black Globe Temperature and Humidity Index (BGHI) (1981); and Radiant Heat Load (RHL), proposed by Esmay (1979). Nonetheless, the primary limitations of thermal comfort indices lie in

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the fact that they were developed and parameterized in temperate regions. Moreover, they frequently classify animals without distinguishing between species and breeding phases.

Another evaluative approach that is based on the physical characteristics of the air is psychrometric relations. Britto (2010) points out that psychrometric relations represent the area of research that investigates changes in the properties of humid air. As one of these properties, enthalpy is considered the energy content (amount of total heat) present in a unit mass of air, incorporating latent and sensible heat contents. With such characteristics, enthalpy has been explored as an indication of the thermal comfort situation for humans (Chu and Jong 2008; Heidari et al. 2016; Heidari et al. 2018) and production animals (Rodrigues et al. 2011; Sarnighausen 2019).

Created in the 1960s, decision trees have consolidated themselves as one of the most effective statistical models for data mining, helping to determine priorities and decision-making from the manipulation of large data sets (Song and Lu 2015). Studies have used decision trees to indicate the thermal comfort of animals (Nascimento et al. 2011; Perissinotto and Moura 2007; Silveira et al. 2023; Vale et al. 2008), but their application in the diagnosis of causes and possible solutions to mitigate or reduce the thermal stress of animals are not reported in literature. The methodological proposal presented in this article can serve as a protocol for diagnosing heat stress in farm animals (dairy cattle, poultry, laying hens, and swine), representing a crucial tool for making informed decisions grounded in psychometric air relationships.

The objective of this work was to develop and validate an evaluative methodology for diagnosing heat stress in production animals, at different stages of rearing, using psychrometric air relationships and decision trees as tools.

Material and methods

Methodological proposal

Being a methodological proposal, this study followed a serial sequence of seven dependent elements (Fig. 1), whose individual results were used as input data in the subsequent steps. The final objective—the last element of the methodological sequencing—was to obtain a diagnosis of the animals' thermal comfort.

In the first element (choice of animals of interest), the most relevant domestic animals in the Brazilian animal protein production chain were considered, extracting beef cattle. Poultry farming, pig farming, dairy cattle farming, and laying poultry farming were contemplated. When it comes to thermal comfort, it is important to highlight that the critical and thermoneutral ranges—intervals that indicate the severity of thermal stress—of each species vary according to the stage of development of the animals (Ribeiro et al. 2018). In this sense, in addition to determining the animals of interest, it was necessary to subdivide them into their rearing phases, as the second element of the methodology. Obtaining the breeding phases (Table 1) followed the traditional nomenclature of each production chain.

Bibliographic review

The next step was the survey of the psychrometric parameters through the bibliographic review (the third element of the methodology). Within the set of psychrometric properties of the air, the most known and used variables are the dry bulb temperature (AT) and the relative humidity of the air (RH), since they are easy to collect and represent the bioclimatic properties of greatest interest in studies of ambience.

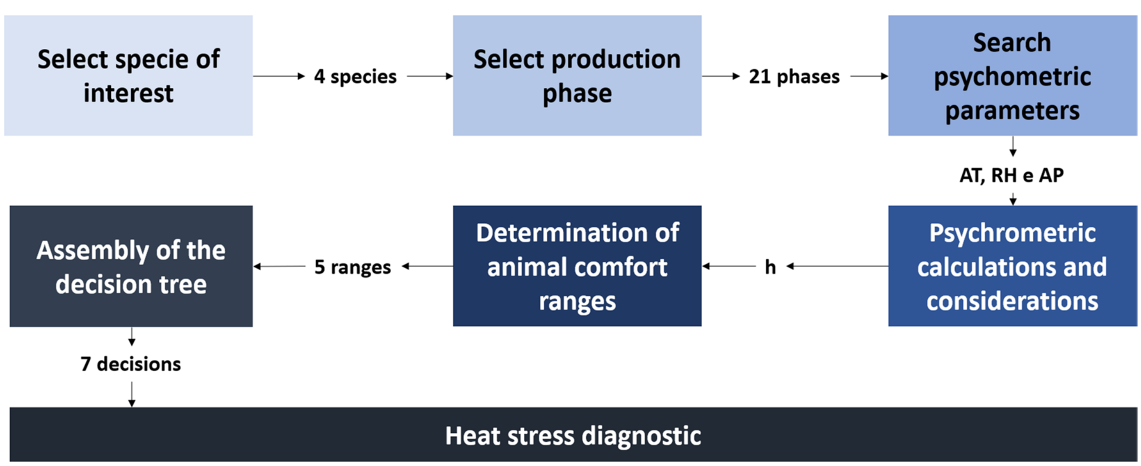

Fig. 1 Methodological sequence: elements (boxes in shades of blue) and their respective individual results (between the arrows). h, enthalpy; Tbs, dry bulb temperature; RH, relative humidity

Table 1 Productions of interest and their respective creation phases

Production	Creation phases	Description
Poultry	1st week	Animals from 0 to 7 days old
	2nd week	Animals from 8 to 14 days old
	3rd week	Animals from 15 to 21 days old
	4th week	Animals from 22 to 28 days old
	5th week	Animals from 29 to 35 days old
	6th week	Animals from 36 to 43 days old
Dairy cattle	Calves	Animals from 0 to 2 months old
	Heifers	Animals from 2 to 24 months old
	Lactating cows	Adult females during the period of gestation and lactation
	Dry cows	Adult females during the dry period
	Bulls	Adult breeding males
Swine	Reproduction	Adult sows
	Reproduction	Adult breeding males
	Piglets	Animals from 0 to 21–28 days old (ideal weight of 8 kg)
	Nursery	Animals from 21 to 28 to 63 days old (ideal weight 20–24 kg)
	Growth	Animals weighing between 20 and 55 kg
	Finisher	Animals weighing over 55 kg
Laying hens	1st week	Animals from 0 to 7 days old
	Growing (Stage 1)	Animals from 1 to 6 weeks old
	Growing (Stage 2)	Animals from 7 to 17 weeks old
	Laying hens	Animals from 18 to 80 weeks old

For each of the 21 breeding phases listed in this work, the classic parameters of AT and RH used in the evaluation of zootechnical installations were investigated in literature. Values recorded for the thermal comfort zone (TCZ), lower critical zone (LCZ), and upper critical zone (UCS) were obtained, which characterize the thermoneutral regions of homeothermic animals. As a bibliographic search method, a systematic review was used (Pereira and Galvão 2014) following the following steps:

1) Compilation of scientific articles published in the main national and international databases that used thermoneutrality zones in their evaluations
2) Identification of the theoretical framework (source text) of the thermoneutrality values used in the articles
3) Search for source texts in gray literature
4) Cataloging of the ZCT, LCZ, and UCS ranges, according to the source text, year of publication, and object of study (creation phase)

Next, the source texts were compared with each other, in order to establish a single acceptable limit of ZCT, LCZ, and UCS for AT and RH. In this standardization, the agreement of at least two authors for each of the thermal zones for the different rearing stages was used as a decision criterion.

Psychrometric properties: local atmospheric pressure (AP)

Still, in the third element, Beltrán-Prieto et al. (2015) point out that the psychrometric properties of air vary according to the local atmospheric pressure (AP) and, consequently, the altitude (A) of the evaluated environment. Thus, the Brazilian municipalities of greater and lesser A were defined, according to the Register of Selected Brazilian Localities, belonging to the Brazilian Institute of Geography and Statistics (IBGE), using a database of 21,304 municipalities, towns, indigenous villages, and national rural settlement areas (IBGE 2016). The maximum and minimum altitude values were converted into minimum and maximum AP, respectively, according to Eq. (1), proposed by Allen et al. (1998):

$$AP = 101.3\,x\left(\frac{293 - 0,0065xA}{293}\right)^{5,26} \quad (1)$$

Prospecting a future use of this methodology in large-volume databases, three fixed values of Pa were determined, facilitating subsequent computational processing that may not support a large number of possible Pa. From the amplitude obtained from the maximum and minimum AP, 3 subintervals of the same spacing were generated: the group of places with low A and high Pa, the group of places with medium A and AP, and the group with places of high A and low AP. The fixed values of high AP, medium AP, and low AP were extracted from the arithmetic mean of each of the sub-intervals, respectively.

Specific Air Enthalpy Index (h)

In the fourth element of the methodology, after obtaining the critical and comfort zones of AT and RH, added to the considerations made for AP, the Specific Air Enthalpy Index (*h*) is calculated (Eq. (2)) corrected by Rodrigues et al. (2011):

$$h = 1{,}006Tbs + \left(\frac{RH}{AP}\right) * 10^{\left[\frac{7{,}5AT}{237{,}3+AT}\right]} * (71{,}28 + 0{,}052AT) \quad (2)$$

Using the ideal and critical values of AT and RH, it was possible to determine the ideal and critical enthalpies for each production phase, for each of the three Pa scenarios. Such results were used in the fifth element to determine the LCZ, UCZ, and ZCS, obtaining five enthalpy categorization intervals. Environments with h below the LCZ and above the UCZ were considered emergency situations of thermal stress; environments with h between LCZ and the minimum value of the UCZ and with h between the maximum value of the ZCT and the UCZ were considered alert situations; environments with h inside the ZCT do not pose risks to the thermal comfort of the animals.

Diagnosis of thermal comfort

From the ranges obtained, it was possible to elaborate the diagnosis of thermal comfort using the principles of the decision tree (sixth and penultimate element). When carrying out an analysis of the enthalpy formula of Rodrigues et al. (2011) and the relationships stipulated by the psychrometric chart (Kresta and Ayranci 2018), it was possible to observe that h and AT, as well as h and RH, are dependent and directly proportional quantities.

Causes of h outside the ideal situation of thermal comfort of the animals are consequences of AT and/or RH in critical or emergency states. Thus, in order to diagnose h stress, it is necessary to understand the primary causes, since AT is related to the heating or cooling of the environment, and RH corresponds to the humidification and drying processes (Britto 2010). Table 2 summarizes the variation of h, its dependence on AT and RH, and the diagnosis of each problem.

Each stage of creation of the productions proposed in this work requires different responses (modifications in the environment) according to the type of problem, using different techniques and air conditioning devices. For this purpose, a general decision tree was elaborated, from a theoretical point of view, for the diagnosis of the comfort situation of production animals, using the 7 possibilities of possible diagnoses.

At first, without using a working data set, a theoretical decision tree with three nodes (AT, RH, and h) was proposed, using the dependent variable (h) as the main attribute, AT as a secondary attribute—because it is more studied when evaluating the thermal comfort of the animals—followed by RH, as the third attribute. In this theoretical formulation, considerations found in the literature were used, based on possible paths determined by a set of rules “IF <conditional> THEN <consequent>” (Andrade et al. 2016; Perissinotto and Moura 2007). As each variable had specific classification ranges, listed in the previous elements in this work, the decision tree was elaborated with ordinarily qualitative values (high, low, and ideal), and not numerical ones. Each diagnosis represented a leaf of the decision tree.

Case study

In a second moment, as a case study, the already finalized modeling was used and evaluated, in order to obtain decision trees built from a database of a facility for dairy calves. The collections were carried out in the dairy cattle sector of the Faculty of Animal Science and Food Engineering (FZEA), the campus of the University of São

Table 2 Possible diagnoses for thermal stress problems

Diagnosis	Dependent variable	Variable Independent	Problem
D1	h = ZCT (ideal)	-	Ideal environment
D2	h > TCZ (high)	AT and RH > TCZ (high)	Hot and humid environment
D3		AT > TCZ (high)	Hot environment
D4		AT > TCZ (high)	Humid environment
D5	h < TCZ (low)	AT and RH < TCZ (low)	The environment is dry and cold
D6		AT < TCZ (low)	Environment is cold
D7		RH < TCZ (low)	Environment is dry

h enthalpy, *Tbs* dry bulb temperature, *RH* relative humidity, *ZCI* lower critical zone, *TCZ* thermal comfort zone, *ZCS* upper critical zone

Paulo (USP), Pirassununga, SP. The municipality is at an altitude of 620 m, latitude 21° 59′ 46″ south and longitude 47° 25′ 33″ west. The climate, according to the Köppen characterization, is Cwa: tropical with rainy summers and dry winters.

As an object of study, an individual shelter for calves was used—a tropical house—with dimensions of 1.57-m long, 1.17-m wide, maximum ceiling height of 1.15 m (in front of the installation), and minimum 1.10 m (at the back), obtaining a useful volume for the calf of 2.4 m^3. The shelter was sealed on the sides and bottom with flat plywood sheets 0.05-m thick and painted white. The covering used was corrugated fiber cement tiles, 1.80-m long, 1.50-m wide, and 0.05-m thick, also painted white. The interior of the shelter contained sand bedding and a feeding trough. There were no physical barriers that caused shading in the shelter during any moment of the day.

To collect the physical variables of the environment, a HOBO datalogger positioned in the geometric center of the installation was used. AT and RH values were collected every 1 h over 24 h, for 65 days (between April, May, and June), in autumn. From the extracted values, the h was calculated, which is the AT and the RH nominally classified between low, ideal, and high according to the parameters for calves extracted from the methodology of this work, following the methodology used by Perissinotto and Moura (2007).

Statistical analysis

For obtaining the decision tree for this case study, based on data mining, the Waitato Environment for Knowledge Analysis (WEKA®) software, version 3.8 of easy manipulation algorithms aimed at machine learning and data mining (Perissinotto and Moura 2007; Smith and Frank 2016; Zhao and Zhang 2008) was used.

The data set was initially evaluated according to the balancing of its attributes, determining whether there were more recurrent diagnoses from D1 to D7 in the evaluated experimental period. After that, two supervised classification algorithms, ID3 and c4.5, were used to create the decision trees. ID3 is a pioneering and widely used recursive algorithm in the induction of decision trees, allowing the use of categorical attributes (Quinlan 1986). The c4.5 algorithm is characterized as an evolution of ID3, using a gain ratio measure which promotes a better division of examples than the information gain, which is used in ID3 (Quinlan 1993). Both models were executed using cross-validation as a test criterion. The two algorithms were evaluated according to their accuracy (data correctly classified), and the trees obtained by the models were compared with the theoretical tree proposed in the methodological development of this study.

Results

In obtaining the AT and RH parameters which are specific for each of the phases of the four productions (Table 3), a total of 189 records were catalogued through the systematic bibliographic review. It is worth noting that some source texts contained more than one catalogued record.

Of the records, 58 (31%) focused on the classification of broiler chickens and 51 (27%) on pigs, which were the groups which presented more stages of creation, six each. Cattle farming was represented by 49 (26%) of the records, while laying hens had the lowest number of observations, with 31 (16%) of the records.

Within the developmental stages of broilers, the catalogued zones were similar for all weeks, and many of the base texts brought a compilation of thermoneutrality zones for all weeks. As for pig farming, a greater expression of records was catalogued for sows and piglets, compared to the other production stages, as they present antagonistic situations of thermal comfort that coexist in the same production environment.

For dairy cattle, most of the work—39% of records for cattle—was catalogued for lactating cows, which are of greater economic interest. The same phenomenon occurred with laying hens, with base texts that bring only the thermoneutrality zones for laying hens—42% of the total records for this production.

The established thermoneutral zones indicate that younger animals, in general, demand warmer environments for their survival, increasing the demand for colder environments throughout their growth.

Considering the classification for the local atmospheric pressure, it was highlighted that the highest city in the country is Campos do Jordão, SP, with its headquarters located at 1639.3 meters of altitude. The municipality with the lowest recorded altitude was Grossos-RN, at 0 meters above sea level. By the conversion of Allen et al. (1998), the lowest atmospheric pressure (Pa) in Campos do Jordão was 625.29 mmHg, while the highest Pa in Grosso was 759.81 mmHg, generating a possible range of 134.52 mmHg in amplitude.

Dividing the interval into three groups and obtaining the arithmetic mean for each of them, the three fixed AP values were extracted: cities with Pa between 625.29 and 670.13 mmHg were grouped in the low Pa group, approximating its actual value to low AP = 647.71 mmHg. Cities with AP between 670.14 and 714.97 mmHg were grouped in the average AP group, with the fixed value of medium AP = 692.55 mmHg. The cities with Pa between 714.98 and 759.81 mmHg had their approximate values for high AP = 737.39 mmHg.

The Tbs and RH values retrieved and standardized from the literature (Table 3), and the three Pa conditions

Table 3 Thermoneutrality zones for Tbs and UR for rearing phases based on literature review

		Dry bulb temperature (°C)			Relative humidity (%)		
		LCZ	TCZ	UCZ	LCZ	TCZ	UCS
Poultry	1st week	30	32–35	39	30	50–70	90
	2nd week	26	28–32	38	40	50–70	90
	3rd week	23	26–28	33	40	50–70	90
	4th week	15	18–28	32	40	50–70	90
	5th week	15	16–28	32	40	50–70	90
	6th week	14	16–28	32	40	50–70	90
Swine	Sows	0	10–23	30	30	50–70	90
	Boars	0	12–21	30	30	60–70	90
	Piglets	15	27–34	35	30	50–70	90
	Nursery	10	20–24	31	30	50–70	90
	Growing	5	16–21	27	30	50–70	90
	Finishing	5	12–21	27	30	50–70	90
Dairy cattle	Calves	10	16–21	26	20	50–70	90
	Heifers	– 5	12–26	30	20	50–70	90
	Dairy cows	– 5	0–25	30	20	50–70	90
	Dry cows	– 10	0–21	27	20	50–70	90
	Bulls	– 10	0–21	27	20	50–70	90
Laying hens	Chicks	30	33–35	39	30	40–60	90
	Growing (stage 1)	12	18–27	30	30	40–60	90
	Growing (stage 2)	12	18–25	30	30	40–70	90
	Laying hens	12	14–28	30	30	40–70	90

LCZ lower critical zone, *TCZ* thermal comfort zone, *UCZ* upper critical zone

obtained were used to calculate the LCZ, ZCT, and UCZ of enthalpy for the 21 phases of interest (Table 4). Generally speaking, it is possible to observe that the ranges of h have higher values for younger animals and progressively decrease as the animals grow. Furthermore, with an increase in Pa, the values of h decrease.

As the final purpose of the methodology, the theoretical decision tree was elaborated based on the enthalpy values obtained (Fig. 2). The root attribute (orange square) was enthalpy, which is the system-dependent variable. According to its result, the AT nodes are opened and, shortly after, the RH (green circles). Nodes that respond to the ideal AT only assume that the humidity is high and/or low. The diagnoses (gray triangles) are reached following the criteria used in Table 2.

In the case study with the database of an individual calf shelter, 1559 instances (data pair of AT and RH) were used. The methodology developed in this work was applied: AT and RH data were categorized into "low," "ideal," and "high" according to Table 3, using the classification for calves; the real atmospheric pressure of Pirassununga, of 692.55 mmHg, was approximated to the fixed value of high AP = 705.15 mmHg; and the enthalpy was calculated and classified as "low," "ideal," or "high" using Table 4. The comfort diagnosis was determined by Table 2, classifying the dataset from D1 to D7.

The data set was initially evaluated by balancing the attributes. By the distribution of the diagnoses (Fig. 3A), it was possible to observe that the majority of the instances (40%) presented as classification the diagnosis D1 (ideal environment), followed by D3 (hot environment) and D4 (humid environment), with 25 % and 18%, respectively. Diagnoses D2 (hot and humid environment) and D5 (cold environment) presented, respectively, 9% and 7% of the diagnosed instances. Only one record was classified as D5 (cold and dry environment), and there was no record of diagnosis D7 (dry environment).

In the distribution of the enthalpy attribute (Fig. 3B), it was possible to observe the imbalance through the greater number of instances classified as high h (812 instances), followed by ideal h (634 instances), and finally low h (113 instances). Within the high category, the final diagnoses were D4 (285 instances), D3 (384 instances), and D2 (143 instances). All environments with ideal h were diagnosed as D1, as well as all those with low h were cataloged as D6 (112 instances) and D5 (1 instance).

The dry bulb temperature (Fig. 3C) was the attribute that showed the least imbalance, still maintaining an irregular distribution of diagnoses within each Tbs classification. Out of the 571 instances that were classified as high Tbs, 44 were diagnosed as D1, 143 as D2, and 384 as D3. Out of the 537 classified as ideal Tbs, 252 were destined for D1 and 285 for

Table 4 Thermoneutral zones for enthalpy (in kJ/kg of dry air)

	Low AP = 647.70 mmHg			Medium AP = 692.55 mmHg			High AP = 737.39 mmHg		
	ZCI	TCZ	ZCS	ZCI	TCZ	ZCS	ZCI	TCZ	ZCS
Poultry									
1st week	57.7	76.1–108.0	155.9	52.1	73.2–103.3	148.3	50.8	70.7–99.1	141.7
2nd week	50.9	63.0–93.6	148.7	49.3	60.7–89.6	141.5	47.9	58.7–86.1	135.2
3rd week	43.8	57.1–76.9	116.8	42.4	55.1–73.7	111.4	41.3	53.3–70.9	106.6
4th week	27.6	37.0–76.9	111.1	26.8	35.8–73.7	106.0	26.1	34.7–70.9	101.5
5th week	26.6	32.7–76.9	111.1	26.8	31.6–73.7	106.0	26.1	30.7–70.9	101.5
6th week	25.8	34.8–76.9	111.1	25.0	33.7–73.7	106.0	24.4	32.7–70.9	101.5
Swine									
Sow	3.4	21.3–59.2	100.5	3.1	20.5–56.9	96.0	2.9	19.9–54.8	92.0
Boar	3.4	24.9–53.0	100.5	3.1	24.0–51.0	96.0	2.9	23.3–49.1	92.0
Piglet	24.5	60–103.0	128.8	23.9	57.8–98.5	122.7	23.3	56.0–94.6	117.4
Nursery	16.8	41.5–62.5	105.7	16.4	40.2–60.0	100.9	16.0	38.9–57.8	96.7
Growing	9.8	32.7–53.0	86.2	9.5	31.6–51.0	82.3	9.2	30.7–49.1	79.0
Finishing	9.8	24.9–53.0	86.2	9.5	24.0–51.0	82.3	9.2	23.3–49.1	79.0
Dairy cattle									
Calves	14.6	32.7–53.0	81.7	14.3	31.6–51.0	78.1	14.0	30.7–49.1	75.0
Heifers	− 3.6	24.9–69.4	100.5	− 3.7	24.0–66.6	96.0	− 3.8	23.3–64.1	92.0
Lactating cows	− 3.6	5.6–65.9	100.5	− 3.7	5.2–63.2	96.0	− 3.8	4.9–60.9	92.0
Dry cows	− 9.1	5.6–53.0	86.2	− 9.2	5.2–51.0	82.3	− 9.2	4.9–49.1	79.0
Bulls	− 9.1	5.6–53.0	86.2	− 9.2	5.2–51.0	82.3	− 9.2	4.9–49.1	79.0
Laying birds									
Chicks	53.7	70.4–97.6	155.9	52.1	68.0–93.6	148.3	50.8	65.9–90.0	141.7
Growing (stage 1)	19.8	33.2–66.5	100.5	19.3	32.3–64.0	96.0	18.8	31.4–61.7	92.0
Growing (stage 2)	19.8	32.2–65.9	100.5	19.3	32.3–63.2	96.0	18.8	31.4–60.9	92.0
Laying hens	19.8	25.8–76.9	100.5	19.3	25.0–73.7	96.0	18.8	24.4–70.9	92.0

LCZ lower critical zone, *TCZ* thermal comfort zone, *UCZ* upper critical zone

D4. Out of the 451 instances classified as low Tbs, 338 were diagnosed as D1, 112 were classified as D6, and 1 as D5.

Relative air humidity (Fig. 3D) was the attribute that showed the greatest imbalance. A total of 1064 instances were classified as high RH, which was diagnosed as D1 (531), D2 (143), D4 (284), and D6 (106). A total of 322 instances were classified as ideal RH. Out of these, 72 were diagnosed as D1, 243 as D3, and 6 as D6. For the 173 records cataloged as low RH, 31 were diagnosed as D1, 141 as D3, and 1 as D5.

Data obtained from calf shelters were trained by ID3 and c4.5 algorithms. For ID3, an accuracy of 99.55% was obtained, with 7 instances misclassified by the cross-validation test. The algorithm did not recognize the D5 diagnosis, classifying the instance as D6. There is also classification confusion between D1 and D6 (2 errors) and D4 and D3 (4 errors). The c4.5 presented an accuracy of 99.87%, accumulating 2 classification errors: D5 was classified by the algorithm as D6 and D3 as D4. Fig. 4 presents the decision trees proposed by the two algorithms. ID3 used enthalpy as the root attribute, with four nodes (Fig. 4A). The D7 diagnosis was not presented, as it was not indicated in the calf shelter database. Algorithm c4.5, in turn, also placed enthalpy as the first evaluated attribute (Fig. 4B). However, the generated decision tree was leaner, with only two nodes, which did not diagnose D5 and D7.

Discussion

When it comes to using AT and RH as thermal comfort parameters for animals based on an assessment of the environment, studies use different base references to compare the collected records with the ideal for the species. However, the base texts differ from each other in determining comfort within the same creation phase, which can lead to diagnostic variations in ambience studies, depending on the criteria used for choosing the theoretical framework.

Moreover, when grouping the base texts, it was possible to observe some limitations of these studies: Many of them present only the ideal zone of thermal comfort, without characterizing the critical zones; most of the works establish

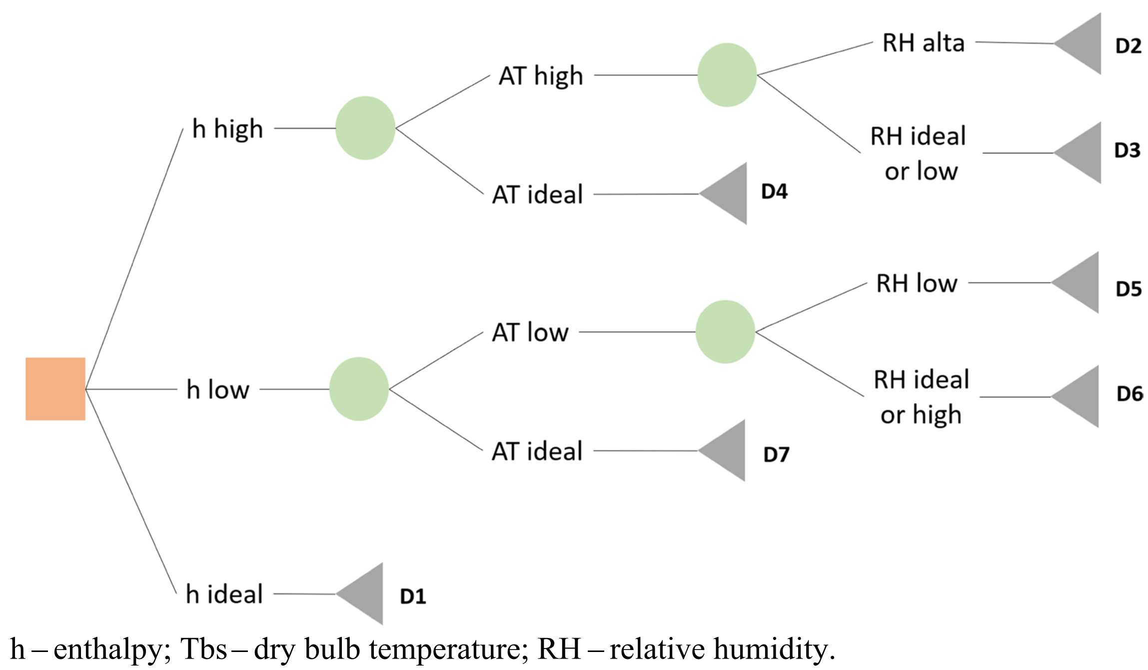

Fig. 2 Generic decision tree for diagnosing thermal comfort. D1, ideal environment; D2, hot and humid environment; D3, hot environment; D4, humid environment; D5, cold and dry environment; D6, cold environment; D7, dry environment

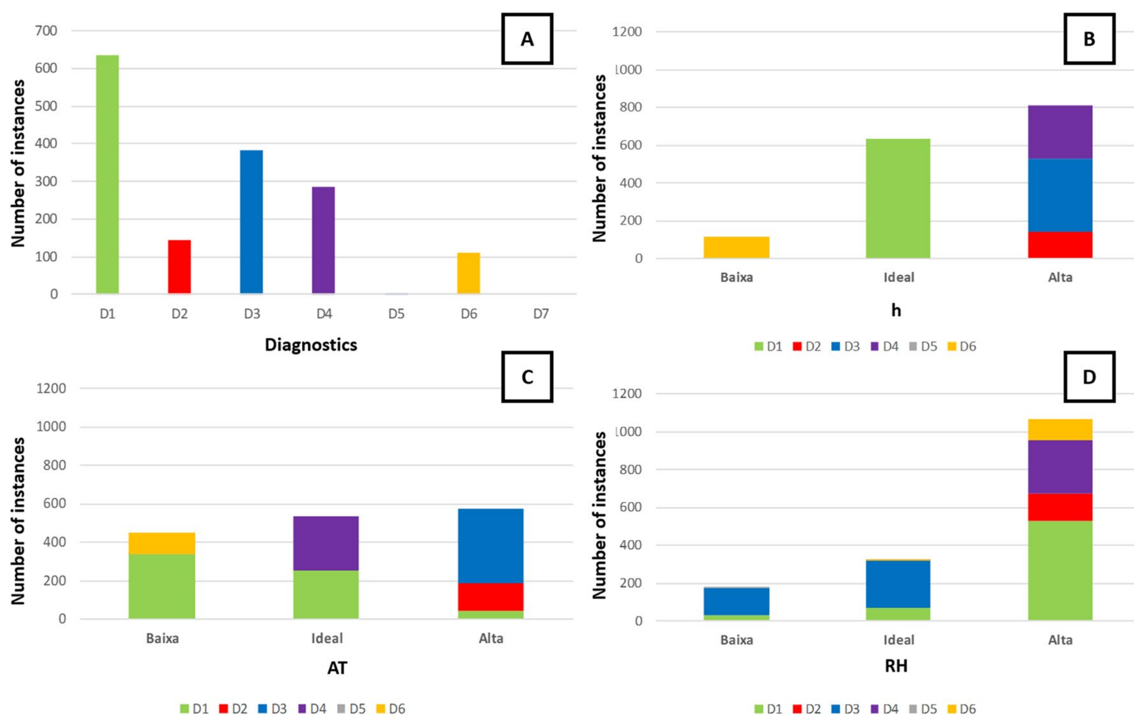

Fig. 3 Distribution of diagnoses in the database (**A**) and distribution of enthalpy (**B**), dry bulb temperature (**C**), and relative humidity (**D**) per diagnosis. h, enthalpy; AT, dry bulb temperature; RH, relative humidity; D1, ideal environment; D2, hot and humid environment; D3, hot environment; D4, humid environment; D5, cold and dry environment; D6, cold environment; D7, dry environment

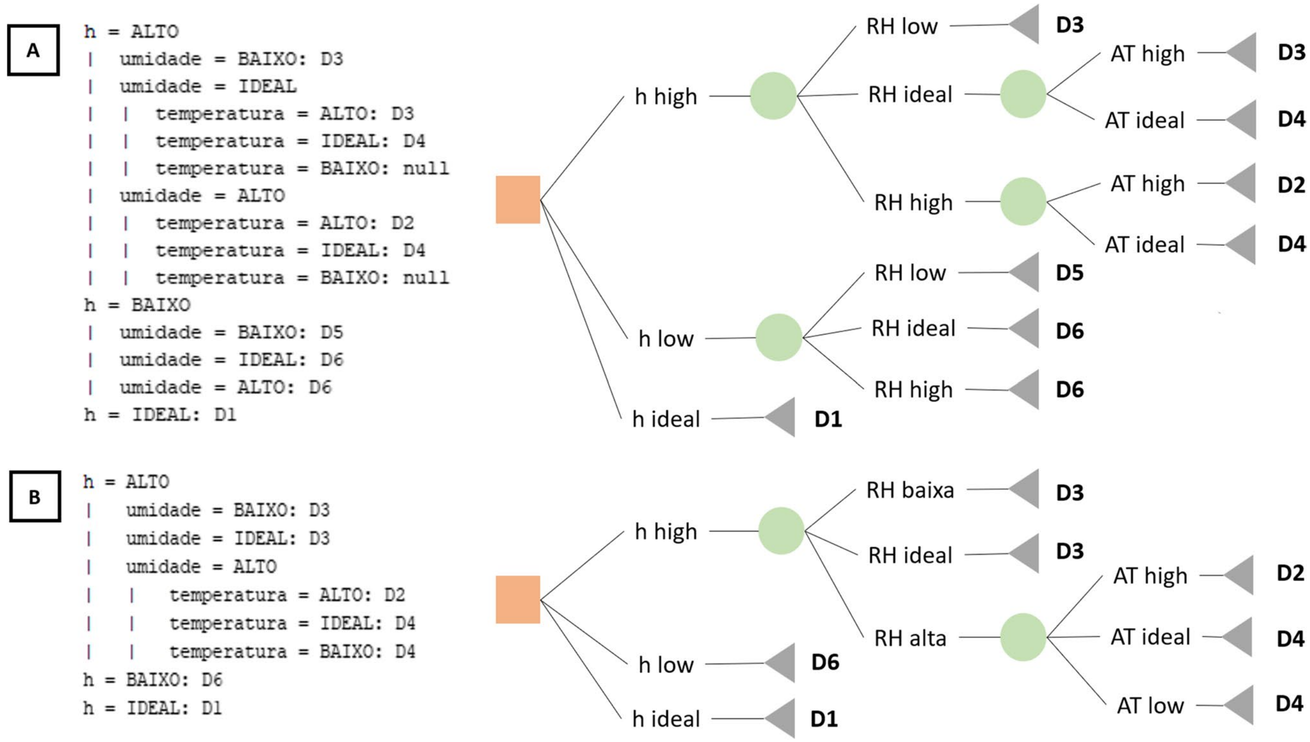

Fig. 4 Structural decision trees, from the Weka ® software, and their graphical representation, using the ID3 algorithm (**A**) and c4. 5 (**B**)

clear parameters for AT, but few present specific limits for RH, placing this variable as a secondary characteristic in the determination of thermal comfort; in the production of milk and eggs, there is a greater interest in establishing criteria for producing animals (dairy cows and laying birds), lacking parameters for young animals; many of the studies—both national and international—date from the 1980s and 1990s, with few updates for modern breeds and lineages. Cassuce et al. (2013) updated the thermoneutral zones for broilers from 0 to 21 days (31.3, 1st week; 25.5, 2nd week; and 21.8 °C, 3rd week), and Andrade et al. (2019) presented similar work for laying hens in the growing phase.

Finally, although several authors agree that the species, breed, sex, age, physiological state, the acclimatization process, and other factors must be considered to understand the thermoneutral ranges of production animals (Martello et al. 2004; Nascimento et al. 2019), literature uses generic parameters. In this context, the standardization of AT and RH based on records found in literature as part of the methodology presented in this study (Table 3) minimized some of the deficiencies in the use of these indices by proposing ranges of LCZ, ZCT, and UCZ that unified the set of base references from the affinities of these texts.

Still, in the development of a methodology that uses the psychrometric ratios of the air, the standardization of the AT and RH ranges was important to establish the critical and comfort zones for the enthalpy. This work updates the enthalpy ranges established by Barbosa Filho et al. (2007) by incorporating the considerations made in Table 3 and allowing us to obtain the enthalpy based on location (by local atmospheric pressure). When calculating the enthalpy, Barbosa Filho et al. (2007) used the equation presented by Furlan (2001), which uses only AT and RH as input variables. Queiroz et al. (2012) recalculated the enthalpy for broilers considering the calculations by Rodrigues et al. (2011), but only for regions at sea level (with pressure at 1 atm). Table 4 shows that for lower altitude locations (and higher atmospheric pressure), the h values are adjusted downwards, mainly the UCZ, concluding that this variable is greatly relevant to obtain a more accurate thermal comfort diagnosis.

Although the h, by itself, already indicates the situation of thermal comfort of the production animals, the methodology developed in this work aimed to discuss the causes and possible indications of improvements in the housing environment, being necessary, therefore, to also evaluate the AT and the RH. Diagnoses 1 to 7 start from the psychrometric curves, which indicate how AT and RH can be adjusted to insert the animals within the ideal zone of h, as graphically exemplified by Kumar et al. (2016) with thermal comfort zones for humans.

The D1 diagnosis indicates that h is within the ideal range of thermal comfort for production animals. In this sense, the recommendation is to keep the psychrometric conditions of the environment constant.

High enthalpy offshoots are diagnosed at D2, D3, and D4. The D2 result indicates that AT and RH are above what is considered comfortable for the animals. In these environments, it is recommended to promote ventilation through curtain management, fans, and/or localized air ducts, with the aim of promoting heat exchange by convection and evaporation (better thermal sensation) (Khongsatit et al. 2019; Santos et al. 2009). Unlike D2, D3 allows the use of RH, which is low or ideal, to regulate Tbs in environments. In this scenario, it is possible to activate mechanisms that use air humidification (e.g., sprinklers and nebulizers) in the air cooling process, with emphasis on evaporative adiabatic cooling systems (Smith et al. 2016). In response, the Tbs decreases, the RH increases, and the enthalpy stabilizes, always remembering that the RH should not exceed what is acceptable for the animals (Martello et al. 2004; Queiroz et al. 2017). D4, in turn, indicates that there are problems related to high humidity. Air renewal in this case is important, as the accumulation of humid air inside the sheds must be removed. Jackson et al. (2018) highlight the importance of minimum ventilation in air exchange processes in facilities for production animals.

Diagnostics D5, D6, and D7 come from environments with low h. The resulting D5 indicates that both AT and RH are below ideal, requiring heating and humidification of the environment. D6, in turn, indicates that the environment is cold, which is a common situation for young animals such as chicks and piglets (Braga et al. 2018; Sartor et al. 2018). For both diagnoses, it is possible to obtain an increase in Tbs with the use of artificial devices, such as hoods, wood stoves, heated floors, and protected areas (protection circles and concealed shelters), among others. For D5, attention should be paid to relative humidity, which can be managed by minimum ventilation (Menegali et al. 2013). D7 indicates that there is a problem with the dry environment. For such a diagnosis, it is important to promote humidification—with nebulizers—discontinuously, to avoid drastic changes in the temperature of the environment.

Diagnostics promote basic solutions, establishing priorities for action in thermally uncomfortable environments for animals. In any case, the specificities and limitations (economic, structural, and regional, among others) of each rural enterprise must be taken into account.

Studies use sophisticated techniques for predicting and determining the thermal comfort of production animals, such as neural networks and fuzzy modeling (Abreu et al. 2015; Damasceno et al. 2017; Sousa et al. 2016). As a methodology of practical use, this work defined the use of decision trees by the following criteria: (a) They are easy to interpret and can be represented graphically; (b) they do not demand a robust and laborious pre-processing of the input data; (c) they are sensitive to multiple label problems (when an instance is associated with more than one class simultaneously); (d) they allow operating with missing values, which is recurrent in environment data; and (e) they allow manipulation of categorical and numeric data. It is worth remembering that the decision tree resulting from the last stage of the developed methodology (Fig. 2) is generic and should be recognized as a starting point for specific studies, considering the animal and the rearing phase of interest, the time of year, and the experiment location.

The case study aimed to apply and validate the methodology proposed in this work, evaluating an individual shelter for calves during the fall. The averages for the database were 19.43 ± 6.21 °C for Tbs, 77.17 ± 18.33 % for RH, and 48.48 ± 12.35 kJ/Kg of dry air for h. Although diagnosis D1 (in comfort) obtained the highest number of instances, diagnoses related to high enthalpy (D2, D3, and D4) characterized the shelter most of the time, adding together 812 (52%) instances. Even in autumn, diagnoses related to low enthalpy (D5, D6, and D7) represented 113 instances added (about 7% of the entire database). The results highlight the difficulty of housing calves in tropical and subtropical climates, as is often observed in the results of other studies (Araujo et al. 2016; Cabral et al. 2017).

The properties of the database used were decisive in the configuration of the decision trees proposed by the ID3 and c4.5 algorithms. As h is directly derived from Tbs and UR, data pre-processing was used (converting numerical values into ordinal categorical data), and all values and classes present in the database were known, both networks showed excellent accuracy. It is worth mentioning that in non-ideal situations (with missing values and uncertainties in the classification), the accuracy may decrease.

The good accuracy of decision trees is recurrent when applying them in thermal comfort classification. Perissinotto and Moura (2007) achieved 96% accuracy using numeric data from UTI. Vale et al. (2008) achieved 89% accuracy using wind speed and ambient temperature as attributes, which are quantities that do not have direct dependence. Nascimento et al. (2011) achieved a maximum accuracy of 60% from several sets of rules, using a complex set of attributes such as relative humidity, dew point temperature, dry and wet bulb temperature, THI, black globe temperature, age of birds and surface temperatures.

When observing the decision trees generated by the algorithms (Fig. 4), it is noted that they are more synthetic when compared to the theoretical model (Fig. 2). It is important to emphasize that the trained trees reflected the reality of the data used in the case study, giving greater emphasis to situations where h was high and discarding diagnoses D7, which did not appear in the database, and D5, misclassified. The case study thus denotes the importance of adapting the standard methodology—through the theoretical decision tree—for each circumstance of use, simplifying the proposed method when necessary.

Conclusion

This work summarizes the development of a methodology for evaluating the thermal stress of production animals using as a basic principle the psychrometric relations of the air. The methodology presents as a tool of great potential because it is simple to understand and to use, thus allowing its adaptation to particular cases. Even so, the methodology does not lose its character of a more complex constitution, which, in addition to classifying the comfort situation, suggests possible changes in the environment.

When applying the methodology developed in the case study, problems of thermal stress in calves caused by the high enthalpy in the housing environment during a good part of the experimental period (autumn) were reported. Based on real data, it was possible to adapt decision-making to a specific system, simplifying decision trees and maintaining a high level of accuracy.

Author contribution S. C. J. and I. J. O. S. led the research and investigation process, data collection, and formal analysis; wrote the original draft; and participated in conceptualization and methodology and the project administration. R. M. F. S. participated in the critical review and wrote the original draft.

Funding This study was financed by the Coordination for the Improvement of Higher Education Personnel (CAPES).

Data availability The data that support the findings of this study are available from the corresponding author, G. B. Mourão, upon reasonable request.

Code availability Not applicable.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Conflict of interest The authors declare no competing interests.

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