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REVIEW ARTICLE

Understanding heat stress in pasture-based dairy cows: Challenges and innovations from thermal indices to multivariate sensor technologies

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ABSTRACT. Heat stress is an increasingly critical challenge for modern dairy production, particularly in pasture-based systems where cows are directly exposed to solar radiation, humidity, wind, and high temperatures. This review synthesises the current evidence on environmental thermal indices, physiological responses, behavioural adaptations, and sensor-based technologies relevant to heat stress assessment in grazing dairy cattle. A narrative review of peer-reviewed and grey literature (2015–2026) was conducted across major scientific databases, focusing on studies that developed or validated thermal indices, compared them with animal-based indicators, or quantified their impacts on performance and health. The findings show that the Temperature Humidity Index (THI), although widely used, has limited accuracy in outdoor conditions owing to its exclusion of solar radiation and wind. Updated indices, including the adjusted THI, Heat Load Index (HLI), Comprehensive Climate Index (CCI), Dairy Heat Load Index (DHLI), and Grazing Heat Load Index (GHLI), demonstrate better alignment with physiological responses under grazing conditions. Early and sensitive indicators, such as respiratory rate (RR), panting, and rising body temperature (BT), provide direct insight into the loss of thermal balance, whereas reductions in rumination, shifts in feeding behaviour, and increased shade-seeking reflect behavioural adaptation. Emerging evidence also highlights heat-induced dysbiosis in the rumen and intestinal microbiome, with implications for metabolism, immunity, and reproductive function. Sensor-based technologies, including rumen boluses, infrared thermography, accelerometers, and subcutaneous or vaginal temperature devices, enhance real-time monitoring and support early detection, particularly in extensive outdoor environments. Overall, integrating multivariable climate indices with animal-centred physiological and behavioural monitoring provides a more accurate and responsive framework for heat stress detection, risk assessment, and management in pasture-based dairy systems, supporting productivity, welfare, and long-term system resilience.

Keywords: heat stress, thermal indices, dairy cattle, pasture-based system, physiological parameters.

INTRODUCTION

Heat stress has become one of the most urgent challenges facing modern dairy production, affecting not only the welfare of the animals but also the productivity and long-term sustainability of both intensive and pasture-based systems (Arias *et al.*, 2024; Hendriks *et al.*, 2025). Heat stress can be defined as “an accumulation of heat within the animal leading to elevated body temperature (BT) beyond the normal range” or “a cow’s inability to dissipate heat into the environment expressed by and increase in the cows body temperature beyond the normal value of 38.5 - 39.0 degrees Celsius” (IDF, 2025, p. 6). In order to cope with heat stress, when the external heat load exceeds the animal’s passive capacity, cows use behavioural and physiological responses, with the aim of increasing heat loss. Climate change drives more frequent, longer, and more intense heat events. When temperature, humidity, wind speed, and solar radiation combine to exceed the animal’s capacity for heat dissipation, normal physiological regulation begins to fail, setting off a cascade of behavioural, metabolic and production-related changes (Mader *et al.*, 2010; Becker *et al.*, 2020; Idris *et al.*, 2021). These challenges are especially pronounced in pasture-based systems, where cows are directly exposed to changing climatic conditions and depend heavily on shade, wind flow, and water access to cope with heat load (Deniz *et al.*, 2021).

Over the past decades, a wide range of thermal indices has been developed to quantify environmental heat load (Ji *et al.*, 2020). However, their performance varies across production systems, climates and breeds, and their limitations become particularly evident in grazing conditions, where solar radiation and wind strongly determine the animal’s thermal experience (Lees *et al.*, 2019; Arias *et al.*, 2021). Alongside these environmental metrics, physiological and behavioural indicators such as BT, respiratory rate (RR), panting, rumination, feeding patterns, shade-seeking, and drinking behaviour offer essential animal-based insights into the real-time thermal state of the cow (Arias *et al.*, 2018; Pinto *et al.*, 2020; Cartes *et al.*, 2021; Schütz *et al.*, 2023).

The extent of the heat load impact on a cow's performance is closely related to their production level and the number of hours during the day and throughout the year, where cows are exposed to conditions above the heat load threshold (IDF, 2025).

This growing complexity highlights the need for an integrated understanding of how cows experience and respond to heat in grazing environments. This narrative review aims to synthesise the current scientific evidence on the development, validation, and application of thermal indices, physiological responses, and behavioural adaptations to heat stress. It also examines the limitations of existing indicators and highlights emerging integrative approaches that combine advanced climate indices with real-time sensor technologies, including those in pasture-based contexts.

MATERIALS AND METHODS

A narrative review was conducted through a comprehensive search using the PubMed, Scopus, Web of Science, and Google Scholar databases. The initial search combined terms related to heat stress and dairy cattle production systems: "heat stress" AND "thermal index" OR "heat load index" OR "temperature humidity index" AND "dairy cattle" OR "lactating cows" AND "environmental indicator" AND "pasture-based system". During the review process, additional search terms were added iteratively when emerging themes require deeper exploration, including "microbiome', "shade provision", "cooling strategies", "behavioural responses", "physiological responses", and "precision technologies for heat stress". Classic foundational publications were consulted when they served as original sources for defining measurement variables or describing thermal indices that are still in use today. In addition, the most recent publications available were also considered.

Inclusion and exclusion criteria

Studies were included if they: (1) developed, validated, or evaluated one or more thermal indices for dairy cattle; (2) evaluated thermal index performance against physiological and/or behavioural indicators of heat stress; (3) reported critical thresholds or quantified the effects of heat stress on milk yield, reproduction, or health outcomes. Studies focusing exclusively on non-bovine species and theoretical models without empirical validation were excluded. Review articles were considered only when they provided novel, systematically synthesized, or extractable data relevant to the objectives of the study; narrative reviews without new data or without clearly traceable empirical evidence were excluded. Therefore, experimental, observational, and eligible review articles were included.

RESULTS

The initial database search yielded 3,727 references in total. Titles and abstracts were screened for relevance to heat stress in dairy cattle, with a particular focus on grazing or mixed systems. After removing duplicates and excluding non-related studies, 427 articles remained for full-text consideration. Ultimately, 120 references were included in the review based on their relevance.

Environmental indices for heat stress assessment

Thermal indices as environmental risk indicators have been used to assess and estimate heat stress in dairy cows (Yan *et al*., 2021; Arias *et al*., 2024) and are diagnostic tools for quantifying ambient parameters to assess the thermal comfort level of animals in their environments. More than 20 different indices have been described and reported in the literature (Ji *et al*., 2020), including the temperature humidity index (THI), with its different versions and adjustments, the black globe humidity index (BGHI) (Buffington *et al*., 1981), the heat load index (HLI), the accumulated heat load units (AHLU), the equivalent temperature index for cattle (ETIC), the comprehensive climate index (CCI), and the estimated respiratory rate index (RRI) (Shephard & Maloney, 2023). Table 1 shows the main indices that have been developed for cattle and that are currently used in dairy cows.

Classical temperature-based indicators

The more typical cattle-related thermal indices are ambient temperature, temperature-humidity index (THI), adjusted temperature-humidity index (THI_{adj}), heat load index (HLI), and comprehensive climate index (CCI). Ambient temperature (both dry and wet bulb temperatures) is commonly used to predict heat stress in housed and grazing cows; however, as a single indicator, it omits other important ambient factors that influence the thermal comfort of animals. In addition to ambient temperature, the main meteorological variables affecting the thermal balance in cattle are solar radiation, humidity, and wind speed (Mader *et al*., 2010; Lees *et al*., 2019). These variables can also contribute to heat load by influencing radiative heat transfer and the efficiency of evaporative cooling (Blackshaw & Blackshaw, 1994).

Historical development of the Temperature-Humidity Index (THI)

The THI is a single value that combines the values of relative humidity and ambient temperature and was adapted from the Discomfort Index for Humans developed by Thom in 1959 (Thom, 1959). Subsequently, in 1970, it was considered as a base to develop the Livestock Weather Safety Index which describes four categories (Normal, Alert, Danger, and Emergency) commonly used for housed cows (Ji *et al*., 2020; Arias *et al*., 2024). Depending on the climate in the region being measured, multiple variations of the THI equation exist to account for differences in relative humidity and temperature (Bohmanova *et al*., 2007; Gunn *et al*., 2019). The model of THI is most often used to evaluate the effect of heat stress in dairy animals and was proposed by the National Oceanic and Atmospheric

Table 1.
Main thermal indices used in cattle

Index	Main formula	Environmental variables included	Typical threshold for heat stress	Main production system	Global region or country	Breed	References
THI (indoor)	THI = (1.8 x AT + 32) – (0.55 – 0.55 x (RH/100)) x ((1.8 x AT + 32) – 58) (NOAA, 1958)	AT (°C), RH_{dec}	THI > 74 THI > 74 THI > 68 THI > 65	Indoor Confinement, Freestall	Equatorial Tropical Subtropical Temperate	Holstein-Friesian	IDF, 2025
THI (pasture-based)	THI = (0.8 x AT) + ((RH/100) X (AT – 14.4) + 46.4 (Hahn *et al.*, 2009) or THI = (1.8 x AT + 32) – 0.55 x (1 – RH / 100) x (1.8 x T – 26) (NRC, 1971)	AT (°C), RH (%)	THI > 65 THI > 64 THI > 67 THI > 73 THI > 72	Confinement and Pasture Pasture Pasture Pasture Pasture	Chile New Zealand Sweden	Holstein-Friesian Holstein-Friesian Kiwi Cross Jersey Breed Swedish Red	Arias *et al.*, 2024 Bryant *et al.*, 2007 Nielsen & Wredle, 2023
THI_{adj}	THI_{adj} = THI + 4.51 – (1.992 x WS) + (0.0068 x SR) (Mader *et al.*, 2006)	WS (m/s), SR (W/m^2)	THI_{adj} > 65	Confinement and Pasture	Chile	Holstein-Friesian	Arias *et al.*, 2024
HLI (Heat Load Index)	i) When BGT > 25, HLI = 8.62+(0.38×RH) + (1.55×BGT) – (0.5×WS) + e(2.4–WS) ii) When BGT < 25, HLI = 10.66 +(0.28×RH) +(1.3×BGT) – WS (Gaughan *et al.*2008)	RH (%), BGT (°C), WS (m/s)	HLI > 70 HLI > 82	Outdoor Indoor	Australia and USA Italy	Beef cattle Holstein-Friesian	Gaughan *et al.*, 2008 Vitali *et al.*, 2020
CCI (Comprehensive Climate Index)	CCI = AT + FRH + FWS + FSR	Adjusts dry bulb temperature by RH, WS, and SR.	CCI > 25°C CCI > 25°C CCI > 25°C CCI > 20°C	Confinement Outdoor (Open Pens) Pasture and confinement Pasture	USA Chile Switzerland Chile	Beef cattle Holstein-Friesian Holstein-Friesian Holstein-Friesian	Mader *et al.*, 2010 Arias *et al.*, 2018 Pontiggia *et al.*, 2025 Arias *et al.*, 2021
DHLI (Dairy Heat Load Index)	D*HLI* = 1.681813 (1 + e-(-8.50749 + 0.206159∗*BGT* + 4.088399∗*RH*))	AT (°C), RH (decimal or %), SR (W/m^2), WS (n/s) and observed panting scores	> 30 Mild Stress (scale 0 to 100)	Outdoors paddock, Pasture	Australia	Holstein-Friesian	Lees *et al.*, 2018a
GHLI (Grazing Heat Load Index)	GHLI = 61.78 + 4.21 x (T -22.48) – 1.70 x (3.6 x WS – 7.05) + 5.89 x (SR – 2.41)	T (°C), WS (m/s), SR (MJ/m^2/h)	> 55 breaths x minute (> 70 marked changes in panting score and % of drooling)	Outdoors, Pasture	New Zealand	Kiwi Cross	Bryant *et al.*, 2023; Hitchman *et al.*, 2024.

THI= Temperature Humidity Index; AT = Ambient Temperature; RH= Relative humidity; WS= Wind Speed; SR= Solar Radiation; m/s = meter per second; W/m^2= watts per square meter; BGT= Black Globe Temperature; THI_{adj}= Temperature Humidity Index Adjusted; HLI= Heat Load Index; e = the base of the natural logarithm; FRH= adjusting Factor of Relative Humidity; FWS= adjusting Factor of Wind Speed; FSR= adjusting Factor of Solar Radiation; DHLI= Dairy Heat Load Index;

Administration (NOAA, USA) in 1976 (IDF, 2025). THI, frequently used in countries with pasture-based production systems, is typically calculated using the formula proposed by the National Research Council (1971). Various THI thresholds have been proposed to indicate heat stress conditions relevant to the different physiological responses of cows of different breeds, ages, health statuses, levels of production, and farm management in different systems. In addition, the critical levels can vary depending on the trait considered, such as milk yield, reproduction, and health outcomes (IDF, 2025). The initial generic approach was to use the threshold THI > 72 to indicate heat stress in Holstein cows, since a decrease in milk production was observed in cows subjected to these ambient conditions, but this threshold was originally proposed for indoor housed systems. Currently, this threshold is decreasing. Recently, Pinto *et al.* (2020) proposed that heat mitigation strategies in high-yielding dairy cows must begin when they are exposed to THIs values above 65. Currently, in New Zealand, a threshold of THI > 69 is being used, considering the predominance of Holstein-Friesian/Jersey crossbreed cows (Woodward *et al.*, 2025). However, in the latest review by the International Dairy Federation (2025), the heat stress scientific team found that the critical thresholds of the THI seem to be influenced by latitude. Although the THI is useful for assessing the potential degree of heat stress in cows, physiological responses to heat should be better indicators of the degree of heat stress (Toledo *et al.*, 2022). Berman (2005) concluded that, due to the large variation in environmental and animal factors, thermal balance-based, or adjusted, indices are justified compared to thermal indices such as the THI.

Limitations of THI in outdoor and grazing conditions and Adjusted Temperature-Humidity Index (THI_{adj})

In outdoor conditions, the THI is less useful because solar radiation and wind conditions modify the thermal comfort state of cows (Hitchman *et al.*, 2024). Therefore, other indices have been developed to address these limitations. Mader *et al.* (2006) proposed the adjusted THI (THI_{adj}) which included the missing variables (solar radiation and wind speed) and has been used in some countries with outdoor livestock farming (Arias *et al.*, 2024). The THI_{adj} was calculated as follows:

$$THI_{adj} = THI + 4.51 - (1.992 \times WS) + (0.0068 \times SR)$$

where WS is wind speed (m/s) and SR is solar radiation (W/m^2). Currently, the commonly used threshold to indicate heat stress conditions is $THI_{adj} > 65$. Arias *et al.* (2024), using the same threshold of > 65 for THI and THI_{adj} for estimating the economic impact of heat stress on the Chilean dairy regions, showed that milk losses were between 2.0 and 6.4 times higher when THI_{adj} was used instead of THI, this could be due to the impact of solar radiation and wind speed.

On the other hand, the same group of researchers who developed the THI_{adj} developed a new thermal index including the four variables (adjusted dry bulb temperature by relative humidity, wind speed, and solar radiation), named Comprehensive Climate Index (CCI). The CCI is a climate model designed to describe the apparent temperature of climatic conditions over a wide range of environmental conditions, and it is the only multiseasonal model that can be used year-round. The CCI is calculated as CCI = AT + FRH + FWS + FSR, where FRH corresponds to the correction factor for AT due to relative humidity, FWS corresponds to the correction factor for AT due to wind speed, and FSR corresponds to the correction factor for AT due to solar radiation (Mader *et al.*, 2010). The algorithm used to estimate each correction factor is described in the original manuscript. The model was based on environmental data compiled from weather stations located in areas where heat waves had occurred over a 15-year period, and during the heat waves, animal deaths in feedlot cattle maintained in outside facilities were documented. Threshold levels indicate intensity of climatic stress experienced by the animal and the thermal stress is given by the following categories: No stress (CCI ≤ 25°C), Mild (> 25 and ≤ 30 °C), Moderate (> 30 and ≤ 35 °C), Severe (> 35 and ≤ 40 °C), Extreme (> 40 and ≤ 45 °C) and Extreme danger (CCI > 45 °C). Thus, the frequently used threshold is > 25 °C for feedlot cattle, although the 20 °C threshold has also been used for dairy cows (Arias *et al.*, 2021), with severe thresholds capable of causing death of animals and extreme thresholds having a high probability of causing death of high-risk animals (Mader *et al.*, 2010).

Heat Load Index (HLI)

The Heat Load Index (HLI) is a bioclimatic index for beef cattle that was developed using a large number of cattle (n = 17,560) across 13 feedlots to estimate the heat load from animals as a function of the time spent above or below specific HLI thresholds in a day (Gaughan *et al.*, 2008; IDF, 2025). The HLI incorporates an accumulated heat load over and above the existing HLI value to allow for the heat that an animal has been unable to dissipate from the previous day or days (Lees *et al.*, 2021) and accounts for the effects of wind speed, solar radiation, relative humidity, and air temperature. A decline in milk production has been demonstrated at high HLI values (Gaughan & Lees, 2010), and a Dairy Heat Load Index (DHLI) model has been developed specifically for dairy cows. The limited number of HLI-based studies makes it challenging to determine the critical heat stress thresholds for this bioclimatic indicator (IDF, 2025).

Recently, some countries with predominant dairy grassland production systems have developed indices that are more accurate for their environment and systems (Hendriks *et al.*, 2025). Lees *et al.* (2018a) developed the dairy heat load index (DHLI) in Australia, which incorporates ambient temperature, humidity, solar radiation, and wind speed. The DHLI uses panting score (PS) and environmental data in dairy cows with pasture and feedlot access. The DHLI needs to be further developed to incorporate animal and management factors to become a valuable heat load management tool (Lees *et al.*, 2021). Subsequently, Bryant *et al.* (2023) developed the grazing heat load index (GHLI) in New Zealand, which combines ambient temperature, solar radiation, and wind speed to better represent the heat stress risk for grazing animals using observed RR, PS, and drooling as heat stress indicators. The GHLI index was developed using respiration rate studies previously conducted in the Waikato region of New Zealand. It was more accurate than other published indices in that environment and was recently updated with more information from different regions of the country (Hitchman *et al.*, 2024). The GHLI is a unitless index, and a threshold of > 55 was adopted for heat stress (Woodward *et al.*, 2024a), because it is consistent when the PS and drooling began to increase in cows.

In Latin American countries, such as Chile, previous research has shown that solar radiation contributes to the daily heat load of animals, especially those under grazing production systems with limited access to shade (Arias *et al.*, 2021), which are predominant in the southern regions of the country. Therefore, the use of indices other than the THI, such as the THI_{adj} and the new indices developed at similar latitudes, as described in Australia and New Zealand, may be of interest for assessing the risk of heat stress in grazing-based production systems in southern Chile.

Physiological indicators of heat stress

Body Temperature (BT)

In dairy cattle, body temperature can be assessed using different measurement sites, each reflecting specific aspects of the animal's thermal status. Common methods include rectal and vaginal temperatures, which are widely used as indicators of core BT, and tympanic temperature, which provides a rapid estimate of central thermal responses. In addition, rumen or reticular temperature measured using boluses offers continuous monitoring, although values may be slightly higher due to microbial fermentation. Surface or skin temperature, often assessed using infrared thermography, reflects peripheral heat exchange and is more influenced by environmental conditions. The selection of the measurement site depends on the objective of the study, as well as the balance between accuracy, invasiveness, and feasibility under field conditions (Bewley *et al.*, 2008; Tresoldi *et al.*, 2020; IDF, 2025)

Body temperature is one of the most direct and reliable physiological indicators for assessing heat stress in dairy cows, as it reflects the animal's ability to maintain a balance between heat production and dissipation. Recent studies have shown that relatively moderate increases in the temperature-humidity index (THI) are sufficient to cause measurable increases in BT, especially in high-producing cows. Pinto *et al.* (2020) identified critical THI thresholds based on physiological variables, reporting significant increases in core BT in lactating cows at THI values close to 68, even before marked reductions in milk production were observed. This aligns with Becker *et al.* (2020), who noted that BT progressively increases with environmental heat load, making it one of the earliest indicators of thermal homeostasis loss.

The tympanic temperature offers a measure of core BT and responds sensitively to heat load. Arias *et al.* (2018) found that tympanic temperature increased from approximately 37.6 - 37.9 °C under normal conditions to values close to 38.2 - 38.4 °C under stressful conditions, with afternoon values consistently higher. These physiological responses are further modulated by management practices. Schütz *et al.* (2023) showed that late-day milking is associated with higher peaks in BT during the afternoon, with increases of approximately 0.3-0.4 °C compared to early milking schedules. In contrast, once-a-day milking (OAD) systems showed lower evening thermal peaks, suggesting a reduction in the thermal load associated with the activity and metabolism.

From a physiological point of view, BT sustained above 39 °C are associated with reduced Dry Matter Intake (DMI) and rumination, hormonal changes, and lower milk yield, reinforcing the value of temperature monitoring (Becker *et al.*, 2020; Idris *et al.*, 2021).

In addition to environmental conditions, animal activity also contributes to an increase in BT. Grazing behaviour and walking to and from the milking parlour involve muscular activity that generates metabolic heat, which can exacerbate the overall heat load, particularly under hot conditions. In pasture-based systems, where cows may walk considerable distances and remain active for prolonged periods, this internally generated heat can represent a significant component of the thermal burden. Recent studies have shown that reducing locomotion and activity (e.g., keeping cows indoors during the hottest hours) leads to lower BT and physiological responses, highlighting the contribution of activity to the heat load (Pontiggia *et al.*, 2025). In addition, behavioural and sensor-based studies indicate that changes in activity patterns are closely associated with heat stress and its physiological consequences, reinforcing the interaction between physical activity and environmental heat in determining thermal status (Leliveld *et al.*, 2025; Hendriks *et al.*, 2025).

Respiratory rate (RR) as an early indicator

The respiratory rate is widely recognised as one of the earliest physiological responses to heat stress, often increasing before the BT rises. Becker *et al.* (2020) and Idris *et al.* (2021) agreed that the RR responds almost immediately to increases in ambient temperature and relative humidity, making it a key parameter for the early detection of heat stress. Pinto *et al.* (2020) reported abrupt increases in RR at THI values of approximately 68-70, proposing this threshold as critical from a physiological perspective. In the study by Arias *et al.* (2018), the average RR increased significantly when moving from normal to stressful conditions. Under normal conditions, the RR was approximately 56.5 ± 0.99 breaths per minute (bpm), whereas under stressful conditions, it reached values close to 68.1 ± 1.35 bpm ($P < 0.001$). Additionally, marked differences were observed between times of day, with higher values in the afternoon (≈ 67.5 bpm) than in the morning (≈ 56.5 bpm). Management again plays a role; Schütz *et al.* (2023) observed that early afternoon milking intensified RR peaks, whereas feeding adjustments or once-a-day milking exhibited lower respiratory peaks.

Panting and drooling

Panting and excessive salivation are visible indicators of advanced heat load, reflecting the activation of evaporative cooling mechanisms. Becker *et al.* (2020) described panting as a key compensatory strategy when other heat loss pathways become limited, increasing pulmonary ventilation to facilitate heat loss through evaporation. Studies have consistently documented that panting intensity increases with THI. In pasture-based systems during the Australian summer, Osei-Amponsah *et al.* (2020) observed that increasing THI from ≤ 72 to ≥ 83 raised RR from 66.7 to 109.1 bpm and PS from 1.4 to 2.3, with most cows showing open mouth panting and visible salivation. Tresoldi *et al.* (2016) reported that cows exhibiting panting characteristics, including drooling, showed higher RR compared to cows without these signs, reinforcing the association between salivation and an increased physiological response to heat.

Panting score systems offer a practical field tool for classifying the severity of heat stress in cattle. This system is based on a categorical scale that ranges from normal respiration (PS = 0), characterised by regular breathing without visible signs of distress, to severe panting (PS ≥ 3), which includes open-mouth breathing, tongue protrusion, and excessive salivation. Intermediate scores reflect increased respiratory effort, including elevated RR and visible flank movements. This scoring system has been widely used under both experimental and commercial conditions to assess heat stress severity (Lees *et al.*, 2019; Schütz *et al.*, 2023). As the heat load increases, the PS rises in parallel with the RR and BT, reinforcing its value as a simple and reliable animal-based indicator.

From a physiological perspective, respiratory responses play a central role in heat dissipation, accounting for approximately 30% of total heat loss under heat stress conditions (Berman, 2005), and are widely recognised as key mechanisms in heat stress adaptation in dairy cattle (Becker *et al.*, 2020; Polsky & von Keyserlingk, 2017). However, sustained activation of these processes is associated with metabolic and productive alterations, including decreases in DMI, rumination time, and milk production.

In dairy cows on pasture, the increase in panting and salivation under high THI conditions coincided with an approximate 14% reduction in daily milk production when comparing low and high THI conditions (Osei-Amponsah *et al.*, 2020). Consistently, studies conducted in tropical systems have reported negative associations between physiological indicators related to panting and energy-corrected milk production, with decreases of up to 0.7 – 0.9 kg/cow/day (Bang *et al.*, 2022).

From the perspective of animal welfare, the presence of intense panting and visible salivation constitutes a clear sign that thermoregulation adaptive mechanisms are being pushed to their limit. In pastoral systems, these responses are usually accompanied by behavioural changes, such as reduced grazing, increased time spent in the shade, and more frequent visits to water sources (Osei-Amponsah *et al.*, 2020; Hendriks *et al.*, 2025).

The relationship between PS, RR, and BT reflects a coordinated physiological response to heat stress. PS and RR act as early indicators of thermal discomfort, increasing rapidly as the environmental heat load rises, whereas BT represents a more delayed and cumulative response. Recent studies have reported strong positive associations between indicators of panting and an increase in core BT, highlighting their value as early predictors of thermal imbalance (Becker *et al.*, 2020; Idris *et al.*, 2021). Although RR generally increases with heat stress, under severe conditions, breathing patterns may shift to slower and deeper respiration, reducing evaporative efficiency and contributing to greater heat accumulation. Temporal dynamics are also relevant, as BT responses may lag behind environmental conditions, with more heat-susceptible animals exhibiting prolonged panting activity and higher internal temperatures (Schütz *et al.*, 2023). Furthermore, early behavioural and respiratory responses have been associated with subsequent increases in BT, suggesting their predictive value for identifying animals at a greater risk of heat stress (Lees *et al.*, 2019; Schütz *et al.*, 2023).

Behavioural indicators of heat stress

Feeding time and ingestive behaviour

Feeding behaviour shifts markedly under heat stress. Cows reduce their intake during uncomfortable thermal hours and try to compensate during the cooler periods of the day (cows are not always able to compensate the DMI). Maia *et al.* (2020), Polsky and von Keyserlingk (2017), and Kendall *et al.* (2006) described a circadian redistribution of intake, with increased grazing activity during cooler periods of the day, which constitutes an adaptive response to limit the rise in BT. Kappes *et al.* (2022) observed reduced daytime feeding, rumination, and milk yield as THI increased. In grazing systems, Schütz *et al.* (2023) showed that adjusting feeding times to cooler periods can significantly promote greater feeding activity and more stable rumination and resting patterns.

Rumination time as a metabolic and welfare indicator

Rumination time decreases under heat stress as cows reduce their intake and metabolic heat production. Müschner-Siemens *et al.* (2020) and Maia *et al.* (2020) demonstrated that rumination time consistently decreased as the THI increased, regardless of the production system. These authors reported progressive reductions in rumination time starting from moderate THI, with drops greater than 20% under conditions of marked heat stress. Kappes *et al.* (2022) evaluated the effects of different THI conditions on rumination time in Holstein cows and Holstein × Jersey crossbreeds. Under THI conditions below 68, rumination time was approximately 480-520 minutes per day, whereas under high THI conditions (≥ 84), it decreased to approximately 360-400 minutes per day, representing a reduction of approximately 20-30%. This effect was consistent across the genetic groups. Sustained decreases in rumination time are associated with lower ruminal pH and digestive efficiency, making rumination a sensitive welfare indicator (Becker *et al.*, 2020; Idris *et al.*, 2021). In addition, decreased rumination and altered feeding behaviour under heat stress conditions are associated with lower DMI and reduced milk yield (Polsky & von Keyserlingk, 2017; Becker *et al.*, 2020). These behavioural adjustments reflect a trade-off between thermoregulation and productivity, in which cows prioritise heat dissipation over feeding and resting activities.

Seeking shade in grazing systems

Shade use is one of the most robust behavioural indicators of heat stress in grazing cattle. In silvopastoral systems, the availability of shade allows cows to actively select microenvironments with lower thermal loads. Deniz *et al.* (2021) found that in silvopastoral systems in Brazil, natural shade provided by trees significantly reduced radiant heat load, with average decreases of 23% during cold seasons and 26% during warm seasons, compared to sunny areas. Likewise, areas without shade showed BGHI values above 74 in all seasons, indicating potential heat stress conditions. Similar results have been reported in other integrated and silvopastoral systems, where staying in the shade is associated with lower body surface temperatures and greater thermal comfort (Giro *et al.*, 2019; Deniz *et al.*, 2020). Social hierarchy strongly influenced access to shaded areas, with dominant cows using shade more frequently, while subordinates remain in sunny areas despite adequate shade availability (Deniz *et al.*, 2021). This pattern is consistent with other studies, indicating that social dominance influences access to environmental resources, such as shade and water, in pastoral and silvopastoral systems (Cardoso *et al.*, 2021; Deniz *et al.*, 2025).

Lying behaviour and thermal comfort

Heat stress reduces lying time, as cows stand to enhance heat dissipation (Tullo *et al.*, 2019; Tucker *et al.*, 2021). Cows exposed to high heat loads tend to spend more time standing to facilitate heat dissipation, which reduces their resting time and is negatively associated with milk yield. For instance, reductions in lying time have been linked to measurable losses in milk production, with primiparous cows showing a decrease of approximately 0.3 kg of milk per day for each additional hour spent standing (Westin *et al.*, 2016). Deniz *et al.* (2021) showed that the probability of lying down was significantly lower in sunny areas, being 62% lower than that in shaded areas. During summer and autumn, cows are more frequently engaged in comfort behaviours, such as lying and ruminating under shade, whereas in winter, these behaviours are more often observed in sunny areas. In particular, during the winter season, cows were 75% less likely to perform comfort behaviours in the shade, suggesting a strategy aimed at gaining heat from solar radiation. In addition to the effect of the microclimate, soil surface temperature plays a significant role in lying behaviour. Deniz *et al.* (2021) reported that for every 1 °C increase in soil temperature, the likelihood of lying increased by 9%, highlighting the importance of heat exchange through conduction. These findings align with those of studies showing that substrate temperature is a key factor in resting behaviour (Tucker *et al.*, 2021; de Sousa *et al.*, 2021).

Drinking behaviour and water intake

Water intake increases with heat load, but drinking behaviour is modulated by the season and social rank. Deniz *et al.* (2021) recorded a higher number of drinking events during summer (319 events), followed by spring (239), autumn (184), and winter (164), reflecting the seasonal influence of the thermal environment. However, the relationship between BGHI and drinking behaviour was not linear. In all social categories, the likelihood of drinking water decreased as BGHI increased, with reductions ranging from 2% to 8% for each additional unit of BGHI, depending on the season. This pattern suggests that under extreme conditions, cows may adjust the timing or strategy of hydration to avoid competition or additional physical activity.

Social hierarchy re-emerged as a determining factor. Dominant cows were approximately 50% less likely to drink water than intermediate and subordinate cows. These results are consistent with those of previous studies indicating that subordinate cows compensate for reduced access to other resources, such as shade, by increasing their frequency of water consumption (McDonald *et al.*, 2020; Vieira *et al.*, 2021).

It is also possible that dominant cows consumed larger volumes of water per visit, resulting in fewer drinking events, whereas subordinate animals may require more frequent visits. However, as individual water intake was not directly measured in this study, this interpretation remains speculative and should be considered with caution.

Effects of heat stress on the bovine microbiota/microbiome

Heat stress is a major challenge for dairy cattle, affecting their thermoregulation, metabolism, and gastrointestinal function (Lamp *et al*., 2015; Chen *et al*., 2024). Beyond reducing DMI, heat stress induces profound changes in the gut microbiome that contribute to a decrease in productivity, metabolic efficiency, and animal health (Chen *et al*., 2018). The microbiota can be understood as a community of microorganisms (bacteria, archaea, viruses, fungi, lower and higher eukaryotes) present in a defined environment, while the microbiome includes not only the microbiota, but also other aspects, such as the metabolites of these microorganisms and the potential impacts that they generate in the host (Chen *et al*., 2022). It has been proposed that the microbiota maintains a constant flow of communication with the body's organs through the gut microbiota-organ axes (GMOA) (Welch *et al*., 2022). The composition of the microbiota is influenced by several factors, including host genetics, age, diet, disease, antibiotic use, rearing environment, and stress (Kraimi *et al*., 2019; Chen *et al*., 2022). Stress is an important factor that can alter the composition of the gut microbiota and contribute to the development of dysbiosis (i.e. an imbalance in the composition of resident commensal microbial communities relative to those found in healthy individuals) (Petersen & Round, 2014).

The rumen microbiome plays a central role in the fermentation of carbohydrates into volatile fatty acids (VFAs) (Chen *et al*., 2018; Zhao *et al*., 2019). Heat stress alters this ecosystem through mechanisms that are not fully explained by reduced DMI alone (Zhao *et al*., 2019). Recently, Li *et al*. (2025) found that heat-resistant Holstein cows maintain a more stable fibre-degrading microbiome enriched in taxa such as *Ruminococcus flavefaciens* and *Succiniclasticum* and activate metabolic pathways (e.g. PPP) that support oxidative stress resilience (Zhuang *et al*., 2021; Wang *et al*., 2022a). Breed differences also modulate responses; Jersey cows showed reduced Actinobacteria and increased fibre-degrading phyla under heat stress, suggesting greater adaptation to warm conditions. Kim *et al*. (2020) compared changes in the rumen microbiome between Holstein and Jersey cows under thermoneutral and heat-stress conditions, observing differences between the two breeds. Unlike Holstein cows, Jersey cows showed a lower abundance of the Actinobacteria group with increasing warm conditions. These bacterial groups have extensive capabilities to metabolise starch, polysaccharides, and starch-like oligosaccharides, producing lactic and acetic acids, which contribute to decreases in rumen pH (Chen *et al*., 2019).

Conversely, the abundance of ruminal bacteria involved in fibre degradation, such as the Fusobacteria and Cyanobacteria phyla, increased in Jersey cows under heat stress, despite the latter being a more thermogenic pathway, suggesting a greater adaptation of this breed to warm conditions (Kim *et al*., 2020).

Age influences microbiome sensitivity. In growing heifers subjected to heat stress, greater microbial taxonomic richness has been observed, along with an increase in lipid metabolic pathways associated with the synthesis of long-chain fatty acids and eicosanoid compounds that act as key mediators of inflammation, vascular regulation, and the immune response, compared to older heifers and lactating cows (Zeineldin *et al*., 2018; Feng *et al*., 2023). This suggests greater resilience to heat stress in older age groups, as they can maintain a more stable community of microorganisms despite adverse conditions.

Environmental variations not only affect bacterial populations in the rumen but also impact other tracts of the digestive system, such as the small intestine. In this regard, Koch *et al*. (2024) found that changes in bacterial diversity primarily depend on the reduction in feed intake induced by heat stress. However, the predominance of certain bacterial groups is independent of reduced feed intake, especially for mucosa-associated bacterial populations rather than the digestive contents themselves (Koch *et al*., 2019; Koch *et al*., 2024). Mucosal-associated microbiota is believed to be more sensitive to microenvironmental changes and nutrient concentrations than luminal microbiota (Koch *et al*., 2019; Kökten *et al*., 2021). In this regard, chronic heat stress can reduce the delivery of oxygen and nutrients to the gastrointestinal tract and compromise intestinal barrier function in cows (Koch *et al*., 2019), thereby favouring the proliferation of certain bacterial groups over others. For example, heat-stressed cows show increased abundances of Gastranaerophilales, Bifidobacteriaceae, and Clostridia, groups linked to lower DMI, reduced milk yield, and impaired gut barrier function (Wang *et al*., 2022b; Koch *et al*., 2021). In the posterior tract of the large intestine, seasonal heat stress reduces Firmicutes and Bacteroidetes and increases Proteobacteria, a phylum associated with dysbiosis and inflammation (Rizzatti *et al*., 2017; Feng *et al*., 2023; Li *et al*., 2025). Interventions such as herbal supplements or live yeast to housed dairy cows under heat stress can reduce Proteobacteria and support rumen stability (Li *et al*., 2023; Wang *et al*., 2025).

Heat stress is a systemic modulator that can reconfigure the microbial ecosystem of the bovine reproductive tract. Cows exposed to severe heat stress exhibit endocrine disruption, with decreased oestradiol concentrations, reduced oestrus duration, and a delayed LH/ovulation peak (Nascimento *et al*., 2025). These changes were consistent with a significant decrease in vaginal diversity, suggesting greater dominance of a few taxa, which tends to reduce community resilience, that is, the capacity to buffer against fluctuations in pH, nutrients, and local immune signals (Um *et al*., 2024). This coupling of effects suggests that a bidirectional mechanism exists, in which heat stress alters the hypothalamic-pituitary-ovarian axis, contributing to the growth of opportunistic bacterial communities, which, in turn, can amplify local inflammatory signals (Um *et al*., 2024). On the other hand, in bulls, heat-induced gut dysbiosis alters bile acid metabolism and retinol absorption, impairing testicular retinoic acid synthesis and spermatogenesis (Wickware *et al.*, 2020; He *et al.*, 2024).

Sensor-based applications (heat stress response)

At present, different precision livestock farming (PLF) techniques have been developed for monitoring dairy cattle production. Sudden changes in the activity, feeding and drinking, physical condition, and health of animals can be detected by different sensors (e.g., radio-frequen- cy identification (RFID), accelerometers, load cells, and cameras) (Stygar *et al.*, 2021).

When assessing heat stress, a cow-centred approach can offer valuable insights tailored to the management and conditions of each dairy operation or scenario (IDF, 2025). Thus, applications based on sensors can be used to measure BT; however, a challenge with BT is that it varies depending on the sensor location on the animal's body (Bewley *et al.*, 2008). BT has been measured in different locations, such as the vaginal (VT), rectum (RT), reticule-rumen, eye, milk, ear canal, and skin (surface and underneath), with measurement devices that range in size and accuracy and also vary by time of day and frequency over a 24-h period (Tresoldi *et al.*, 2020).

In terms of devices, BT has been recorded using thermometers, thermal imaging cameras, and infrared technology (eye, skin), data loggers, or wearable sensors such as rumen boluses, ear tags, and skin-mounted devices used for continuously monitoring BT (Tresoldi *et al.*, 2020; Woodward *et al.*, 2024b).

Vaginal Probes

Thermal sensors, such as vaginal probes, facilitate the accurate measurement of core BT in heat-stressed animals. The results of Tresoldi *et al.* (2020) indicate that the type of device (i.e. data logger) and sampling strategies affect BT outcomes and that these decisions affect the interpretation of BT data. It is crucial to use high-accuracy loggers with an accuracy equal to or less than 0.1 °C. The use of low-accuracy loggers can lead to inaccurate temperature readings, potentially disrupting the decision-making process (Tresoldi *et al.*, 2020; IDF, 2025).

Tympanic Probes

This sensor has been used in dairy cows to measure heat stress (Arias *et al.*, 2008; Jara *et al.*, 2016); however, some limitations may affect its application in practice, such as cows behaving uncomfortably around these strange objects and ear infections potentially occurring after installation, especially with prolonged use. Additionally, the probes must be placed correctly near the eardrum, and any displacement can result in inaccurate readings. However, nowadays, some wireless temperature sensors that can be attached to the ear canal have already been marketed. Despite the difficulty in measuring tympanic temperature in adult animals, it is the only validated indicator of BT in calves (Setser *et al.*, 2020). Although some studies have used tail-attached devices on calves to monitor tail skin temperature, they have reported acceptable correlations with rectal temperature and appear useful under field conditions (Hill *et al.*, 2016; Furukawa *et al.*, 2024).

Infrared thermography or thermal imaging

Infrared thermography is a remote method for detecting sources of thermal radiation and monitoring the surface temperature distribution of a measurement object. It is based on optical radiometry and has many different applications. Hristov (2025) showed that under dangerous heat stress, the surface temperatures of the udder and thigh were strongly affected and could be used as monitoring points for thermal stress. However, despite being an increasingly popular tool, there are several practical limitations in accurately determining the thermal status of animals using this tool. For example, environmental factors such as wind speed and debris can affect temperature readings, and there is no consensus on which body area accurately reflects internal BT. Even those that are found to correlate can be influenced by other forms of stress (IDF, 2025).

Rumen/reticular temperature boluses

The rumen and reticulum are also locations of interest for measuring BT. Rumen temperature (RUT) and reticular temperature (RET) have been measured with the hope of developing a continuous and less invasive method for monitoring BT than Rectal Temperature or Vaginal Temperature (Bewley *et al.*, 2008). A rumen or reticulum bolus is a configured device placed in the reticulum or at the junction between the rumen and reticulum, consisting of a temperature sensor, a telemetry system, and a battery (Koltes *et al.*, 2018). These sensors have been shown to be correlated with rectal temperature and have been used to evaluate the effects of heat stress on beef (Boehmer, 2015; Lees *et al.*, 2018b) and dairy cattle (Bewley *et al.*, 2008). The temperatures recorded in the rumen and reticulum are approximately 0.5 °C higher than the rectal temperature due to the heat produced by rumen microorganisms (Bewley *et al.*, 2008). Currently, the identification and prediction of heat stress events in grazing dairy cows using ruminal temperature boluses have been proposed (Woodward *et al.*, 2024b).

Subcutaneous Implantable Devices

Subcutaneous temperature (ST) is also a place where BT can be measured using a sensor, as heat-stressed cows would drive more blood from the core to the peripheral body parts (Chung *et al.*, 2020). van Erp-van der Kooij *et al.* (2024) suggested that automatic monitoring of subcutaneous BT in cows might be informative of the health status of dairy cows. In addition, they found that the subcutaneous temperature of the skin was higher when outside temperatures increased, which could be used in the future as another tool to monitor heat stress in livestock under non-stabled conditions.

Large datasets collected by sensor technologies provide an alternative approach to train models for predicting heat stress risk and determining the efficacy of management mitigations when heat stress conditions exist (Woodward *et al*., 2024b). Further research investigating the genetic background of sensor-based BT variability in dairy cattle is still needed (Brito *et al*., 2025), especially in pasture-based systems.

As previously described, thermal comfort can be assessed on an individual basis by the application of invasive (e.g. boluses) and non-invasive sensors (thermal cameras). Both options are available in the market; however, there is a clear shortage of validation studies for monitoring systems based on these sensors (Stygar *et al*., 2021).

To measure other physiological indicators, such as respiration rate, panting and drooling, and rumination time, other PLF technologies, such as accelerometers for monitoring at the cow level and cameras for monitoring at the herd and cow levels, have been used. However, there may be limitations to the use of video surveillance in pasture-based systems due to the movement of grazing dairy cows around a large grazing area compared with housed cows, where these monitoring systems have been studied (Islam *et al*., 2021; Hendriks *et al*., 2025).

Accelerometers

Accelerometers are devices that measure the acceleration of a structure or object in 2D or 3D space. They calculate and record the static and dynamic acceleration along the x-, y-, and z-axes using electromechanical sensors. These acceleration data can be converted using effective algorithms to understand the state of an object. Each animal's behaviour has a characteristic movement of the body or idleness. Static or dynamic animal movements captured in 3D can be used to classify core behaviours through defined algorithmic transformations (Islam *et al*., 2021). One sensor-based approach is to use accelerometer data to predict heavy breathing. Accelerometer-based technology that automatically records heavy breathing provides a practical means of continuously assessing the heat load status of lactating or dry dairy cows and their response to cooling interventions (Bar *et al*., 2019). The proportion of cows breathing heavily in a group has been shown to mirror changes in vaginal temperature.

Overall behavioural organisation, including timing and duration of eating, rumination, panting, lying, standing, and activity, as determined by accelerometer-based sensors, can indicate whether an individual animal is coping with hot conditions (Islam *et al*., 2020; Islam *et al*., 2021).

New Approaches

Under heat stress, various key biomarkers in dairy cows undergo specific changes (Razzaghi *et al*., 2023). Endocrine markers such as cortisol (the primary stress hormone) which increases significantly during heat stress, and critical metabolic markers such as beta-hydroxybutyrate (βHB), non-esterified fatty acids (NEFA), and glucose undergo specific changes due to heat stress, which often leads to a Negative Energy Balance (NEB) due to reduced feed intake. In addition, Immune/Protein Markers: Heat Shock Protein 70 (HSP70) (Pathirana & Garcia, 2022) and Interleukin-6 (IL-6) concentrations in the blood increase as a direct cellular response to thermal stress, and oxidative stress Markers such as Total Antioxidant Capacity (TAC) decrease as heat-stressed cows suffer from oxidative imbalance. These changes not only reflect the impact of heat stress on cellular functions, immune status, and production- and reproduction-related physiological processes, but also provide a molecular basis for assessing heat stress severity and investigating its mechanisms (Razzaghi *et al*., 2023). In this sense, emerging approaches, such as graphene-based biosensors capable of real-time metabolite monitoring, are transitioning from laboratory prototypes to commercial validation stages. These technologies have shown promise for the detection of ketosis (Chick *et al*., 2024) and may also be extended to heat stress assessments. Such biosensors are anticipated to enable noninvasive, continuous physiological monitoring of livestock.

Farmers perception

Farmers' perceptions regarding heat stress have been addressed in different countries, such as Australia, Brazil, Sweden, South Africa, the USA, and Chile (Cardoso *et al*., 2018; Lane *et al*., 2019; Diniso *et al*., 2022; Hendriks *et al*., 2022; Tamminen *et al*., 2024; Arias *et al*., 2025). To gather insights, Arias *et al*. (2025) conducted a survey in Chile using the QuestionPro platform and emailed it to dairy farmers across the country. Responses were received from 98 dairy farmers from 28 districts, providing representative geographic coverage of Chile's main dairy regions and production systems. Most respondents were farmers with herds exceeding 500 cows, operating primarily pasture-based systems, and managing year-round calving. A total of 91.6% of the participants expressed interest in formal training on heat stress management. The top three topics of interest were nutritional and reproductive management under heat stress and thermal comfort indices as a management tool. Milk producers from all three production systems were willing to receive training, with producers from grazing systems standing out, and 88% were open to using a mobile application for real-time risk monitoring and practical mitigation tips. In addition, 73% of the respondents indicated a willingness to pay an annual subscription fee to ensure continued maintenance and technical support. In contrast, only 27% expressed a preference for a free basic version of the application, which would offer only heat stress risk prediction capabilities.

In New Zealand, Verhoek *et al*. (2026) used a survey to quantify farmers' knowledge, attitudes, and practices related to heat stress in dairy cows across two regions: Waikato/Bay of Plenty and Canterbury/North Otago.

Farmers showed strong awareness of heat stress indicators, citing an average of 2.8 indicators per respondent, with panting or breathing faster (56% of respondents), standing more or grazing less (48%), and increased drinking (43%) being the most frequently cited indicators. Among the 216 respondents implementing mitigations, an average of 2.2 strategies per respondent were reported, mostly sprinklers or misting systems in the dairy (59%) and natural shade (29%). Perceptions varied regionally, with 28% of Waikato/Bay of Plenty farmers rating heat stress as a moderate-to-severe issue, versus 16% in Canterbury/North Otago.

Future research investigating short-term mitigation options for grazing dairy cows should be considered to ensure that farmers receive advice that supports effective mitigation while meeting the cows biological, behavioural, and mental needs (Hendriks *et al.*, 2025).

DISCUSSION

Heat stress is increasingly recognised as a major environmental factor affecting productivity, reproduction, and animal welfare in dairy systems (Dž ermeikaitė *et al.*, 2025). With climate change leading to more frequent, prolonged, and intense heat events, its impact has become a persistent challenge for livestock (Dž ermeikaitė *et al.*, 2025). This issue is especially relevant in pasture-based systems, where cows are directly exposed to changing weather conditions, increasing their risk of heat stress compared to cows in confined systems (Herbut *et al.*, 2018; Arias *et al.*, 2025). Although dairy farmers are generally aware of the negative effects of heat stress, such as reduced milk yield, lower feed intake, and poorer reproductive performance (Wankar *et al.*, 2021; Foroushani & Amon, 2022; Hendriks *et al.*, 2022), important knowledge gaps remain, especially in grazing systems, where early signs of heat stress may be harder to detect (Arias *et al.*, 2025).

Beyond its visible effects, heat stress triggers deeper physiological disruptions, particularly within the gut microbiome, and causes structural and functional damage to the intestinal epithelium. Recent studies have shown that heat stress induces substantial shifts in rumen and intestinal microbial communities, contributing to dysbiosis and amplifying the negative consequences of thermal load (Welch *et al.*, 2022). These changes in the microbiome can have wide-ranging impacts on the animal's health. New findings also suggest that the gut communicates with other organs, such as the mammary gland and reproductive system; therefore, heat-related changes in the microbiome can affect milk quality, ovarian function, and fertility (Nascimento *et al.*, 2025). These findings highlight the need for more precise and integrative tools to assess the effects of heat stress.

Traditionally, the temperature-humidity index (THI) has been the main indicator used to evaluate heat load. However, the THI has clear limitations, particularly in outdoor systems, because it does not account for solar radiation or wind speed, two factors that strongly influence the actual thermal environment (Hendriks *et al.*, 2019). As a result, THI often underestimates heat stress in pasture conditions, where sunlight can intensify the heat load and wind can alleviate or exacerbate it depending on the direction and intensity (Cartes *et al.*, 2025). In this case, more complex indices, such as THI_{adj}, HLI, GHLI, and CCI, are useful tools for estimating heat stress in cattle, although each differs in focus and limitations. One of the main limitations of using alternative indices to the THI is the limited research (IDF, 2025), which makes it difficult to determine the critical thresholds of thermal stress for this bioclimatic indicator and its use. In addition, no single climate index can account for individual physiological variability in animals; therefore, they should be combined with biological indicators to achieve a more precise assessment of heat stress.

In this context, the relationship among RR, BT, and PS is of central relevance as a practical diagnostic tool. These variables represent direct physiological responses to increased heat load and allow for the assessment of stress levels at the individual level (Becker *et al.* 2020). However, their application in the field presents challenges, especially in pasture-based systems, where continuous and standardised measurements can be limited by operational conditions, environmental variability and extensive management practices. Faced with these limitations, new trends are emerging that rely on advanced technologies, particularly in the fields of artificial intelligence (AI) and biosensors. The development of real-time sensors capable of monitoring variables such as BT, activity, rumination, and RR enables the generation of large volumes of data that, when integrated with machine learning algorithms, can be used to build predictive models of heat stress (Becker *et al.*, 2021). These approaches overcome the limitations of traditional indices by incorporating individual variability and temporal dynamics of physiological responses. These technologies also reveal differences between animals in terms of how they handle heat, which depends on genetics, physiology, and productivity, and how they support more precise and flexible management strategies for heat stress. These technologies are especially useful in pastoral systems, where the environment varies widely and there are few options for structural change. By spotting early changes in behaviour, rumination, or BT, farmers can act before major production losses occur. These tools also help objectively measure the effectiveness of different strategies, such as providing shade, changing grazing and milking times, or selecting animals that better tolerate heat.

Given the multifaceted nature of heat stress, mitigation strategies must adopt a broader perspective that not only reduces BT but also prevent long-term physiological and microbial disruptions. In pasture-based systems, shade remains the most effective and accessible intervention (Aubé *et al.*, 2026). However, its effectiveness depends on factors such as type, placement, density, distribution, and interaction with natural airflow. Therefore, designing shade systems that optimise both thermal comfort and animal behaviour is essential for improving resilience to future heat events.

CONCLUSION

This review presents evidence that heat stress in dairy cows extends far beyond simple thermal discomfort and impacts their physiological function, behaviour, and microbial dynamics. These effects may be more noticeable in pasture-based systems, where cows are directly and continuously exposed to environmental conditions. However, the vulnerability of pasture-based systems depends on the local climate, management, infrastructure, and the animal's ability to release heat.

As climate change intensifies, dairy systems, especially those that depend on grazing, will increasingly depend on integrated approaches that combine improved environmental indices, precision monitoring technologies, and well-designed mitigation strategies to tackle the challenges of outdoor systems.

Improving farmers' capacity to detect early signs of heat stress and implement evidence-based interventions will be essential for maintaining productivity, promoting animal welfare, and ensuring the long-term resilience of pasture-based dairy systems.

DECLARATIONS

Competing Interests Statement

The authors declare that they have no competing interests.

Author contributions

Conceptualization: EB, DC, GT, AS; Visualization: EB, DC, GT, AS; Writ- ing – Original Draft: EB, DC, GT, AS; Writing – Review & Editing: EB, DC, GT, AS.

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