Italian Journal of Animal Science

ISSN: 1828-051X (Online) Journal homepage: www.tandfonline.com/journals/tjas20

Infra-red thermography and behavioural observations for non-invasive monitoring of heat stress in Italian Alpine dairy goats

Martina Zappaterra, Naod Thomas Masebo, Valeria Bocchi, Barbara Padalino, Martina Felici, Marilena Bolcato, Rossella Gecchele & Leonardo Nanni Costa

To cite this article: Martina Zappaterra, Naod Thomas Masebo, Valeria Bocchi, Barbara Padalino, Martina Felici, Marilena Bolcato, Rossella Gecchele & Leonardo Nanni Costa (2026) Infra-red thermography and behavioural observations for non-invasive monitoring of heat stress in Italian Alpine dairy goats, Italian Journal of Animal Science, 25:1, 371-388, DOI: 10.1080/1828051X.2026.2639196

To link to this article: https://doi.org/10.1080/1828051X.2026.2639196

© 2026 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.

View supplementary material

Published online: 07 Mar 2026.

Submit your article to this journal

Article views: 255

View related articles

View Crossmark data

Full Terms & Conditions of access and use can be found at
https://www.tandfonline.com/action/journalInformation?journalCode=tjas20

ITALIAN JOURNAL OF ANIMAL SCIENCE
2026, VOL. 25, NO. 1, 371–388
https://doi.org/10.1080/1828051X.2026.2639196

Taylor & Francis
Taylor & Francis Group

RESEARCH ARTICLE

OPEN ACCESS Check for updates

Infra-red thermography and behavioural observations for non-invasive monitoring of heat stress in Italian Alpine dairy goats

Martina Zappaterra[a*], Naod Thomas Masebo[a*], Valeria Bocchi[a], Barbara Padalino[a,b], Martina Felici[a], Marilena Bolcato[c], Rossella Gecchele[c] and Leonardo Nanni Costa[a]

[a]Dipartimento di Scienze e Tecnologie Agro-Alimentari, Università di Bologna, Bologna, Italia; [b]Faculty of Science and Engineering, Southern Cross University, Lismore, Australia; [c]Dipartimento di Scienze Mediche Veterinarie, Università di Bologna, Bologna, Italia

ABSTRACT

This study investigated the physiological and behavioural responses of seventeen Italian Alpine dairy goats to heat stress (HS) during the peak summer heat of 2023 in Northern Italy. Infra-red thermography (IRT) and behavioural observations were used as non-invasive monitoring tools. The goats were monitored indoors and outdoors for six days. Temperature-Humidity Index (THI) was calculated, and superficial skin temperatures (SSTs) were measured at multiple body regions using IRT. A clinical examination of the goats was performed in the morning, and behavioural observations were extrapolated from video recordings. Correlation, multivariate, and regression analyses assessed the associations between THI, SSTs, clinical parameters, and behaviours. All SSTs positively correlated with goats' rectal temperature ($p < 0.05$), suggesting the validity of the IRT. The results showed that SSTs increased significantly with THI measured indoors (all $p < 0.001$), supporting the hoof, loin, and flank regions as potential thermal windows for detecting HS. Under higher THI, the goats spent more time in sternal recumbency ($p < 0.01$) and reduced their rumination time ($p < 0.001$) indoors. Outdoors, as the THI increased, the goats increased their respiratory rate and SST, and exhibited more shade-seeking and inactivity, while reducing their nutritional behaviours (all $p < 0.001$). These adaptive responses were consistent with established thermoregulatory mechanisms. Overall, this study suggests that combining IRT with physiological and behavioural observations provides a comprehensive and non-invasive approach to assessing heat stress in goats. Integrating these indicators could improve the detection of HS and the development of management strategies to safeguard goat welfare in a Mediterranean climate increasingly affected by global warming.

HIGHLIGHTS

- Infra-red thermography (IRT) and behavioural observations were used to non-invasively assess the impact of peak summer heat on dairy goats.
- Superficial skin temperatures (SSTs) increased with the Temperature-Humidity Index (THI), especially in the hoof, loin, and flank regions.
- At high THI, goats exhibited sternal recumbency, sought shade, and were inactive. They also reduced nutrition-related behaviours.

ARTICLE HISTORY
Received 12 November 2025
Revised 9 February 2026
Accepted 25 February 2026

KEYWORDS
Infra-red imaging; dairy goats; thermal stress; behaviour; Temperature-Humidity Index

Introduction

Climate change affects the health, welfare, and productivity of livestock (Gupta and Mondal 2021; Sejian et al. 2021; World Health Organization 2025). Recent years have been characterised by abrupt and short-lived peaks of extreme heat, often occurring during the hottest days of the summer. These episodes, which can only be predicted a few days in advance (i.e. 1–5 days), are particularly critical for livestock, as they may expose animals to acute heat stress (HS) conditions within a very limited time window (McGregor et al. 2015; Godde et al. 2021; Thornton et al. 2021).

HS arises when physiological mechanisms are triggered to preserve thermal balance under elevated temperatures (Gupta and Mondal 2021). The susceptibility of livestock to HS varies based on the species,

CONTACT Martina Felici martina.felici6@unibo.it
*These authors contributed equally to the work.

Supplemental data for this article can be accessed online at https://doi.org/10.1080/1828051X.2026.2639196.

© 2026 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited. The terms on which this article has been published allow the posting of the Accepted Manuscript in a repository by the author(s) or with their consent.

age, genetics, and management (Gupta and Mondal 2021; Kitajima et al. 2021). High-producing cows, for example, are more vulnerable to HS due to their high metabolic heat production (Kitajima et al. 2021). Conversely, goats are considered climate-resilient livestock due to their morphological and thermophysiological features (Samara 2024), which provide them with better thermotolerance (Sejian et al. 2021).

The goat population density in the Mediterranean region exceeds the global average (Morand-Fehr et al. 1983). In the Mediterranean region, goat management is either extensive, occasionally incorporating cultivated forages, or intensive, where natural pastures only marginally contribute to the animals' nutritional requirements (Morand-Fehr et al. 1983). However, the Mediterranean region is warming up 20% faster than the rest of the world (UNEP/MAP 2021), suggesting that the frequency and intensity of heat stress HS events affecting livestock may increase in the coming decades. This rapid warming suggests that the frequency of HS events in goats may increase in the future. Although specific long-term projections for HS in goats under Mediterranean conditions are currently limited, modelling studies conducted in other hot regions provide useful contextual insights. For example, a study in East Africa predicted a 4% increase in the number of days with severe or dangerous HS conditions for goats between 2071–2100 compared to 1981–2010 (Rahimi et al. 2021). While climatic patterns differ between regions, such projections highlight a broader global trend towards increased thermal challenges for small ruminants. Moreover, experimental evidence indicates that incremental increases in ambient temperature (e.g. from 25 °C to 30 °C or from 30 °C to 35 °C) exacerbate the severity of HS in goats, particularly in breeds not adapted to hot climates, such as Alpine goats (Lu 1989). Therefore, even goats, with their extraordinary adaptability, could be negatively impacted by the exceptionally high temperatures of recent years (Samara 2024; Samara et al. 2024).

During HS conditions, which in goats are estimated to occur at ambient temperatures above 30 °C, goats' pulse and respiration rate increase, they sweat more, and their rectal temperature rises (Berihulay et al. 2019; Gupta and Mondal 2021). The increase in pulse rate aims to dissipate the heat by increasing the blood flow to the body surfaces (Shilja et al. 2016). These physiological adaptations are paired with impairment of appetite, feed intake, feed efficiency and utilisation, growth, milk yield and reproduction (Gupta and Mondal 2021). Together with physiological changes, goats experiencing HS also exhibit behavioural changes.

Seeking shade and lying in the shade are two common behaviours exhibited by goats in HS (Gupta and Mondal 2021; Sejian et al. 2021; Ghezzi et al. 2024). Also observed are reduced feed intake and urination and defaecation frequency, as well as increased water intake, drinking frequency, and standing time (Berihulay et al. 2019; Gupta and Mondal 2021; Sejian et al. 2021; Ghezzi et al. 2024). Moreover, agonistic behaviour is common among goats when resources, such as water, are scarce (Sejian et al. 2021).

There is little literature on monitoring changes in body surface temperature in relation to HS in goats (Gupta and Mondal 2021; Samara et al. 2024). It is not widely known which regions of the body experience the greatest increase in temperature during HS in goats, or if there are regions that can serve as indicators of HS. Using non-invasive parameters, such as infra-red thermography (IRT), is an advance in assessing goat welfare in relation to the environment.

IRT is a non-invasive technique that detects infrared radiation and converts it into thermographic images (Samara 2024; Samara et al. 2024). These images can be used to detect changes in body temperature and blood flow in livestock relating to the thermal environment (Čukić et al. 2023). Indeed, IRT has been employed in animal science to evaluate stress and welfare, heat stress, heat tolerance, and thermal thresholds (Čukić et al. 2023; Samara et al. 2024). Previous studies have found associations between the Temperature-Humidity Index (THI) and the temperature of the forehead, flank, legs and abdomen regions of dairy cows, cattle and sheep, suggesting that these are reliable regions for assessing HS (Salles et al. 2016; Peng et al. 2019; Čukić et al. 2023). In goats, IRT has already been successfully used in studies related to rearing under stressful conditions (Samara 2024), changes in mammary tissue (Alejandro et al. 2014), and HS and water deprivation (Samara et al. 2024), and it is considered an appropriate method for assessing the goats' body-thermal status.

We hypothesised that goats exposed to HS conditions would show an increase in superficial skin temperatures (SSTs), particularly in body regions that were highly exposed to direct sunlight/radiation (e.g. loin and flank regions). We also anticipated observing an increase in the frequency or duration of behaviours such as drinking, seeking shade, and agonistic behaviour, alongside a decrease in feed intake. Our study aimed to investigate the physiological and behavioural responses of goats housed indoors (i.e. in pens) and

outdoors (i.e. at pasture) to HS conditions in Italy using non-invasive IRT and behavioural observations.

Materials and methods

This study was approved by the animal welfare committee of the *Alma Mater Studiorum* - University of Bologna (Protocol Number 77988 of 08/04/2022) and was conducted on a teaching dairy goat farm, located in the province of Bologna, Ozzano Emilia, at the Department of Veterinary Medical Science, University of Bologna. Data was collected for six days during the study period, from July 19 to August 9, 2023. Specifically, in field data collection was performed on July 19, 20, 24, 25 and on August 7 and 8. The monitoring was intentionally scheduled to coincide with the peak heat of the season, identified based on local meteorological forecasts and confirmed by recorded temperature peaks.

Animal and housing conditions

The study included seventeen Alpine dairy goats (12 lactating and 5 non-lactating) aged from 1.5 to 8 years. The goats were accommodated in a barn consisting of two main exit doors, different-sized pens with straw bedding, equipped with feeding troughs and drinking bowls, and a dedicated milking area. The pens varied in size and accommodated different numbers of goats; pen one housed six goats, pen two housed two goats, pen three housed two goats, and pen four housed three goats. Pen five was located outside of the main barn and was covered by a canopy. It housed five goats.

In the summer season (April to October), access to the pasture was provided to goats during daylight hours (usually from 8.30 AM to 7:00 PM). The goats were all kept together in a 2500 m^2 pasture, which has both shaded and direct sunlight areas, and a single watering point (consisting of two plastic water tanks).

Environmental parameters

During the study periods, the temperature (dry bulb) and humidity of the inside environment of the goat's barn were continuously monitored using a weather station (Kestrel 4000, Nielsen-Kellerman Company, Boothwyn, PA, USA) placed approximately 1.5 metres from the ground. This allowed for monitoring the environmental parameters (i.e. temperature and humidity) even before the data collection days (i.e. during the previous 12 h). Additionally, the environmental temperature, humidity, and floor temperature of each of the five pens were measured at the time of data collection and recorded using a weather station and thermal camera (FLIR E76 24; FLIR Systems AB, Danderyd, Sweden) in the early morning around 7:00 AM and evening around 7:30 PM (Table S1).

Likewise, we monitored the environmental dry bulb temperature, humidity, and floor temperature in the pasture where the goats spent the day using a weather station and a thermal camera, respectively. This involved splitting the pasture into two zones: the sunny pasture, which received direct sunlight, and the shaded pasture, sheltered by trees. Recordings were performed at 9:00 AM (i.e. morning), 11:00 AM (i.e. late morning), 1:00 PM (i.e. early afternoon), 3:00 PM (i.e. afternoon), and 5:00 PM (i.e. late afternoon; Table S2).

Superficial skin temperatures

The superficial skin temperature (SST) of the goats was measured while they were in their pens using a thermal camera (FLIR E76 24; FLIR Systems AB, Danderyd, Sweden). Measurements were taken in the early morning around 7:00 AM and in the evening around 7:30 PM, after the goats returned to their pens from pasture. Infra-red thermography (IRT) images were taken of the following body regions: the caruncle of the left eye, the left flank, the loin, the carpus and the front hoof of each goat. Additionally, in lactating goats, IRT images of the udder were taken before and after morning milking. Depending on the best focus of the image taken, the SST measurement from the carpus, hoof and or udder could refer to either the right or left forelimb or udder. The loin region, on the other hand, was taken from above. The thermal camera was positioned approximately at 80 cm.

In the pasture, a subsample of goats from under the direct sunlight and from the shaded zones of the pasture were randomly selected, and infra-red thermography images of the loin region of the goats were taken using a thermal camera (FLIR E76 24; FLIR Systems AB, Danderyd, Sweden) to assess the SST (Table S2).

Clinical examination

A clinical examination of the goats was performed by a single trained veterinarian in the morning before the goats were let out to the pasture. The clinical examination was conducted, giving special emphasis on the udder and respiratory systems. The rectal temperature

and body condition score (BCS; Mattiello et al. 2018) of each goat were also recorded (Table S3).

Behavioural observations

The goats were video recorded during the study period to observe their behavioural patterns. A 10–minute video was recorded using a Sony HDR-CX405 camera (Sony Inc, Minato, Tokyo, Japan) at 7:00 AM while the goats were inside the pens before milking. Then another 10–minute video recording was performed after the goats returned from the pasture to their respective pens around 7:00 PM. The videos were recorded by three researchers who positioned themselves in front of each pen at approximately 1.5 metres to ensure they could capture every subject. Additionally, during the daytime, when the goats were in the pasture, a 10–minute video recording was conducted at 9:00 AM, 11:00 AM, 1:00 PM, 3:00 PM, and 5:00 PM.

One trained observer then analysed the videos. Concerning the video recorded in the pens, the behaviour of the goats was analysed with an ad libitum sampling method (Altmann 1974; Powell and Baskir 2021) using the ethogram shown in Table 1. Behavioural states (e.g. walking, standing, etc.) were registered by evaluating their duration (seconds), while behavioural events (e.g. defaecation, vocalisations, etc.) were collected by considering their frequency (number of behavioural manifestations/ten minutes). The different behavioural states (walking, standing, sternal and lateral recumbency, rumination while standing and while lying) were considered mutually exclusive.

The behavioural analysis of the videos recorded in the pasture was conducted using the instantaneous scan sampling method and the ethogram shown in Table 2. A scan was analysed every minute (10 scans per video). Each scan was viewed to record the number of goats exhibiting that behaviour, and it was noted whether the goat exhibited that behaviour while in the sun or in the shade. When an animal had more than half of its body (and at least two legs) in the shaded area, it was considered to be in the shade (Zappaterra et al. 2021).

Subsequently, videos recorded in the pasture were examined a second time to assess the goats' respiratory rate.

Data handling

Names, definitions, types, categories, and statistics applied to all the categorical and continuous variables subjected to descriptive or further statistical analysis are shown in Table 3.

One of the goats housed in pen two received anti-inflammatory drug therapy for lameness that manifested during the data collection period. The treatment altered the detection of the parameters of interest, resulting in the exclusion of the subject from the study.

The dry bulb temperature and humidity of the pens were used to calculate the Temperature-Humidity Indices (THIs), following the equations proposed by

Table 1. Ethogram employed to examine the behaviours of the dairy goats in pens.

Behaviour	Definitions
Behavioural states	
Walking* (D)	A goat standing on all four legs and moving around by taking more than one full step.
Standing* (D)	A goat standing on all four legs, without moving.
Sternal recumbency* (D)	The goat is lying with its sternum in contact with the ground and all its limbs under its body. Alternatively, one front limb is extended.
Lateral recumbency* (D)	A goat lying with most of its body on the left or right side, with all limbs outstretched in the same direction.
Rumination while standing*	The goat stands on all four legs without moving while a bolus goes back into its mouth. The goat then chews the bolus.
Rumination while lying*	The goat lies down while a bolus goes back into its mouth. Then, the goat chews it.
Feeding	The goat takes food into its mouth.
Drinking	The goat drinks from a drinking bowl/water tank.
Behavioural events	
Urination (F)	The goat bends their hind legs and partially raises its tail to excrete urine.
Defaecation (F)	The goat bends their hind legs and partially raises its tail to eliminate faeces.
Vocalisation (F)	The goat employs a range of sounds to communicate with each other (e.g. bleating, snorting, grunting).
Self-grooming (F)	Repeated movement of the mouth, tongue or horns directed at the goat's own body parts.
Self-rubbing (F)	Repeated movement of the neck or other body parts against iron bars/walls/trees or to the ground.
Negative interactions (F)	A group of agonistic behaviours includes the goat pawing, rushing towards, or directing its forehead towards the opponent without physical contact; pushing another animal that is resting or another active goat (standing, eating, or moving) with its head; and physically forcing another goat to leave its resting or feeding position by pushing or butting from the side or behind.

Behavioural states are expressed as durations (D) while behavioural events are expressed as frequencies (F). Mutually exclusive behaviours are marked with an asterisk.

Bøe et al. 2007 (for the definition of Standing); Pucora et al. 2019 and Menchetti et al. 2021 (for the definitions of Sternal recumbency and Lateral recumbency); Siebert et al. 2011, Morgan 2023, and Naidu 2023 (for the definition of Vocalisation); (Andersen and Bøe 2007); Andersen and Bøe 2007 (for the definition of Negative interactions).

Table 2. Ethogram employed to examine the behaviours of the dairy goats at pasture.

Behaviour	Definitions
Idle	A goat showing no apparent activity or purpose at the time of the sampling (Duve and Jensen 2012; Webb et al. 2017). This includes behaviours such as standing, sternal recumbency, and lateral recumbency.
Not idle	A goat exhibiting any activity or purpose at the time of sampling, such as walking, rumination while standing, rumination while lying, feeding, drinking, urination, defaecation, vocalisation, self-grooming, self-rubbing, sniffing each other[a], and allo-grooming[b], as well as resting together[c] and engaging in negative interactions.
Nutrition	Any feeding behaviour exhibited by a goat, such as rumination while standing or lying down, or feeding.
Other	A goat showing different behaviour from feeding-related activities, such as walking, standing, sternal recumbency, lateral recumbency, drinking, urination, defaecation, vocalisation, self-grooming, self-rubbing, sniffing each other[a] and allo-grooming[b], as well as resting together[c] and engaging in negative interactions.

For each behaviour, the number of goats performing it was indicated, as well as whether it was performed in the sun or shade.
[a]Sniffing each other: a goat sampling odour to gain information on conspecifics. This involves inhaling scents and directing them towards the vomero-nasal organ for processing (Cann et al. 2019).
[b]Allo-grooming: a goat licking, nibbling, or scraping the body (head, neck, torso) of another with tongue, lips, or teeth (Toinon et al. 2022).
[c]Resting together: A goat lying down in physical contact or proximity with one or more conspecifics (Andersen and Bøe 2007).

the National Research Council (National Research Council 1971).

The animals were exposed to both the pen/barn and pasture environments daily, which may have introduced carry-over effects from prior heat exposure. For this reason, the NRC THI of the previous 12 h (night hours from 9:00 PM to 7:00 AM for the barn and from 9:00 AM to 5:00 PM for the pasture) was calculated and included among the independent variables in the statistical models. THI and THI of the previous 12 h were calculated using the temperatures and humidities recorded in the pens/barn or at pasture. Then, all the THIs and THIs of the previous 12 h were divided into three thresholds of environmental stress based on the literature: mild (<75), moderate (75–80), and severe (>80) (Srivastava et al. 2021).

Of the body regions monitored using IRT, the average SST was retained for the flank, loin, carpus, hoof, and udder, and the maximum SST was retained for the eye.

All data were checked for outliers using box plots and evaluating the distribution of measures within each of the six days. No outliers were detected.

The data were organised in Microsoft Excel® (Microsoft® Excel® for Microsoft 365 MSO Version 2306 Build 16.0.16529.20100). In the Excel spreadsheets, each row represented a goat, and each column represented a variable related to the environmental parameters, SSTs, clinical examinations, and behavioural observations.

Statistical analysis

Descriptive statistics were presented for continuous variables as the mean ± standard deviation (SD) and for categorical variables as counts and percentages. Moreover, descriptive graphs of SSTs and behaviour distribution according to Pen THI were realised.

An exploratory analysis using Spearman's rank correlation coefficient was conducted to investigate the correlations between Rectal T and SSTs, and between SSTs and behaviours.

The relationships among behaviours and Pen THI were displayed through principal component analysis (PCA).

Associations with Pen THI classes and Barn THI of the previous 12h classes were investigated using different modelling approaches. Univariable and multivariable Linear Mixed Effects Regression (LMER) models were used for SSTs. Behavioural states, expressed as transformed proportions, were analysed through Generalised Additive Models for Location, Scale and Shape (GAMLSS) with an inflated beta distribution, whereas behavioural events were evaluated with Zero-Inflated Negative Binomial (ZINB) models.

Univariable linear models tested the associations between Respiratory Rate and Loin Taver, Shade THI and Sun THI, and Negative Binomial Generalised Linear Models (NBGLM) were used to test Idle, Not Idle, Nutrition, and Other in association with Pasture THI adjusted.

The results of the univariable linear models, LMERs, and NBGLMs are reported as estimates, odds ratios (OR), 95% confidence interval (CI), and Wald test/ANOVA p-values. The results of GAMLSS and ZINB models are reported as estimates, 95% CI, as well as p-values related to the 'mu' and 'nu' parameters, and to the count and zero-inflated models, respectively. The goodness of the regression models was assessed using indicators such as R-squared (R^2), Akaike Information Criterion (AIC), Likelihood Ratio Test (LRT), and Pseudo R-squared (Pseudo-R^2), depending on the type of regression model.

Significance was set at $p < 0.05$. All the statistics were performed using R software (R Version 4.4.2; www.r-project.org).

Table 3. Names, definitions, types, categories, and statistics applied to the variables included in the study.

Name	Definition	Type of variable	Categories	Statistics
Environmental parameters				
Pen T	The dry bulb temperature of the five pens	Continuous	–	Descriptive
Pen H	The humidity of the five pens	Continuous	–	Descriptive
Pen floor T	The temperature of the floor of the five pens	Continuous	–	Descriptive
Pen THI	The Temperature Humidity Index calculated using Pen T and Pen H according to the equations proposed by the National Research Council	Continuous	–	Descriptive, Regression
Pen THI classes	Thresholds of the Pen THI to define the degree of environmental stress	Categorical	Mild (<75), Moderate (75–80), Severe (>80)	Descriptive, Regression
Barn T of the previous 12h	The dry bulb temperature inside the goats' barn 12 h before data collection	Continuous	–	Descriptive
Barn H of the previous 12h	The humidity inside the goats' barn 12 h before data collection	Continuous	–	Descriptive
Barn THI of the previous 12h	The Temperature Humidity Index recorded 12 h before data collection. It was calculated using T of the previous 12h and H of the previous 12h according to the equations proposed by the National Research Council	Continuous	–	Descriptive, Regression
Barn THI of the previous 12h classes	Thresholds of the Barn THI of the previous 12 h to define the degree of environmental stress	Categorical	Mild (≤75), Moderate (75–80), Severe (≥85)	Descriptive, Regression
Shade T	The temperature in the shaded areas of the pasture	Continuous	–	Descriptive
Shade H	The humidity in the shaded areas of the pasture	Continuous	–	Descriptive
Shade ground T	The temperature of the ground in the shaded areas of the pasture	Continuous	–	Descriptive
Shade THI	The Temperature Humidity Index recorded in the shaded areas of the pasture. It was calculated using Shade T and Shade H according to the equations proposed by the National Research Council	Continuous	–	Descriptive, Regression
Sun T	The temperature of the sunny areas of the pasture	Continuous	–	Descriptive
Sun H	The humidity of the sunny areas of the pasture	Continuous	–	Descriptive
Sun ground T	The temperature of the ground in the sunny areas of the pasture	Continuous	–	Descriptive
Sun THI	The Temperature Humidity Index recorded in the sunny areas of the pasture. It was calculated using Shade T and Shade H according to the equations proposed by the National Research Council	Continuous	–	Descriptive, Regression
Pasture THI of the previous 12 h	The Temperature Humidity Index recorded in the pasture 12 h before data collection. It was calculated according to the equations proposed by the National Research Council	Continuous	–	Descriptive
Wind speed	Wind speed in metres per second (m/s)	Continuous	–	–
Shade radiation	The solar energy received by one square metre of shaded surface area over the course of a day expressed as Megajoule/square metre/day (MJ/m^2/day)	Continuous	–	–
Sun radiation	The solar energy received by one square metre of sunny surface area over the course of a day expressed as Megajoule/square metre/day (MJ/m^2/day)	Continuous	–	–
Pasture THI adjusted	The Temperature Humidity Index recorded in the pasture and adjusted for the shade THI, Sun THI, Wind speed, Shade radiation, and Sun radiation	Continuous	–	Regression
Clinical examination and SSTs				
BCS	The Body Condition Score of the goats during the data collection period	Continuous	–	Descriptive
Rectal T	The goats' rectal temperatures (°C) measured in the morning before they were let out to pasture	Continuous	–	Descriptive, Correlation
Respiratory Rate	The goats' respiratory rate (breaths per minute, bpm) measured while the goats were at pasture	Continuous	–	Descriptive, Regression
Eye Tmax	The maximum temperature of the goats' caruncle on the left eye	Continuous	–	Descriptive, Regression
Flank Taver	The average temperature of the goats' flank on the left side	Continuous	–	Descriptive, Regression
Loin Taver	The average temperature of the goats' loin. This measure was taken both in pen and at pasture	Continuous	–	Descriptive, Regression
Carpus Taver	The average temperature of the goats' carpus	Continuous	–	Descriptive, Regression
Hoof Taver	The average temperature of the goats' hoof	Continuous	–	Descriptive, Regression
Udder Before Milking Taver	The average temperature of the goats' udder before milking	Continuous	–	Descriptive, Regression
Udder After Milking Taver	The average temperature of the goats' udder after milking	Continuous	–	Descriptive, Regression

(*continued*)

Table 3. Continued.

Name	Definition	Type of variable	Categories	Statistics
Behavioural observations				
Walking	Walking behaviour expressed as the duration in seconds. See Table 1 for the definition of the behaviour	Continuous	–	Descriptive
Walking proportion	Walking behaviour expressed as the ratio between the duration of the behaviour and the total duration of the video recording (i.e. 600 s)	Continuous	–	Regression
Standing	Standing behaviour expressed as the duration in seconds. See Table 1 for the definition of the behaviour	Continuous	–	Descriptive
Standing proportion	Standing behaviour expressed as the ratio between the duration of the behaviour and the total duration of the video recording (i.e. 600 s)	Continuous	–	Regression
Sternal recumbency	Sternal recumbency behaviour expressed as the duration in seconds. See Table 1 for the definition of the behaviour	Continuous	–	Descriptive
Sternal recumbency proportion	Sternal recumbency behaviour expressed as the ratio between the duration of the behaviour and the total duration of the video recording (i.e. 600 s)	Continuous	–	Regression
Lateral recumbency	Lateral recumbency behaviour expressed as the duration in seconds. See Table 1 for the definition of the behaviour	Continuous	–	Descriptive
Lateral recumbency proportion	Lateral recumbency behaviour expressed as the ratio between the duration of the behaviour and the total duration of the video recording (i.e. 600 s)	Continuous	–	Regression
Rumination while standing	Rumination while standing behaviour expressed as the duration in seconds. See Table 1 for the definition of the behaviour	Continuous	–	Descriptive
Rumination while standing proportion	Rumination while standing behaviour expressed as the ratio between the duration of the behaviour and the total duration of the video recording (i.e. 600 s)	Continuous	–	Regression
Rumination while lying	Rumination while lying behaviour expressed as the duration in seconds. See Table 1 for the definition of the behaviour	Continuous	–	Descriptive
Rumination while lying proportion	Rumination while lying behaviour expressed as the ratio between the duration of the behaviour and the total duration of the video recording (i.e. 600 s)	Continuous	–	Regression
Feeding	Feeding behaviour expressed as the duration in seconds. See Table 1 for the definition of the behaviour	Continuous	–	Descriptive
Feeding proportion	Feeding behaviour expressed as the ratio between the duration of the behaviour and the total duration of the video recording (i.e. 600 s)	Continuous	–	Regression
Drinking	Drinking behaviour expressed as the duration in seconds. See Table 1 for the definition of the behaviour	Continuous	–	Descriptive
Drinking proportion	Drinking behaviour expressed as the ratio between the duration of the behaviour and the total duration of the video recording (i.e. 600 s)	Continuous	–	Regression
Urination	Urination behaviour expressed as frequency. See Table 1 for the definition of the behaviour	Discrete	0, 1	Descriptive, Regression
Defaecation	Defaecation behaviour expressed as frequency. See Table 1 for the definition of the behaviour	Discrete	0, 1	Descriptive, Regression
Vocalisation	Vocalisation behaviour expressed as frequency. See Table 1 for the definition of the behaviour	Discrete	0, 1, 2, 4	Descriptive, Regression
Self-grooming	Self-grooming behaviour expressed as frequency. See Table 1 for the definition of the behaviour	Discrete	0, 1, 2, 4, 5	Descriptive, Regression
Self-rubbing	Self-rubbing behaviour expressed as frequency. See Table 1 for the definition of the behaviour	Discrete	0, 1, 2	Descriptive, Regression
Negative interactions	Negative interactions behaviour expressed as frequency. See Table 1 for the definition of the behaviour	Discrete	0, 1, 3, 4, 5, 7, 8	Descriptive, Regression
Shade	The number of goats in the shaded areas of the pasture at the time of data collection	Continuous	–	Descriptive, Regression
Sun	The number of goats in the sunny areas of the pasture at the time of data collection	Continuous	–	Descriptive, Regression
Idle	The number of goats being idle at the time of data collection. This variable was also considered in relation to Shade/Sun. See Table 2 for the definition of the behaviour	Continuous	–	Descriptive, Regression
Not idle	The number of goats being not idle at the time of data collection. This variable was also considered in relation to Shade/Sun. See Table 2 for the definition of the behaviour	Continuous	–	Descriptive, Regression
Nutrition	The number of goats showing nutrition behaviour at the time of data collection. This variable was also considered in relation to Shade/Sun. See Table 2 for the definition of the behaviour	Continuous	–	Descriptive, Regression

(*continued*)

Table 3. Continued.

Name	Definition	Type of variable	Categories	Statistics
Other	The number of goats showing other behaviours at the time of data collection. This variable was also considered in relation to Shade/Sun. See Table 2 for the definition of the behaviour	Continuous	–	Descriptive, Regression

National Research Council 1971 (for THI calculations); Srivastava et al. 2021 (for the definition of the THI thresholds); Choi et al. 2024 (for the calculation of the Pasture THI adjusted.

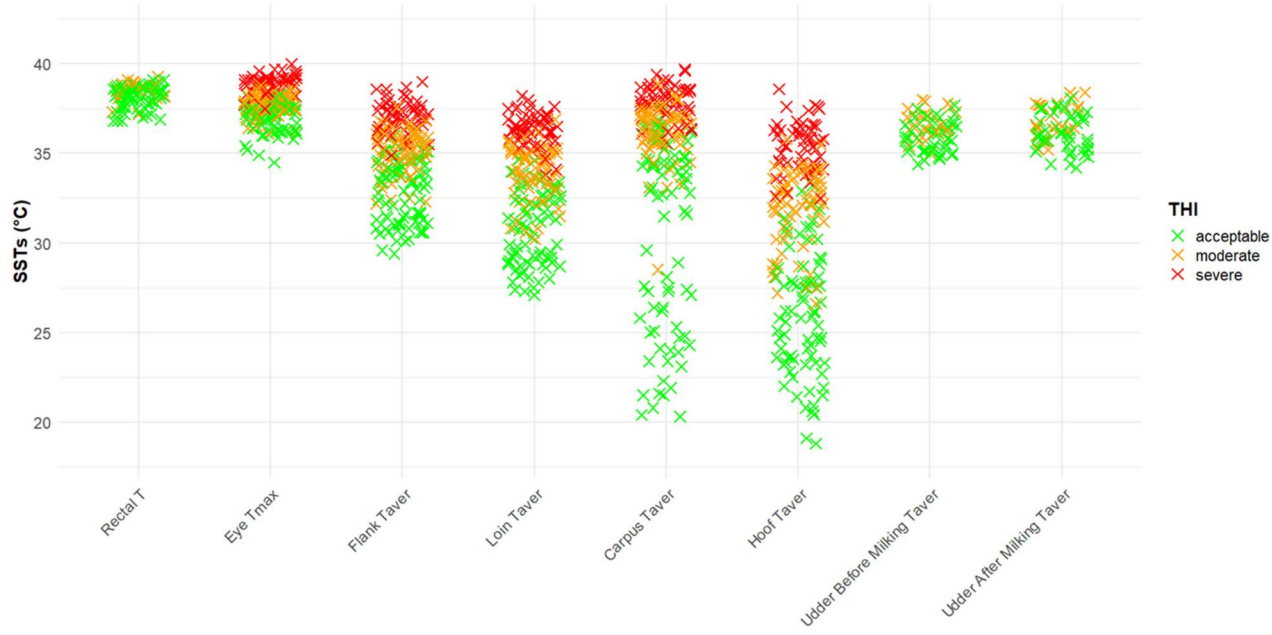

Figure 1. Strip plot of rectal T and SSTs according to THI. There are no red crosses for rectal T and udder SSTs because these measures were recorded in the morning when the THI never reached severe levels.

Results

Descriptive statistics

Environmental parameters

Across the observation period, Pen T, Pen floor T and Pen THI were higher during the evening (Pen T: 31.6 ± 1.7 °C; Pen floor T: 33.4 ± 2.8 °C; Pen THI: 80.3 ± 3.0) than in the early morning (Pen T: 22.2 ± 3.6 °C; Pen floor T: 25.2 ± 2.8 °C; Pen THI: 69.5 ± 5.3). Pen H showed the opposite pattern, with higher values in the early morning (63.7 ± 6.1%) and lower values during the evening (47.8 ± 9.1%). Barn T, H and THI of the previous 12h were consistent with the same parameters observed in the pen. Pen THI classes and Barn THI of the previous 12h classes appeared to be acceptable/moderate in the morning and tended to be moderate/severe in the evening (Table S4).

Throughout the data collection period, the mean values of Shade and Sun T, Shade and Sun ground T and Shade and Sun THI were higher in the afternoon/late afternoon than in the morning. The mean values of Shade T varied between 22.0 °C and 39.9 °C, while Sun T reached 40.2 °C in the afternoon. Shade ground T varied from a mean of 18.8 °C and 35.7 °C. Sun ground T reached values of 70.0 °C in the afternoon. Shade THI varied between a mean of 78.8 and 88.1. Sun THI showed a similar pattern, varying between a mean of 69.3 and 88.8. Conversely, the mean values of Shade and Sun H varied from 80.0% and 27.6% or 27.0%, respectively. Pasture THI of the previous 12h tended to decrease from morning to late afternoon.

Clinical examination and SSTs

The goats had BCS ranging from 2.5 to 3.5 and experienced no respiratory or udder health issues. The respiratory rate ranged from 76.2 ± 23.1 bpm to 82.1 ± 27.9 bpm when the goats were in the shade or sun, respectively.

Figure 1 shows a descriptive representation of Rectal T and Superficial Skin Temperatures (SSTs) of the goats recorded during the data collection period. Rectal T and SSTs seemed to increase across higher THI.

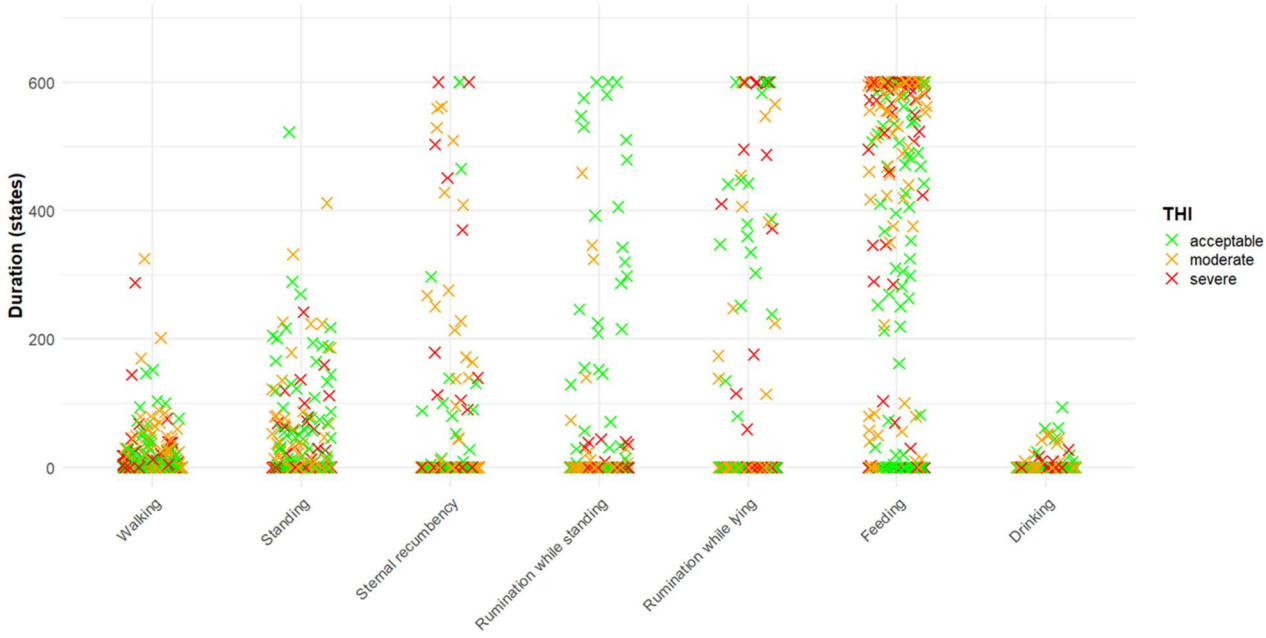

Figure 2. Strip plot of the behavioural states observed in the pens according to the THI classes. The state behaviour lateral recumbency was not observed during the data collection period.

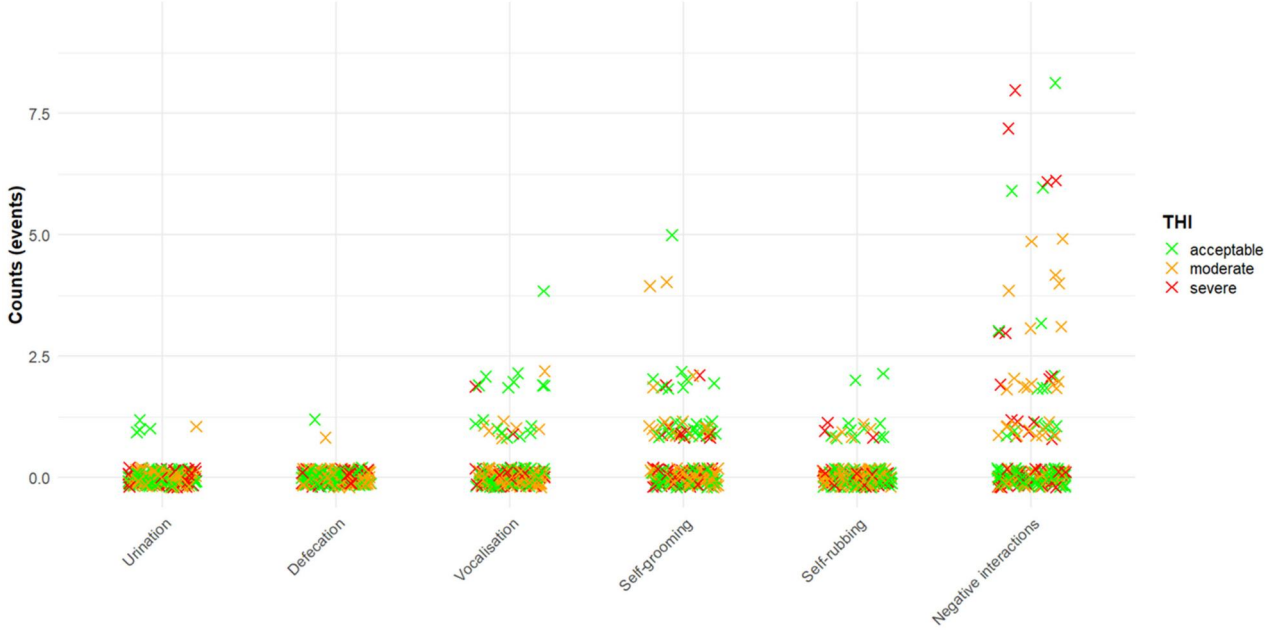

Figure 3. Strip plot of the behavioural events observed in the pens according to the THI classes.

Behavioural observations

Figures 2 and 3 show descriptive representations of the behavioural states and events observed in the pens during the data collection period. Some behaviours, such as Feeding and Sternal recumbency, appeared to increase at higher THI. Conversely, other behaviours, such as Standing and Rumination while standing, seemed to be performed more frequently when the THI was acceptable/moderate. There were no trends evident in the behavioural events.

Figure 4 shows the behaviours observed at pasture during the data collection period. The goats appeared to stay in shaded areas during the hottest part of the day, while they chose the sunny areas during the morning. Idle behaviour tended to be observed at higher temperatures, particularly in shaded areas. Nutrition-related behaviours seemed to decrease from morning to early afternoon. See the supplementary materials (Figure S1) for the graph of the behaviours observed at pasture throughout the day.

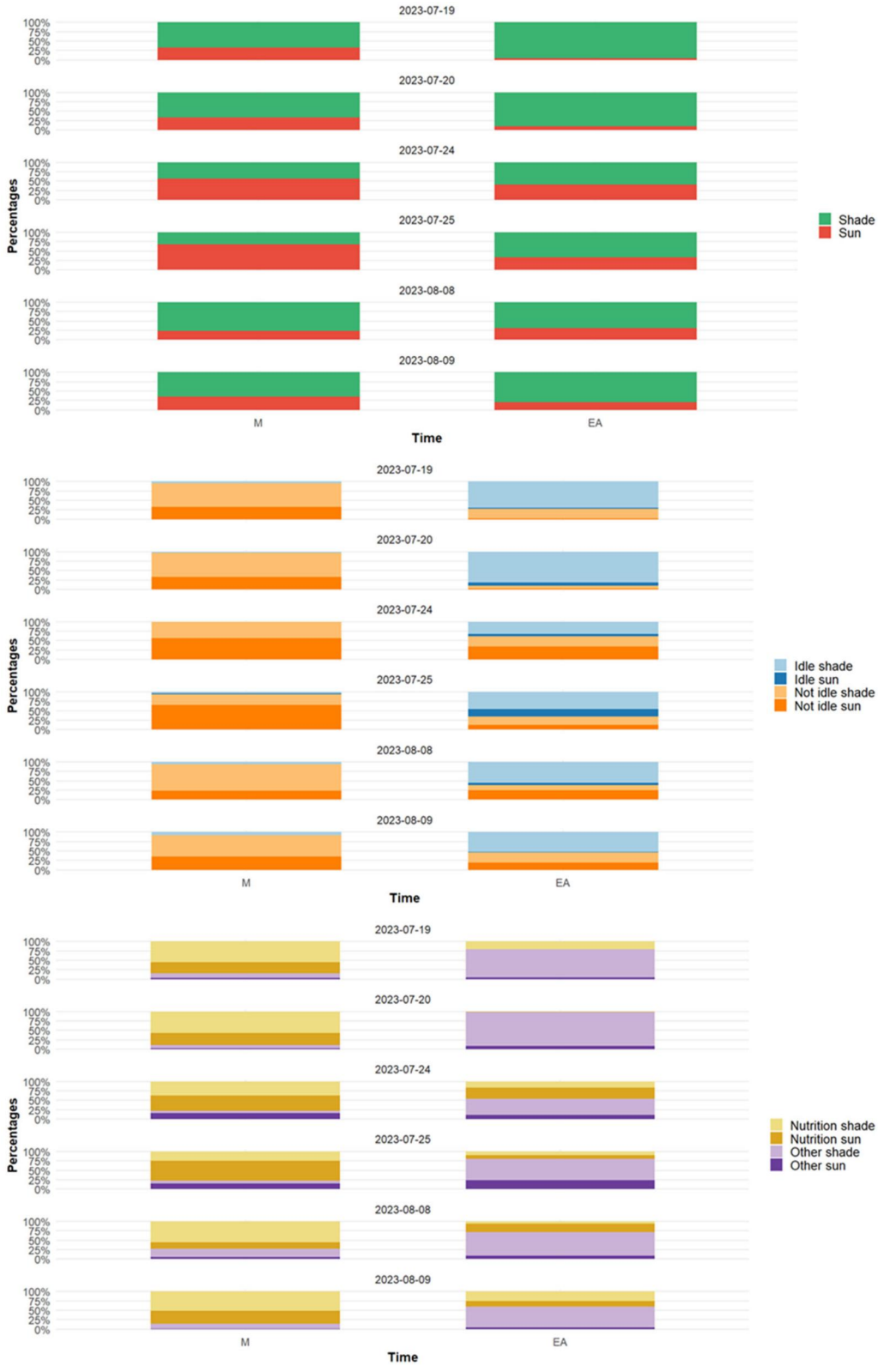

Figure 4. Stacked bar graph of the behaviour observed at pasture in the morning (M, 9:00 AM) and in the early afternoon (EA, 1:00 PM).

Correlation and PCA

Figure 5 shows the correlation between the Rectal T and the SSTs measured in the pens at 7:00 AM. All the SSTs of the considered body regions were positively correlated with Rectal T; in particular, the udder showed the strongest correlation, while the eye showed the weakest.

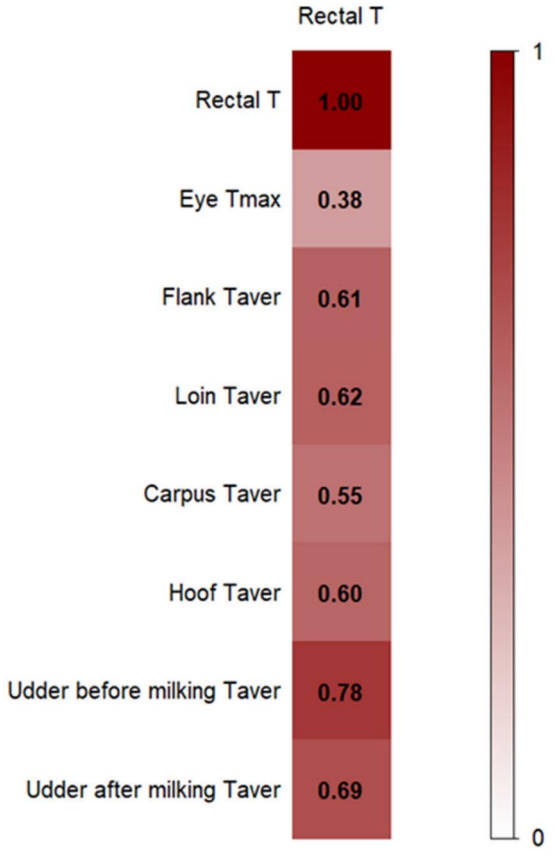

Figure 5. Correlation plot of rectal T vs SSTs. The plot shows the Spearman's rho values for each SST. Bold rho values indicate a significant correlation ($p < 0.05$).

Figure 6 shows the correlation between SSTs and behaviours. There was a moderate positive correlation between Feeding and Hoof Taver, and positive weak correlations between Drinking and Flank and Loin Taver (Akoglu 2018). Conversely, there were moderate and weak negative correlations between Rumination while standing and Loin and Carpus Taver. There were moderate/weak negative correlations between Self-grooming and all the SSTs, except Eye Tmax and Hoof Taver.

Figure 7 shows the descriptive biplot of the Principal Components Analysis (PCA) for the observed behaviours in the pens. PC1 was characterised primarily by Feeding, Standing, Rumination while lying, Negative interactions and Sternal recumbency. PC2 was explained by Standing, Vocalisation, Rumination while lying, Self-grooming, Walking and Negative interactions. In PC1, Feeding and Negative interactions appeared to occur concurrently with higher Pen THI values. Standing, Rumination while lying, and Sternal recumbency seemed to occur especially in lower THI. In PC2, Rumination while lying went in opposite directions compared to Standing, Vocalisation, Self-grooming, Walking and Negative interactions. However, PC2 does not appear to follow temperature trends.

Regressions

Associations between pen THIs and SSTs

Univariable linear regression models (LMER) to test the associations between SSTs and Pen THI classes and Barn THI of the previous 12h classes were reported in

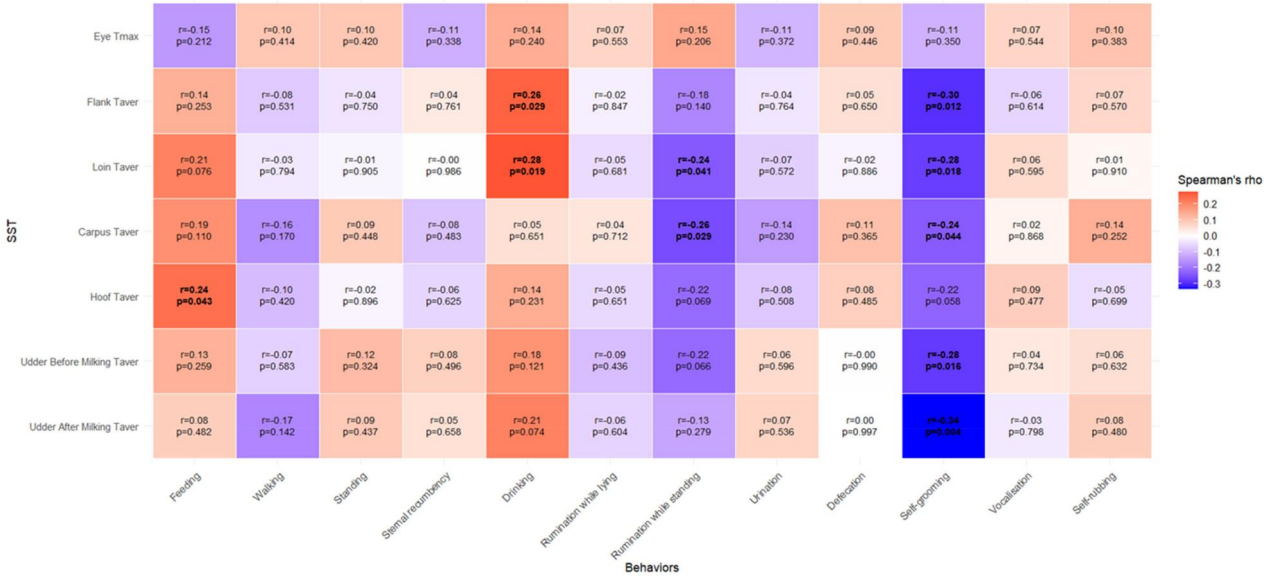

Figure 6. Correlation plot of SSTs vs behaviours. The plot shows the Spearman's rho values. Bold rho and p-values indicate a significant correlation ($p \leq 0.05$).

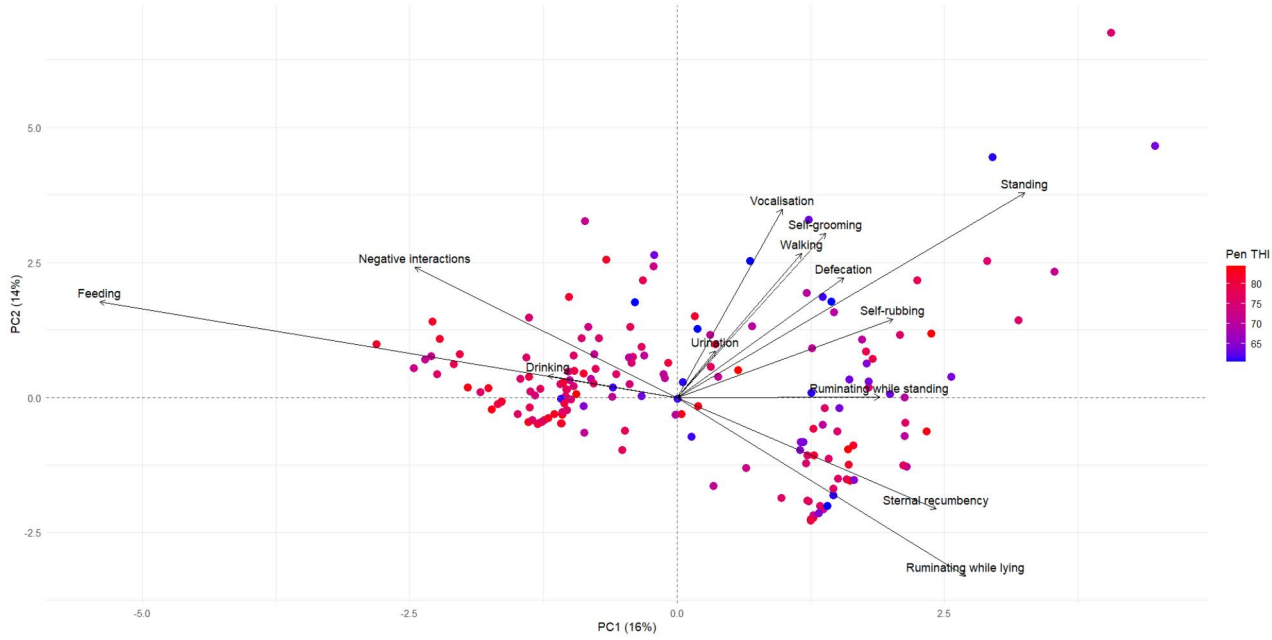

Figure 7. PCA biplot showing both PC scores of samples (dots) and loadings of behaviours (vectors). The dots are coloured according to the pen THI values. Incidentally, the percentage of variability explained by each of the two principal components.

Table 4. Multivariable Linear Mixed Effects Regression (LMER) models for the SSTs, with pen THI classes and barn THI of the previous 12h classes as the fixed effects and goat ID as the random effect.

Variable	Fixed effect	Categories	Estimate (CI)	Wald test P -value	ANOVA P-value	R^2M/R^2C	AIC
Eye Tmax	Pen THI classes	Moderate	0.350 (0.120–0.580)	**0.003**	**<0.001**	0.635/0.635	393
		Severe	0.820 (0.300–1.340)	**0.002**			
	Barn THI of the previous 12h classes	Moderate	0.870 (0.600–1.140)	**<0.001**			
		Severe	1.580 (1.000–2.160)	**<0.001**			
Flank Taver	Pen THI classes	Moderate	1.170 (0.820–1.520)	**<0.001**	**<0.001**	0.801/0.834	575
		Severe	2.050 (1.270–2.840)	**<0.001**			
	Barn THI of the previous 12h classes	Moderate	2.880 (2.470–3.290)	**<0.001**			
		Severe	4.030 (3.140–4.910)	**<0.001**			
Loin Taver	Pen THI classes	Moderate	1.580 (1.170–1.980)	**<0.001**	**<0.001**	0.840/0.860	624
		Severe	2.700 (1.790–3.610)	**<0.001**			
	Barn THI of the previous 12h classes	Moderate	3.560 (3.090–4.030)	**<0.001**			
		Severe	5.080 (4.060–6.100)	**<0.001**			
Carpus Taver	Pen THI classes	Moderate	2.930 (2.010–3.850)	**<0.001**	**<0.001**	0.661/0.743	970
		Severe	3.220 (1.120–5.320)	**0.003**			
	Barn THI of the previous 12h classes	Moderate	6.670 (5.590–7.750)	**<0.001**			
		Severe	8.140 (5.790–10.480)	**<0.001**			
Hoof Taver	Pen THI classes	Moderate	3.930 (3.210–4.650)	**<0.001**	**<0.001**	0.814/0.840	864
		Severe	5.450 (3.820–7.090)	**<0.001**			
	Barn THI of the previous 12h classes	Moderate	4.830 (3.990–5.680)	**<0.001**			
		Severe	7.000 (5.170–8.830)	**<0.001**			
Udder Before Milking Taver	Pen THI classes	Moderate	−0.000 (−0.340 to 0.34)	1.000	**<0.001**	0.574/0.574	144
	Barn THI of the previous 12h classes	Moderate	1.450 (1.120–1.790)	**<0.001**			
Udder After Milking Taver	Pen THI classes	Moderate	−0.010 (−0.430 to 0.42)	0.970	**<0.001**	0.496/0.496	176
	Barn THI of the previous 12h classes	Moderate	1.580 (1.150–2.010)	**<0.001**			

The 'acceptable' category of pen THI classes and barn THI of the previous 12h classes serves as the reference.
CI: confidence interval; R^2M: marginal R-squared; R^2C: conditional R-squared; AIC: Akaike Information Criterion.
Notes: Udder SSTs were recorded in the morning when the THI never reached severe levels.

Tables S5 and S6. Table 4 shows the results of multivariable LMER analysis that included both Pen THI class and 'Barn THI of the previous 12h classes as fixed effects. The model highlighted that all the SSTs were significantly associated with the THI values ($p < 0.001$). The models for the hoof, loin and flank regions showed high performance (i.e. higher R^2). Moving from the moderate to the severe THI category, the estimates increased for all observed regions.

Associations between pen THIs and behaviours

Univariable regression models to test the associations between behavioural states (as proportions) and events, and Pen THI and Barn THI of the previous 12h

Table 5. Multivariable generalised additive models for location, scale and shape (GAMLSS) with inflated beta distribution to test the association between state behaviours and Pen THI and Barn THI of the previous 12h.

Variable	THI	Estimate (CI) Mu	*P*-value Mu	Estimate (CI) Nu	*P-value* Nu	LRT	Pseudo R^2	AIC
Walking proportion	Pen THI	0.020 (−0.020 to 0.060)	0.386	−0.030 (−0.110 to 0.050)	0.488	0.418	−0.029	−122
	Barn THI of the previous 12h	−0.030 (−0.100 to 0.040)	0.390	0.080 (−0.030 to 0.200)	0.157			
Standing proportion	Pen THI	−0.020 (−0.070 to 0.020)	0.335	0.050 (−0.030 to 0.130)	0.208	0.092	0.075	114
	Barn THI of the previous 12h	0.010 (−0.060 to 0.080)	0.867	−0.001 (−0.120 to 0.110)	0.986			
Sternal recumbency proportion	Pen THI	0.190 (0.100–0.280)	**<0.001**	−0.010 (−0.100 to 0.090)	0.891	**0.006**	0.063	231
	Barn THI of the previous 12h	−0.220 (−0.360 to −0.080)	**0.001**	0.010 (−0.130 to 0.140)	0.937			
Rumination while standing proportion	Pen THI	−0.130 (−0.260 to −0.010)	**0.039**	0.160 (0.060–0.270)	**0.003**	**<0.001**	0.163	202
	Barn THI of the previous 12h	0.090 (−0.080 to 0.260)	0.286	−0.060 (−0.210 to 0.090)	0.440			
Rumination while lying proportion	Pen THI	−0.010 (−0.140 to 0.110)	0.825	0.108 (0.005–0.210)	**0.042**	0.293	0.020	256
	Barn THI of the previous 12h	0.040 (−0.150 to 0.240)	0.667	−0.152 (−0.300 to −0.002)	**0.048**			
Feeding proportion	Pen THI	0.020 (−0.040 to 0.080)	0.505	−0.080 (−0.180 to 0.010)	0.085	**<0.005**	0.043	344
	Barn THI of the previous 12h	0.040 (−0.040 to 0.120)	0.351	0.040 (−0.100 to 0.180)	0.578			
Drinking proportion	Pen THI	−0.040 (−0.160 to 0.070)	0.486	0.050 (−0.090 to 0.200)	0.456	0.061	0.181	57
	Barn THI of the previous 12h	−0.040 (−0.190 to 0.110)	0.585	−0.190 (−0.410 to 0.020)	0.082			

CI: confidence interval; mu (μ): Location Parameter; nu (ν): Zero-Inflation Probability; LRT: Likelihood Ratio Test; Pseudo-R^2: pseudo R-squared; AIC: Akaike Information Criterion.

were reported in Tables S7–S10. Tables 5 and 6 present the results of multivariable GAMLSS and ZINB analyses, which included the fixed effects of Pen THI classes and Barn THI of the previous 12h classes.

In Table 5, significance for the location parameter (μ) indicates an effect of THI on the proportion of time spent performing each behaviour. In contrast, significance for the parameter ν reflects changes in the probability of the behaviour being absent (0). For Sternal recumbency, goats spent a larger proportion of time lying in sternal position when Pen THI was high ($p < 0.001$), but an increase in Barn THI of the previous 12h reduced this behaviour ($p = 0.001$). No effects were detected for ν. For Rumination while standing, the average time spent in this activity decreased as Pen THI increased ($p = 0.039$). At the same time, higher Pen THI increased the probability of not observing Rumination while standing ($p = 0.003$). Similarly, for Rumination while lying, an increase in Pen THI amplified the non-occurrence of this behaviour ($p = 0.042$), while an increase in Barn THI of the previous 12h amplified its occurrence ($p = 0.048$). However, the LRT p-value was not significant, suggesting poor model fit compared to a null model. For Feeding, no effects were observed. The LRT nevertheless indicated a significant overall effect ($p < 0.005$), although pseudo-R^2 values were low, suggesting that THI had a limited explanatory power for feeding behaviour. No significant effects of Pen THI and Barn THI of the previous 12h were found for Walking, Standing, or Drinking.

In Table 6, significance in the count component indicates an effect of THI on the expected number of behavioural events, while significance in the zero-inflated component reflects changes in the odds of observing no occurrence of the behaviour.

For Vocalisation and Self-grooming, neither the count nor the zero-inflated components showed consistent associations with THI. The LRTs nevertheless indicated that inclusion of THI variables improved models' fit ($p < 0.001$). No significant effects of Pen THI and Barn THI of the previous 12h were found for Self-rubbing or Negative interactions.

Associations between Shade THI, Sun THI, respiratory rate and loin Taver

Table 7 shows the univariable linear models evaluating the effects of Shade THI and Sun THI on the goats' Respiratory Rate and Loin Taver. Both THIs were significantly associated with the examined variables ($p < 0.001$).

Table 6. Multivariable zero-inflated Negative binomial (ZINB) model to test the association between event behaviours and Pen THI and Barn THI of the previous 12h.

Variable	THI	Estimate (CI) - count model	*P*-value	Estimate (CI) - zero-inflated model	P- value	LRT	Pseudo R^2	AIC
Vocalisation	Pen THI	0.030 (−0.130 to 0.190)	0.734	4.330 (−1.470 to 10.130)	0.144	**<0.001**	0.109	194
	Barn THI of the previous 12h	−0.210 (−0.440 to 0.007)	0.058	−6.780 (−15.700 to 2.140)	0.136			
Self-grooming	Pen THI	−0.070 (−0.150 to 0.010)	0.089	−2.880 (−5.990 to 0.220)	0.069	**<0.001**	0.059	332
	Barn THI of the previous 12h	0.020 (−0.100 to 0.140)	0.760	5.540 (−0.500 to 11.580)	0.072			
Self-rubbing	Pen THI	−0.130 (−0.250 to 0.002)	0.054	−1.340 (−7.240 to 4.550)	0.655	0.064	0.064	145
	Barn THI of the previous 12h	−0.020 (−0.230 to 0.180)	0.824	0.480 (−3.190 to 4.160)	0.797			
Negative interactions	Pen THI	0.030 (−0.060 to 0.120)	0.538	−0.240 (−0.810 to 0.330)	0.407	0.201	0.014	443
	Barn THI of the previous 12h	−0.030 (−0.170 to 0.100)	0.601	−0.020 (−0.640 to 0.600)	0.951			

CI: confidence interval; LRT: Likelihood Ratio Test; Pseudo-R^2: pseudo R-squared; AIC: Akaike Information Criterion.

Table 7. Univariable Linear (LM) models for the respiratory rate and loin Taver, with shade THI and sun THI as the fixed effects.

Variable	Fixed effect	Estimate (CI)	Wald test P-value	ANOVA P-value	R^2M/R^2C	AIC
Respiratory Rate	Shade THI/Sun THI	4.040 (3.320–4.760)	**<0.001**	**<0.001**	0.453/0.453	1298
Loin Taver	Shade THI	0.470 (0.410–0.530)	**<0.001**	**<0.001**	0.630/0.630	581
Loin Taver	Sun THI	0.430 (0.240–0.620)	**<0.001**	**<0.001**	0.167/0.167	607

CI: confidence interval; R^2M: marginal R-squared; R^2C: conditional R-squared; AIC: Akaike Information Criterion.

Table 8. Negative Binomial Generalised Linear model (NBGLM) to test the association between the behaviours displayed at pasture and the pasture adjusted THI.

Variable	Estimate	IRR (CI)	Wald test P-value	ANOVA P-value	AIC
Sun	−0.040	0.970 (0.950–0.980)	**<0.001**	**<0.001**	1576
Idle	0.050	1.050 (1.040–1.070)	**<0.001**	**<0.001**	1841
Nutrition	−0.050	0.950 (0.940–0.960)	**<0.001**	**<0.001**	1664

IRR: Incidence Rate Ratio; CI: confidence interval; AIC: Akaike Information Criterion.

Respiratory Rate increased markedly with rising THI values. For Loin Taver, both Shade THI and Sun THI were associated, but the relationship was stronger under shaded conditions ($R^2 = 0.630$) than under sun exposure ($R^2 = 0.167$).

Associations between pasture adjusted THI and behaviours

Table 8 summarises the results of the Negative Binomial Generalised Linear Model (NBGLM) that evaluated the relationship between Pasture adjusted THI and behaviours displayed in the pasture. An increase in THI was significantly associated with a reduced number of goats staying in the sun or engaging in nutrition behaviours ($p < 0.001$). In contrast, idle behaviour increased with rising THI ($p < 0.001$).

Discussion

This study assessed the physiological and behavioural responses of dairy goats to varying levels of heat stress (HS) during the peak summer heat of 2023 in Italy. Changes in the superficial skin temperatures (SSTs) of goats, as detected by infra-red thermography (IRT), as well as changes in their activity, nutrition, rumination, and shade-seeking behaviour, were observed in relation to an increase in the Temperature and Humidity Index (THI). These results suggest that IRT and behavioural observations could be useful for detecting thermal stress in goats, particularly when used together. Despite being considered heat-resistant, goats implement physiological and behavioural adaptations in response to HS. Recognising and monitoring these adaptive responses is essential for implementing appropriate management strategies that help prevent thermal stress and safeguard goats' welfare, both indoors and outdoors.

Pasture-related findings

Similar to this study, other studies have reported high THI values during the summer, with the highest values occurring in the afternoon (Hossein-Zadeh 2013; McManus et al. 2015). This exposed the goats to moderate to severe HS conditions. Under higher HS, goats' respiratory rate and SST of the loin region seemed to increase, suggesting possible thermal stress (Gupta and Mondal 2021). This is consistent with what has been documented for dairy cows and sheep subjected to heat stress (Srikandakumar et al. 2003; Oliveira et al. 2025).

In our case, the goats had access to shaded areas and drinking troughs while they were out on the pasture. This allowed them to choose where to stay during the hottest hours. In line with previous studies, goats showed shade-seeking behaviour during the peak heat (Sejian et al. 2021; Most et al. 2023),

alongside reduced feed intake and increased idle time (De et al. 2020; Sejian et al. 2021) as one of the primary behavioural responses exhibited by heat-stressed animals. All the abovementioned physiological and behavioural adaptations are known to reduce body temperature and avoid heat input from solar radiation (Gupta and Mondal 2021; Most et al. 2023; Ghezzi et al. 2024).

Taken together, these findings highlight the importance of implementing targeted management strategies to mitigate HS in grazing goats, particularly during the hottest periods of the day.

Recommendations for the 'thermal' management of goats at pasture

Shade and water availability are considered among the most effective infrastructural components for preventing or reducing HS in livestock (De et al. 2020; Most et al. 2023). Trees cool the ambient air temperature by evaporating water from their leaves (Most et al. 2023). Artificial shades could promote air movement and shade areas that move with the sun (Most et al. 2023). Therefore, it would be advisable to provide natural or artificial shaded areas and water for goats in the pasture during the hottest hours of the day. This will enable them to implement the mechanisms to cope with the heat.

Pen-related findings

Similar to the pasture, daily variations in THI and related physiological adaptations were observed in pens.

Our results also confirmed positive moderate/strong correlations between Rectal T and SSTs of all the body regions we monitored. These results differ slightly from those reported in studies on goats (Gopikrishnan et al. 2024; Sun et al. 2024), dairy cows (Peng et al. 2019), and lambs (Vicente-Pérez et al. 2019). However, the ambient temperatures and THI values in those studies were lower than those recorded in our study.

The SSTs measured from multiple regions of the goats' bodies while they were in pens increased according to the THI. This finding aligns with earlier studies in goats and other livestock (Čukić et al. 2023; Mullakkalparambil Velayudhan et al. 2023; Ghezzi et al. 2024). An increase in SSTs allows for peripheral heat dissipation through the skin, thereby decreasing body core temperature (Čukić et al. 2023; Ghezzi et al. 2024). Our results revealed that goats were more responsive to HS in certain body regions than in others. This is not surprising, given that different regions of the body, known as 'thermal windows', are directly connected to the autonomic nervous system and tend to dissipate heat (Čukić et al. 2023). Ocular, nasal, and vulvar thermal windows are particularly useful in the thermographic evaluation of species such as cattle and buffalo (Mota-Rojas et al. 2021). In addition to the ocular region, we also determined the temperatures of the regions we considered to be under the direct influence of the ambient environment. The hoof, loin, and flank regions seemed to be particularly relevant thermal windows, in which SSTs increased proportionally with the increase in THI. The potential role of these thermal windows has been documented in goats (Gopikrishnan et al. 2024), sheep (Čukić et al. 2023) and buffaloes (Ghezzi et al. 2024). However, it has also been noted that these regions may be highly responsive to changes in the external climate without indicating actual thermal stress (Ghezzi et al. 2024). Furthermore, the sensitivity and specificity of all thermal windows can be affected by various factors, such as age, sex and health conditions. Specific studies on SST variations in these regions, in conjunction with other physiological and behavioural indicators, would be necessary. Nevertheless, the loin and flank regions could be of particular interest when monitoring the welfare of goats exposed to HS conditions.

The same changes in idle and rumination that were observed in the pasture were also observed in the pens. These changes have already been reported in goats experiencing HS (Alam et al. 2013; De et al. 2020; Sejian et al. 2021). Under hot conditions, sheep and goats instinctively limit their feed intake to the morning or evening. This shift peaks ruminal metabolic heat production to the cooler overnight hours (Most et al. 2023). However, we observed opposite effects of THI when monitored within 12 h prior. This is likely because the THI from the previous 12 h was estimated over the entire period, which included acceptable THI values during the night and morning. In fact, during the hot season, animals shift their physical activities and digestive processes to the night-time to minimise heat production during the hottest hours of the day (Most et al. 2023). All the other behaviours we monitored showed non-significant variations, suggesting that they were less influenced by HS than resting and rumination.

Overall, these results underline the complexity of interpreting physiological and behavioural responses to HS and highlight the need for integrated assessment frameworks when evaluating goat welfare under hot conditions.

Recommendations for the 'thermal' management of goats in pens

The variability of the environment, moving from the pens to the pasture and back, likely allowed the goats to better manage HS by taking advantage of the best features of each environment. This could explain the limited behavioural changes observed while the goats were in pens. Therefore, shifting indoor and outdoor environments could be an infrastructural solution for managing goats during the summer, particularly in Mediterranean regions like Italy, if essential resources are accessible. This could help goats adapt to and cope with HS conditions without compromising their welfare. Moreover, it would be best to provide one-half of the usual ration in the morning and the remaining half in the evening during summer to avoid peak ruminal metabolic heat during the hottest hours.

Limitations of the study

Despite the valuable insights this study provides into aspects that are still poorly understood in goats, there are some limitations. The sample size was small and consisted only of females. This limitation was primarily because data collection was planned for the peak heat of 2023. Forecasts of this peak allowed for only a few days' advance notice and organisation. The small sample size has reduced the inferential strength of the results. However, the statistical approach adopted was chosen according to the characteristics and structure of the data to account properly for repeated measures and non-Gaussian distributions, thereby reducing potential bias associated with inappropriate model specification. Nevertheless, findings should be interpreted cautiously and validated in future studies, including a larger number of animals. Moreover, it was not possible to collect the same data from all subjects, and in some cases, data could only be collected at certain times of the day. For example, midday SSTs were collected only for the loin region, limiting the detection of peak thermal load. Both lactating and non-lactating goats were included in the study, and this may have influenced their heat stress responses. Finally, the effects of cumulative thermal load were incorporated into the statistical models, but it remains challenging to fully isolate environment-specific effects. In the future, we plan to standardise data collection to include both sexes and balance lactating vs non-lactating animals. We also intend to increase the number of animals and attempt to collect data multiple times throughout the day.

Notwithstanding these limitations, our study is one of the few to combine IRT with assessing clinical and behavioural parameters to evaluate HS in goats.

Conclusions

This study provides insights into the physiological and behavioural responses of dairy goats exposed to HS under Mediterranean summer conditions. Our findings revealed that goats, despite being considered heat-resistant, still exhibited measurable physiological and behavioural adjustments at elevated THIs.

The observed associations between SSTs, Rectal T, and THI support the potential usefulness of IRT as a non-invasive tool for HS monitoring in goats. When integrated with behavioural indicators, such as shade-seeking, rumination, and activity patterns, these measures provide a more complete picture of how goats respond to environmental challenges through thermoregulation.

This integrative, non-invasive approach could advance research into heat tolerance and resilience in goats by identifying the animals best suited to production in Mediterranean conditions. Combining physiological and behavioural assessments supports the development of welfare-friendly selection and management strategies, helping to maintain productivity while safeguarding animal welfare.

Overall, the study highlights the value of integrating physiological, behavioural, and environmental indicators for assessing goat welfare under HS in Mediterranean climates. Although further studies involving larger and more diverse populations are needed, this approach shows clear potential for improving both research and practical goat management within the region.

Acknowledgments

This study is part of Rossella Gecchele's veterinary medicine degree thesis.

Ethical approval

This study was approved by the Animal Welfare Committee of the Alma Mater Studiorum - University of Bologna (Protocol Number 77988 of 08/04/2022).

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This study was carried out within the Agritech National Research Centre and received funding from the European Union Next-GenerationEU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1032 17/06/2022, CN00000022).

ORCID

Martina Zappaterra http://orcid.org/0000-0001-5085-4811
Naod Thomas Masebo http://orcid.org/0000-0002-9616-5015
Valeria Bocchi http://orcid.org/0009-0002-6368-0552
Barbara Padalino http://orcid.org/0000-0002-7630-8285
Martina Felici http://orcid.org/0000-0002-6797-1659
Marilena Bolcato http://orcid.org/0000-0002-0605-3344
Leonardo Nanni Costa http://orcid.org/0000-0002-5260-7248

Data availability statement

The data presented in this original paper are available upon reasonable request from the corresponding author.

References

Akoglu H. 2018. User's guide to correlation coefficients. Turk J Emerg Med. 18(3):91–93. https://doi.org/10.1016/j.tjem.2018.08.001

Alam MM et al. 2013. Effect of heat stress on behaviour, physiological and blood parameters of goat. Progress Agric. 22(1-2):37–45. https://doi.org/10.3329/pa.v22i1-2.16465

Alejandro M, Romero G, Sabater JM, Díaz JR. 2014. Infrared thermography as a tool to determine teat tissue changes caused by machine milking in Murciano-Granadina goats. Livest Sci. 160:178–185. https://doi.org/10.1016/j.livsci.2013.11.0

Altmann J. 1974. Observational study of behaviour: sampling methods. Behav. 49(3):227–267. https://doi.org/10.1163/156853974X00534

Andersen IL, Bøe KE. 2007. Resting pattern and social interactions in goats: the impact of size and organisation of lying space. Appl Anim Behav Sci. 108(1-2):89–103. https://doi.org/10.1016/j.applanim.2006.11.013

Berihulay H, Abied A, He X, Jiang L, Ma Y. 2019. Adaptation mechanisms of small ruminants to environmental heat stress. Animals. 9(3):75. https://doi.org/10.3390/ani9030075

Bøe KE, Andersen IL, Buisson L, Simensen E, Jeksrud WK. 2007. Flooring preferences in dairy goats at moderate and low ambient temperature. Appl Anim Behav Sci. 108(1-2):45–57. https://doi.org/10.1016/j.applanim.2007.01.002

Cann P et al. 2019. The olfactory secretome varies according to season in female sheep and goat. BMC Genomics. 20(1):794. https://doi.org/10.1186/s12864-019-6194-z

Choi E, Carneiro de Souza V, Dillon JA, Kebreab E, Mueller ND. 2024. Comparative analysis of thermal indices for modeling cold and heat stress in US dairy systems. J Dairy Sci. 107(8):5817–5832. https://doi.org/10.3168/jds.2023-24412

Čukić A et al. 2023. Influence of heat stress on body temperatures measured by infrared thermography, blood metabolic parameters and its correlation in sheep. Metabolites. 13(8):957. https://doi.org/10.3390/metabo13080957

De K et al. 2020. Tree shade improves the comfort of sheep during extreme summer. J Vet Behav. 40:103–107. https://doi.org/10.1016/j.jvetbeh.2020.08.002

Duve LR, Jensen MB. 2012. Social behaviour of young dairy calves housed with limited or full social contact with a peer. J Dairy Sci. 95(10):5936–5945. https://doi.org/10.3168/jds.2012-5428

Ghezzi MD et al. 2024. Utilization of infrared thermography in assessing thermal responses of farm animals under heat stress. Animals. 14(4):616. https://doi.org/10.3390/ani14040616

Godde CM, Mason-D'Croz D, Mayberry DE, Thornton PK, Herrero M. 2021. Impacts of climate change on the livestock food supply chain: a review of the evidence. Glob Food Sec. 28:100488. https://doi.org/10.1016/j.gfs.2020.100488

Gopikrishnan P et al. 2024. Estimation of rectal temperature of goats based on surface temperature. Int J Vet Sci Anim Husb. 9(2):80–82. https://doi.org/10.1590/1809-4430-eng.agric.v41n6p591-598/2021

Gupta M, Mondal T. 2021. Heat stress and thermoregulatory responses of goats: a review. Biol Rhythm Res. 52(3):407–433. https://doi.org/10.1080/09291016.2019.1603692

Hossein-Zadeh NG. 2013. Effects of main reproductive and health problems on the performance of dairy cows: a review. Span J Agric Res. 11(3):718–735. https://doi.org/10.5424/sjar/2013113-4140

Kitajima K et al. 2021. Effects of heat stress on heart rate variability in free-moving sheep and goats assessed with correction for physical activity. Front Vet Sci. 8:658763. https://doi.org/10.3389/fvets.2021.658763

Lu CD. 1989. Effects of heat stress on goat production. Small Rumin Res. 2(2):151–162. https://doi.org/10.1016/0921-4488(89)90040-0

Mattiello S et al. 2018. AWIN Welfare assessment protocol for goats. European Commission. FP7:26. https://doi.org/10.13130/awin_capre_2018

McGregor GR, Bessemoulin P, Ebi K, Menne B, editors. 2015. Heatwaves and health: guidance on warning-system development. World Meteorological Organization and World Health Organization.

McManus C et al. 2015. Infrared thermography to evaluate heat tolerance in different genetic groups of lambs. Sensors. 15(7):17258–17273. https://doi.org/10.3390/s150717258

Menchetti L, Nanni Costa L, Zappaterra M, Padalino B. 2021. Effects of reduced space allowance and heat stress on behaviour and eye temperature in unweaned lambs: a pilot study. Animals. 11(12):3464. https://doi.org/10.3390/ani11123464

Morand-Fehr P, Bourbouze A, Le Houérou HN, Gall C, Boyazoglu JG. 1983. The role of goats in the Mediterranean area. Livest Prod Sci. 10(6):569–587. https://doi.org/10.1016/0301-6226(83)90050-7

Morgan A. 2023. What does a goat sound like? Online Field Guide. https://www.online-field-guide.com/what-does-a-goat-sound-like/

Most M, Gibbs RL, Yates DT. 2023. Managing sheep and goats for heat stress. Univ Nebraska–Lincoln Extension. G2355. https://extensionpubs.unl.edu/publication/g2355/2023/pdf/view/g2355-2023.pdf

Mota-Rojas D. 2021. Clinical Applications and Factors Involved in Validating Thermal Windows Used in Infrared Thermography in Cattle and River Buffalo to Assess Health and Productivity. Animals (Basel). 11(8):2247. https://doi.org/10.3390/ani11082247

Mullakkalparambil Velayudhan S et al. 2023. Novel insights to assess climate resilience in goats using a holistic approach of skin-based advanced NGS technologies. Int J Mol Sci. 24(12):10319. https://doi.org/10.3390/ijms241210319

Naidu I. 2023. What sound do goats make and what is their purpose? Animals Research. https://animalsresearch.com/what-sound-do-goats-make/

National Research Council. 1971. A guide to environmental research on animals. National Academies Press.

Oliveira CP et al. 2025. Heat stress in dairy cows: impacts, identification, and mitigation strategies: a review. Animals. 15(2):249. https://doi.org/10.3390/ani15020249

Peng D et al. 2019. Infrared thermography measured body surface temperature and its relationship with rectal temperature in dairy cows under different temperature-humidity indexes. Int J Biometeorol. 63(3):327–336. https://doi.org/10.1007/s00484-018-01666-x

Powell DM, Baskir EA. 2021. A matter of time: comparing observation methods. In: Zimbler-DeLorenzo H, Margulis SW, editors. Exploring animal behaviour in laboratory and field. Academic Press (Elsevier). p 49–61. https://linkinghub.elsevier.com/retrieve/pii/B9780128214107000297

Pucora E, Schiffmann C, Clauss M. 2019. Resting postures in terrestrial mammalian herbivores. J Mammal. 100(2):552–563. https://doi.org/10.1093/jmammal/gyz023

Rahimi J, Mutua JY, Notenbaert AMO, Marshall K, Butterbach-Bahl K. 2021. Heat stress will detrimentally impact future livestock production in East Africa. Nat Food. 2(2):88–96. https://doi.org/10.1038/s43016-021-00226-8

Salles MSV et al. 2016. Mapping the body surface temperature of cattle by infrared thermography. J Therm Biol. 62(Pt A):63–69. https://doi.org/10.1016/j.jtherbio.2016.10.003

Samara EM, Al-Badwi MA, Abdoun KA, Al-Haidary AA. 2024. Applicability of thermography as a potential non-invasive technique to assess the body-thermal status of heat-stressed and water-deprived goats (*Capra hircus*). J Therm Biol. 119:103790. https://doi.org/10.1016/j.jtherbio.2024.103790

Samara EM. 2024. Profiling the dynamic variations in body and scrotal surface temperatures of goats reared under stressful conditions using infrared thermography: analytical perspectives. J Therm Biol. 125:103960. https://doi.org/10.1016/j.jtherbio.2024.103960

Sejian V et al. 2021. Heat stress and goat welfare: adaptation and production considerations. Animals. 11(4):1021. https://doi.org/10.3390/ani11041021

Shilja S et al. 2016. Adaptive capability as indicated by behavioural and physiological responses, plasma HSP70 level and PBMC HSP70 mRNA expression in Osmanabadi goats subjected to combined (heat and nutritional) stressors. Int J Biometeorol. 60(9):1311–1323. https://doi.org/10.1007/s00484-016-1152-5

Siebert K, Langbein J, Schön PC, Tuchscherer A, Puppe B. 2011. Degree of social isolation affects behavioural and vocal response patterns in dwarf goats (*Capra hircus*). Appl Anim Behav Sci. 131(1-2):53–62. https://doi.org/10.1016/j.applanim.2010.11.011

Srikandakumar A, Johnson E, Mahgoub O. 2003. Effect of heat stress on respiratory rate, rectal temperature and blood chemistry in Omani and Australian Merino sheep. Small Ruminant Res. 49(2):193–198. https://doi.org/10.1016/S0921-4488(03)00097-X

Srivastava A et al. 2021. Appropriate THI model and its threshold for goats in semi-arid regions of India. J Therm Biol. 96:102845. https://doi.org/10.1016/j.jtherbio.2021.102845

Sun L, Liu G, Jiang X. 2024. Relationships of infrared thermography temperature with core temperature in goat. Trop Anim Health Prod. 56(4):138. https://doi.org/10.1007/s11250-024-03995-z

Thornton P, Nelson G, Mayberry D, Herrero M. 2021. Increases in extreme heat stress in domesticated livestock species during the twenty-first century. Glob Chang Biol. 27(22):5762–5772. https://doi.org/10.1111/gcb.15825

Toinon C, Waiblinger S, Rault JL. 2022. Maternal deprivation affects goat kids' social behaviour before and after weaning. Dev Psychobiol. 64(4):e22269. https://doi.org/10.1002/dev.22269

United Nations Environment Programme/Mediterranean Action Plan (UNEP/MAP). 2021. Climate change in the Mediterranean. United Nations Environment Programme. https://www.unep.org/unepmap/resources/factsheets/climate-change

Vicente-Pérez R et al. 2019. Relationships of body surface thermography with core temperature, birth weight and climatic variables in neonatal lambs born during early spring in an arid region. J Therm Biol. 82:142–149. https://doi.org/10.1016/j.jtherbio.2019.04.001

Webb LE, Engel B, van Reenen K, Bokkers EAM. 2017. Barren diets increase wakeful inactivity in calves. Appl Anim Behav Sci. 197:9–14. https://doi.org/10.1016/j.applanim.2017.08.005

World Health Organization. 2025. Climate change. World Health Organization. https://www.who.int/health-topics/climate-change

Zappaterra M, Menchetti L, Nanni Costa L, Padalino B. 2021. Do camels (*Camelus dromedarius*) need shaded areas? A case study of the camel market in Doha. Animals. 11(2):480. https://doi.org/10.3390/ani11020480