South African Journal of Animal Science 2025, VOL 55

Heat stress in dairy cows: A review of abiotic and biotic factors, with reference to the subtropics

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(Submitted 27 August 2024; Accepted 27 November 2024; Published January 2025)

Abstract

Heat stress has been identified as one of the major challenges for livestock production. Global temperatures are steadily increasing, with South African temperatures increasing at nearly twice the global rate. Of the livestock used for food production, dairy cows are the most sensitive to thermal changes, which have detrimental effects on their health, welfare, and overall productivity. Several abiotic factors that influence the heat load experienced by the cow are not commonly included in thermal indices used to measure heat stress; these include solar radiation, wind speed, and soil quality. Furthermore, the thermal comfort zone of cows has been altered by years of intense selection for increased milk yield, causing cows to become heat stressed at lower temperatures. Considering the abiotic and biotic factors affecting the cow's heat load, it can be argued that dairy cows in tropical and subtropical climates are experiencing constant heat stress. In this review, the abiotic and biotic factors influencing the heat load experienced by dairy cows are reviewed, along with the available thermal indices that can be utilised at farm level.

Keywords: climate change, heat load, Holstein cattle, Jersey cattle, thermal indices

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Introduction

Dairy cows are homeotherms that strive to maintain their body temperature by regulating their thermal energy balance, and this can be threatened during periods of high temperatures (Ouellet *et al.*, 2021). Heat stress is a physiologically driven response that occurs when an animal produces more heat than it can dissipate (Cartwright *et al.*, 2023). Of the livestock species used for food production, dairy cows are the most sensitive to thermal changes (Herbut *et al.*, 2018; Cheruiyot *et al.*, 2022). Exposure to either short- or long-term high ambient temperatures will thus have detrimental consequences for the health and production of dairy cows (Schüller *et al.*, 2016; Amamou *et al.*, 2019).

The consequences of climate change are multifactorial, with heat stress highlighted as one of the major burdens on livestock production (Lees *et al.*, 2019). Even regions known for more temperate climates, such as Ireland and Scotland, are experiencing periods of heat stress (Haskell *et al.*, 2023). The Southern African region is experiencing intensified heat conditions, with temperatures increasing at nearly twice the global rate (Scholes & Engelbrecht, 2021). South Africa is regarded as a semi-arid country with a unique blend of climates, biomes, and rainfall patterns, and has been identified as one of the sectors of the world that will be most affected by climate change, with an estimated average temperature increase of 1.5 to 2.0 °C (Williams *et al.*, 2016). This increase in temperature will be characterised by an increase in the occurrence of droughts, coupled with exposure to extreme summer temperatures, which may be as high as 40 to 45 °C (Roffe *et al.*, 2021).

A number of abiotic factors can influence the degree of heat stress experienced by dairy cows, with ambient temperature and relative humidity being among the most important because of their significant impact on the heat abatement abilities of cattle (Ji *et al.*, 2020). In addition, biotic factors such as size, production potential, and stage of lactation influence the cow's ability to respond to heat stress (Polsky & von Keyserlingk, 2017). Several studies have highlighted the billions in financial losses resulting from the direct and indirect effects of heat stress on the dairy production industry (Moore *et al.*, 2024). Unwanted physiological responses triggered by exposure to heat stress contribute to reduced quality of life, behavioural changes, and, in severe cases, death (Oliveira *et al.*, 2019; Godde *et al.*, 2021).

Dairy farming is a highly intensive industry, producing more than 965 million tonnes of milk annually (FAO, 2023) and employing an estimated 240 million people worldwide (Bojovic & McGregor, 2023). In addition, this industry plays a vital role in the livelihood of communities in developing regions, – such as Africa, India, Brazil, and Pakistan – where a wide spectrum of production systems are employed, ranging from subsistence and small holder farmers to intensive production systems (Bang *et al.*, 2022). In sub-Saharan Africa, indoor housing is limited and 75% of milk is produced using extensive production systems (Hernández-Castellano *et al.*, 2019). In South Africa specifically, 70% of dairy production systems are pasture-based, with the remaining 30% defined as total mixed ration systems, which entail dirt lots with shade and/or open-sided houses (Williams *et al.*, 2016). The effect of heat stress is expected to be more severe for extensively managed, pasture-based cows because of the higher temperatures and increased exposure to radiation (Veissier *et al.*, 2018). Heat stress will also be exacerbated by the long walking distances often required for grazing in extensive systems, which can cause an increase in body temperature (Saizi *et al.*, 2019).

Heat stress poses a threat to the sustainability of dairy production. The global dairy industry is already expected to increase milk yield without utilising any additional resources, such as land and water (Cartwright *et al.*, 2023). However, sustainability may decrease because of the pressures of heat stress on production efficiency, health, and welfare (Polsky & von Keyserlingk, 2017). A major concern is the prolonged effects of heat stress on the physiology and overall well-being of dairy cows (Perano *et al.*, 2015). In this review, abiotic and biotic factors influencing heat stress in dairy cows are reviewed, with reference to the available thermal indices that can be applied as monitoring tools.

Abiotic factors and heat stress

The abiotic environment includes a range of factors, as shown in Figure 1; these factors interact and contribute, either directly or indirectly, to the potential heat abatement and overall comfort of dairy cows.

Ambient temperature affects relative humidity, and vice versa, so these two factors should be considered together (Herbut *et al.*, 2018; Islam *et al.*, 2021). However, several other abiotic factors that are not included in the temperature-humidity index (THI) model also play a key role in the heat load carried by the cow (Lees *et al.*, 2019).

Solar radiation affects the severity of heat stress experienced by cows (Ji *et al.*, 2020), and several consequences of dairy cows' exposure to solar radiation have been reported. These include an increase in respiration rate (Becker *et al.*, 2020), increased panting score (Veissier *et al.*, 2018), increased occurrence of DNA damage due to chromosome dissociation and fragmentation and altered DNA-repair signalling (De Abreu *et al.*, 2020), increased metabolic rate (Broucek *et al.*, 2020), decreased feeding behaviour and increased shade-seeking behaviour (Oliveira *et al.*, 2019), increased body temperature (Tucker *et al.*, 2008), increased rectal temperature (Shephard & Maloney, 2023), and decreased fertility and follicular activity (Sesay, 2023). Research has shown that access to shade and shelter can alleviate some heat stress by decreasing the heat load and improving heat dissipation capabilities (Zhou *et al.*, 2022).

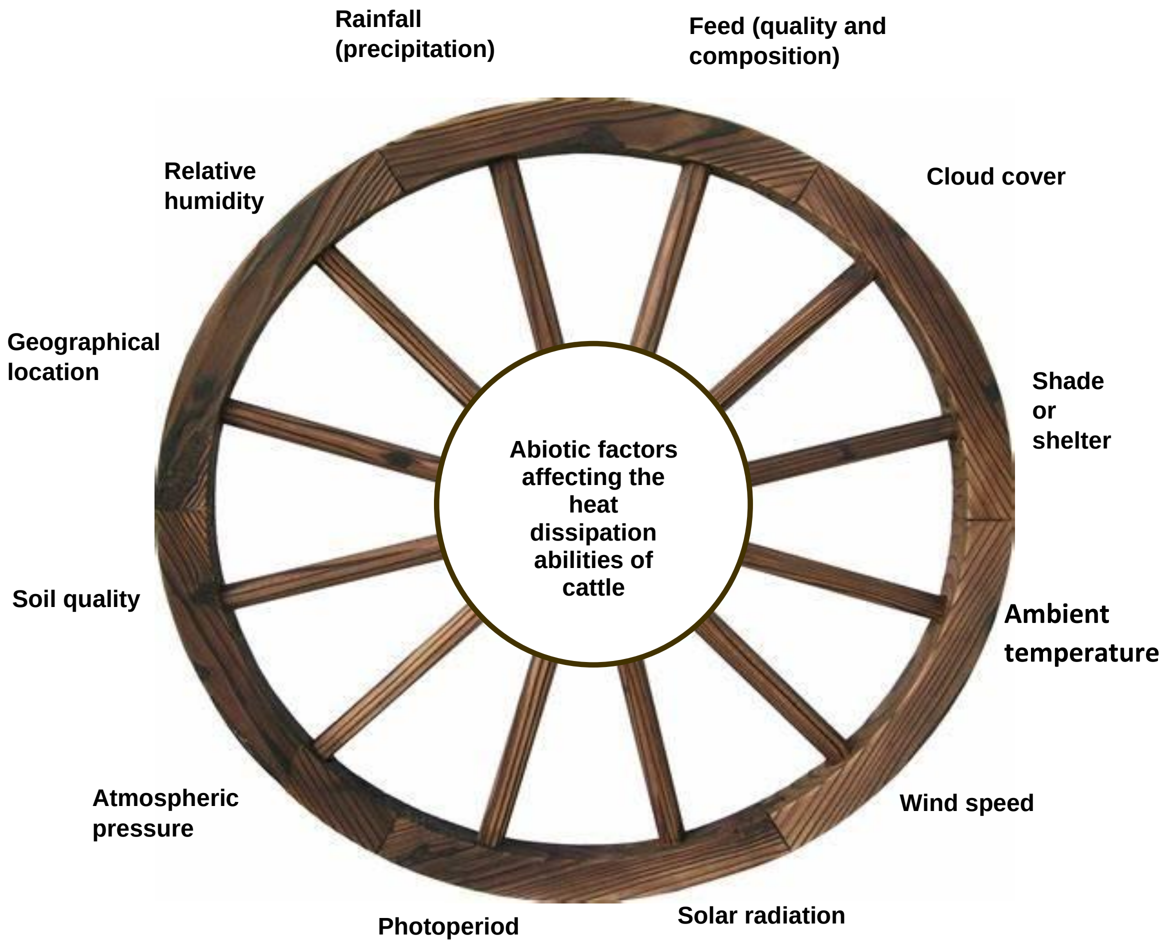

Figure 1 Abiotic factors affecting heat dissipation in dairy cows (adapted from Bonsma, 1983).

Wind speed may have a positive effect by reducing the ambient temperature experienced by the animal, and may thus provide some short-term relief. Wind improves heat loss through convection by replacing hot air near the surface of the cow's skin with cooler air, whether the cow is standing or lying down (Wang *et al.*, 2018; Becker *et al.*, 2020). Studies have found that moderate wind speeds (0.2–0.5 m/s) are preferable (Hill & Wall, 2015), and can play a major role in the thermoregulation of dairy cows. Researchers have thus argued for the inclusion of wind into the THI model, and housing systems try to imitate wind through the incorporation of airflow and ventilation (Zhou *et al.*, 2022). Wind can assist in alleviating the heat load of cows, and thereby decrease rectal temperature, improve feed intake, and increase the display of normal behaviour, resulting in improved milk yields and animal welfare (Dikmen & Hansen, 2009; Haskell *et al.*, 2023).

The geographical locations of cows determine several environmental factors that can influence heat load (Figure 2), including photoperiod, atmospheric pressure, and rainfall patterns. Photoperiod is generally defined as the duration of time that an animal is exposed to light within a 24-hour cycle, and this changes seasonally (Hut & Beersma, 2011). A shorter day length is associated with cooler temperatures and decreased incidences of heat stress (Velasco *et al.*, 2008). A short-day photoperiod also increases the secretion of melatonin, which is known to improve heat dissipation methods and lower internal heat production (Collier *et al.*, 2006). Melatonin, in turn, influences the secretion of several other hormones, including cortisol, prolactin, and gonadotropin-releasing hormone (Pal *et al.*, 2022). Studies have found that cows require exposure to long-day photoperiods to increase their dry matter intake and water intake, with this being correlated with weight gain and improved production (Macmillan *et al.*, 2018; Tang *et al.*, 2022). Cows therefore require a balance of short and long days for adequate growth and development, and individuals that are underweight or underdeveloped will be at risk of heat stress (Suarez-Trujillo *et al.*, 2020).

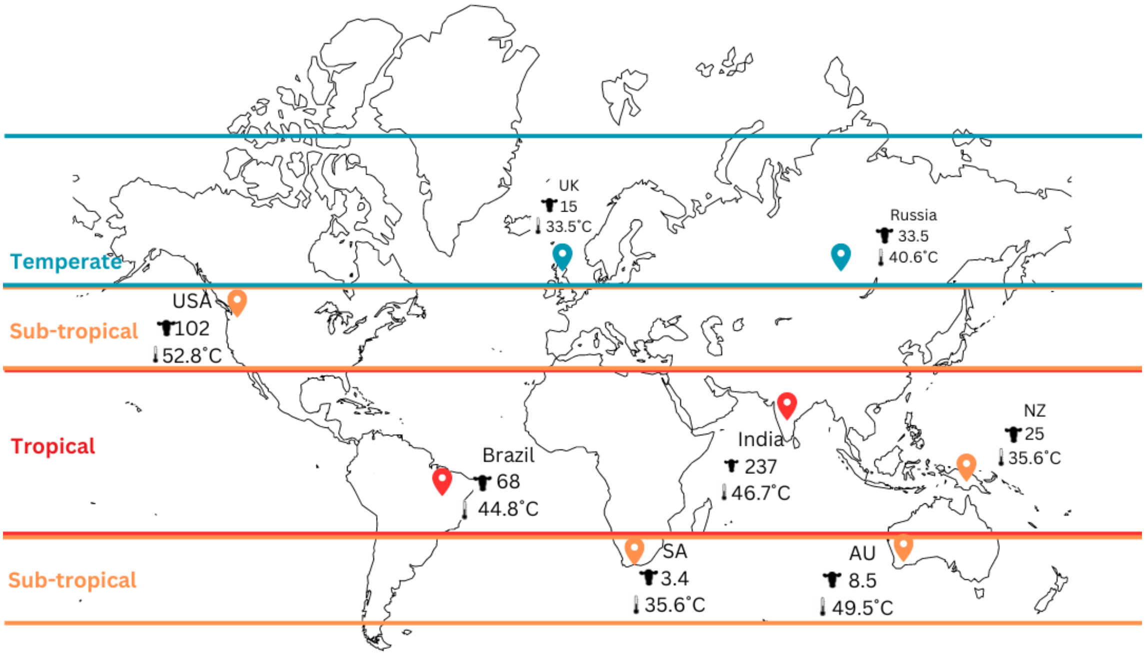

Figure 2 Geographical locations of milk-producing countries worldwide. The cow symbol indicates the average milk production, in million tonnes, for 2023, whereas the thermometer symbol indicates the highest recorded temperature for 2023. India is the highest milk-producing country worldwide and faces extreme temperatures, causing severe heat stress in dairy cows.

Areas with higher altitudes are characterised by lower atmospheric pressures, and therefore cooler temperatures and lower incidences of heat stress (Martí-Herrero *et al.*, 2015). The evaporative cooling abilities of cows are improved at lower atmospheric pressures, as the moisture-holding capacity of the air increases (Schüller *et al.*, 2016; Broucek *et al.*, 2020). Tropical and subtropical areas are primarily found at low to moderate altitudes, and are characterised by high temperatures and minimal relief from heat (Jeelani *et al.*, 2019).

Rainfall patterns are dependent primarily on geographical location, including aspects such as latitude, altitude, and ocean proximity (Oettli & Camberlin, 2005). Rainfall can decrease the ambient temperature and therefore the heat load of the cow, with the added benefit of cloud cover, which decreases the amount of solar radiation (Tucker *et al.*, 2008).

It is well known that South African soils are deficient in phosphorus, but several of the highest milk-producing tropical countries, including India and Brazil, also have soils that are deficient in phosphorus (Balemi & Negisho, 2012; Magnone *et al.*, 2022). This phosphorus-poor soil can aggravate the effects of heat stress in cows by impairing energy metabolism, further increasing their energy requirements and making it even harder for them to cope under heat stress conditions (Goselink *et al.*, 2015). Phosphorus deficiencies can also lead to poor bone growth and development, resulting in weaker animals that are unable to survive under heat stress conditions (Hill *et al.*, 2008), and can reduce feed intake, impair digestion, and increase fluid loss, further exacerbating the effects of heat stress (Keanthao *et al.*, 2021).

Plants grown in poor-quality soils are of inferior nutritional quality because of the limited absorption of nutrients (El-Ramady *et al.*, 2014). The composition of ingested feed plays a vital role as it determines the amount of internal heat generated by the animal; providing an appropriate diet will thus support improved production during episodes of heat stress (Herbut *et al.*, 2021). Diets containing large quantities of concentrates will increase the risk of ruminal acidosis during heat stress (Cartwright *et al.*, 2023). Feed and water intake, along with the composition of the feed and expected rumination time, will influence the risk of heat stress occurrence in cows (Herbut *et al.*, 2018).

Considering these abiotic factors – with temperature being a major factor – it can be argued that dairy cows in subtropical regions are under constant heat stress, especially with warmer average temperatures being recorded over the past decade (Hernández-Castellano *et al.*, 2019).

Biotic factors and heat stress sensitivity

The thermoneutral zone (TNZ) is the range of ambient environmental temperatures at which the cow is not required to expend energy to maintain her normal body temperature (Shephard & Maloney, 2023). The TNZ of a lactating dairy cow is reported as ranging from −5 to 22 °C, with some researchers reporting a discrepancy of ± 5 °C (Müschner-Siemens *et al.*, 2020). Each individual cow has a heat stress threshold beyond which a decline in performance will be observed (Saizi *et al.*, 2020; Herbut *et al.*, 2021). As a result, upper and lower critical limits are identified, which are temperatures beyond which the cow's ability to thermoregulate will become challenged (Pinto *et al.*, 2020; Ouellet *et al.*, 2021). The ideal habitat for cows is defined as one with suitable air flow, temperatures below 25 °C, and relative humidity values of 50% to 80% (Herbut *et al.*, 2018). However, this perfect habitat, based on data from Dragovich (1979), does not account for the effects of production-focused breeding objectives or intense climate change (Kadzere *et al.*, 2002; Sesay, 2023). Decades of intense selection for cows with increased milk yield have resulted in an altered TNZ, causing cows to experience heat stress at lower ambient temperatures (Cartwright *et al.*, 2023). Several individual and breed-based factors can influence the sensitivity of the dairy cow to heat stress, as shown in Figure 3.

Genetic factors

A cow's genetic production potential has a direct impact on her ability to tolerate hot climates (Becker *et al.*, 2020). The TNZ shifts to lower temperatures for higher-producing cows (Hill & Wall, 2015), because of the inverse relationship that exists between the metabolic production of internal heat and heat tolerance (Cartwright *et al.*, 2023). Once the upper critical limit has been exceeded, the cow has to use more energy to cool down, thereby depleting the energy reserves needed for milk production (Williams *et al.*, 2016; Archer *et al.*, 2021).

Breed plays a significant role in determining the heat dissipation capacity of cows (Hoffmann *et al.*, 2020; Ji *et al.*, 2020). Some breeds simply dissipate heat more effectively, allowing them to have a higher critical limit (Correa-Calderon *et al.*, 2004; Fabris *et al.*, 2019). *Bos taurus* breeds are typically less tolerant of hot climates than their *Bos indicus* and Zebu conspecifics (Kadzere *et al.*, 2002; Polsky & von Keyserlingk, 2017). Holstein cows are particularly sensitive to heat stress and exhibit a significant decrease in production performance under conditions of moderate (THI = 72–75) heat stress (Liang *et al.*, 2013; Amamou *et al.*, 2019). In contrast, Jersey cows only experienced a decrease in production performance during severe (THI = 75–80) heat stress, and remain unaffected during moderate heat stress (Smith *et al.*, 2013). Breed can also affect basal body temperature, as demonstrated by the lower reticulorumen temperatures exhibited by Jersey cows under heat stress conditions (Liang *et al.*, 2013). Research has found that some milk breeds (Jersey and Brown Swiss) and cross-breeds (Holstein-Gyr and Holstein-Boran) have a higher rate of cutaneous evaporation than the Holstein breed, supporting a lower internal temperature (da Cruz *et al.*, 2016; Galán *et al.*, 2018).

Several breed-specific factors affect the rate of energy exchange, including the type of hair coat (length and thickness), hair colour, and skin pigmentation (Anzures-Olvera *et al.*, 2019). Cattle breeds with short hair have a higher tolerance to heat stress than those with long hair, mainly due to their increased evaporative ability (Galán *et al.*, 2018). The thickness of a cow's hair is positively correlated with rectal temperature (Hansen, 2020), with thick hair acting as a layer of insulation that reduces the ability of the cow to dissipate heat (Dikmen *et al.*, 2014).

Cows with dark-coloured coats experience higher rates of solar absorption, which compromise their ability to lose heat through convection or evaporation (Tucker *et al.*, 2008). Consequently, these dark-coloured breeds often exhibit higher respiratory rates, panting scores, and skin surface temperatures (Kadzere *et al.*, 2002; Becker *et al.*, 2020). Holsteins typically have thicker and darker coats, and, as a result, they tend to experience a greater degree of thermal discomfort (Anzures-Olvera *et al.*, 2019).

Cattle have apocrine sweat glands (one sweat gland per hair fibre), and hair density thus directly affects the number of active sweat glands and the cow's ability to lose heat evaporatively (Collier *et al.*, 2008). Sweating is the primary mode of heat loss for cattle (Hansen, 2020). The sweating response of *Bos indicus* cattle is triggered at temperatures 8 °C higher than in other breeds, making them less efficient at dissipating heat (Islam *et al.*, 2021). Evaporative heat loss is facilitated by sweating until heat stress becomes too severe, at which point heat loss through respiratory mechanisms is needed (Dahl *et al.*, 2020).

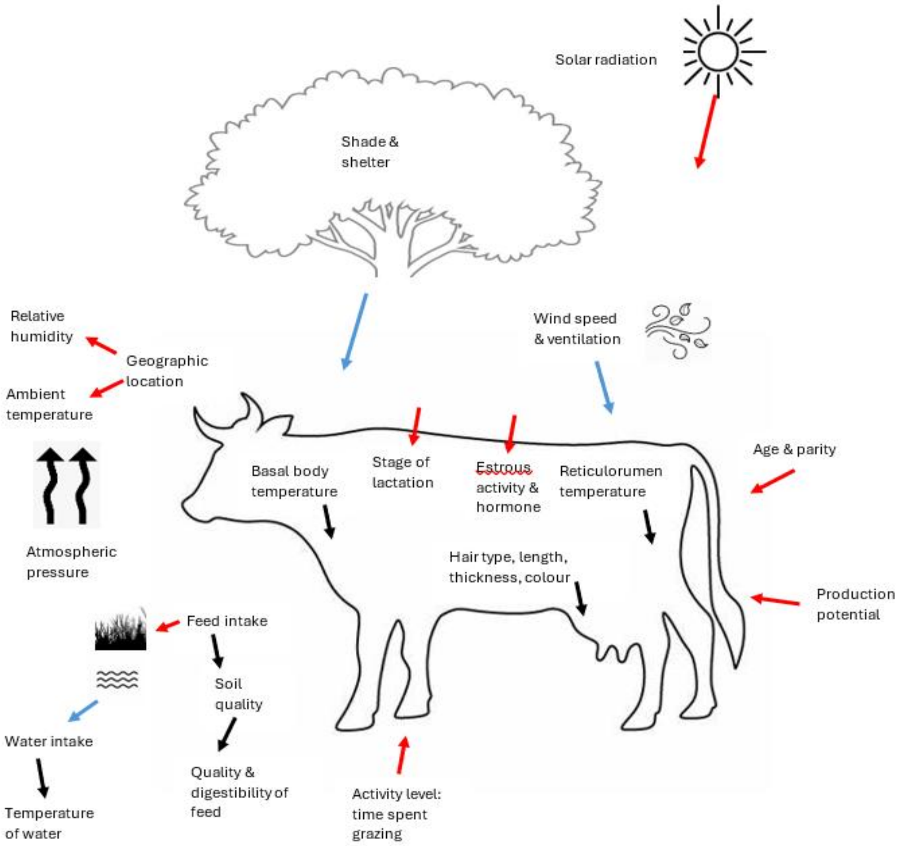

Figure 3 Abiotic and biotics factors affecting a dairy cow's heat dissipation capabilities. Red arrows indicate factors that increase the heat load of the cow, blue arrows indicate factors that help alleviate the heat load of the cow, and black arrows indicate factors that may increase or alleviate the heat load of the cow. For example, black hair colour increases the absorption of solar radiation, whereas lighter hair colour decreases the amount of solar radiation absorbed by the cow.

A frameshift mutation in the bovine prolactin receptor gene has been associated with a short, sleek coat (Hansen, 2020). This mutation, called the SLICK1 mutation, has been mapped to chromosome 20 (Scheffler, 2022). SLICK1 is a dominant allele and, therefore, for progeny to exhibit the associated phenotype, only a single parent needs to be a homozygous carrier (Dikmen *et al.*, 2014). This specific mutation has caught the attention of researchers because of its improvement of the thermoregulatory abilities of cows, including enhanced heat dissipation from reduced coat thickness, increased sweating rates, and an improved ability to regulate core body temperature (Cheruiyot *et al.*, 2022). Dairy cows with the SLICK1 allele exhibit lower vaginal temperatures, lower skin temperatures, and increased sweating, enabling them to cope with higher thermal temperatures (Carmickle *et al.*, 2022). Therefore, the introduction of the SLICK1 allele has the potential to improve efficiency by minimising the reduction in milk yield in warm climates, as well as enhancing welfare through reduced discomfort and suffering (Pozzebon *et al.*, 2024). The SLICK1 allele has already been introduced into the Senepol, Red Angus, and United States Holstein cattle breeds (Hansen, 2020).

The breed of cow genetically dictates the size of the animal (Godde *et al.*, 2021). Cow frame size is positively correlated with intake capacity and, as a result, larger cows have higher feed intakes and higher maintenance energy requirements, which impacts their ability to regulate their body temperature (Walker *et al.*, 2015). Larger cows also have a higher metabolic rate and produce a larger amount of internal heat (Ji *et al.*, 2020). The heat load of large cows is exacerbated further when they need to walk long distances while grazing to fulfil their maintenance requirements (Polsky & von Keyserlingk, 2017; Pontiggia *et al.*, 2023). Smaller cows also have greater sweating rates and a higher surface area-to-volume ratio, making them lose heat more efficiently through evaporation (Saizi *et al.*, 2019; Zhou *et al.*, 2022). Moreover, smaller cows can increase their respiratory rate more efficiently than larger cows can (Scharf *et al.*, 2012).

Physiological factors

Several factors influence the thermoregulatory abilities of cattle (Herbut *et al.*, 2018). Previous exposure to heat stress will affect the cow's susceptibility to subsequent heat stress exposure, with the extent of this effect depending on the intensity and duration of the exposure, as well as the acclimatisation ability of the cow (Godde *et al.*, 2021). The ability of a cow to adapt to extreme weather conditions depends on her specific endocrine, metabolic, and immune system, all of which are directly related to the mechanisms of heat loss in dairy cows (Aggarwal *et al.*, 2013; Tang *et al.*, 2022). Cows have an increase in core body temperature mid-oestrus, limiting their ability to thermoregulate efficiently, and this is further exacerbated by the increase in physical activity associated with the onset of oestrus (Suthar *et al.*, 2011). The circadian and seasonal rhythms of cows become altered during episodes of heat stress, causing variation in the production and metabolism of glucose, non-esterified fatty acids, urea, and cholesterol, thereby decreasing the energy available to dissipate heat (Shehab-El-Deen *et al.*, 2010). Seasonal fluctuations can also disrupt the autonomic nervous systems of cows, resulting in altered internal signalling and cardiac fluctuations (Kovács *et al.*, 2016).

A higher body condition score is indicative of a higher amount of body fat. Cows with high body condition scores have an increased rate of metabolic activity, which generates a larger amount of internal heat and places them at risk of experiencing heat stress (Shephard & Maloney, 2023). Not only do these cows produce more internal heat, but they also have a reduced ability to dissipate heat (Lees *et al.*, 2019). Fat is an insulator that traps heat within the cow's body, making it more difficult for the cow to regulate her internal temperature (Kadzere *et al.*, 2002). Furthermore, fat cows become insulin-resistant, which is correlated with a reduced ability to regulate body temperature, further restricting the cow's ability to dissipate heat through panting and altered blood flow (Dunshea *et al.*, 2013; Zeng *et al.*, 2023). Heat stress alters the pattern of blood flow in cattle, increasing cutaneous blood flow that carries heat from the core to the periphery, and thereby facilitating heat loss (Dahl *et al.*, 2020). In addition, under heat stress conditions, blood flow to the epithelium decreases, hindering reticular motility and rumination (Sesay, 2023), and blood flow to the skin increases, enhancing the sweating rate (Dunshea *et al.*, 2013).

Cow age plays a significant role in determining susceptibility to heat stress – determining not only the upper critical limit, but also the thermoneutral range (Becker *et al.*, 2020). The parity of a cow is normally closely linked to her age because of the intensive breeding practices used in dairy production systems. In South Africa, for instance, heifers are bred when they reach 60% of their mature body weight, and this typically occurs at approximately 14–16 months of age (Muller, 2017). Most studies thus prefer to describe cow age in terms of parity number, as it allows for easier classification. Multiparous cows (cows that have calved more than once) are significantly more susceptible to heat stress than their primiparous counterparts (Ji *et al.*, 2020). This susceptibility is evident through a larger decrease in milk production (Adriaens *et al.*, 2021), lower quality colostrum due to decreased concentrations of immunoglobulin G, solid non-fat, protein and fat (Avendaño-Reyes *et al.*, 2023), and a higher increase in the somatic cell count (Smith *et al.*, 2013). Heat-stressed multiparous cows also tend to have a greater decrease in the time spent ruminating (Müschner-Siemens *et al.*, 2020), a lower threshold for respiration rate and rectal temperatures (Yan *et al.*, 2021), and a higher proportion of cows that have to be re-bred because of failed insemination (Biffani *et al.*, 2016).

The physiological state of a cow will determine the severity of heat stress that she experiences (Pontiggia *et al.*, 2023). Pregnant cows have higher energy demands than dry cows and, as a result, they have higher metabolic heat production (Becker *et al.*, 2020). The stage of lactation will also affect the cow's heat dissipation rate, as lactating cows have more heat to dissipate than non-lactating cows do (Ji *et al.*, 2020). A study by Calamari *et al.* (2007) found that mid-lactation cows experienced heat stress more severely than cows in early- or late-lactation stages, which Galán *et al.* (2018) supported with the observation that early-lactation cows produce less metabolic heat per kilogram of milk yield because of the mobilisation of stored tissue. Even though dry cows are more tolerant of heat, exposure to heat stress will affect their subsequent lactation period, primarily by decreasing milk production (Fabris *et al.*, 2019).

Thermal indices

The temperature-humidity index (THI) was developed to quantify the intensity of heat stress experienced by dairy cows (Hoffmann *et al.*, 2020). Initially designed for humans, the THI model was adapted by Berry *et al.* (1964) for cows and is still accepted as the global standard (Ji *et al.*, 2020). The most important abiotic factors influencing heat stress are relative humidity and air temperature, or a combined effect thereof (Islam *et al.*, 2021). The THI has been utilised to assess the degree of heat stress experienced by dairy cows under various conditions, including in indoor and outdoor housing, and in different climates and production systems (Hill & Wall, 2015). However, the THI has some limitations that must be considered.

Several studies have reported that THI predictions underestimate the severity of heat stress experienced by dairy cows (Pinto *et al.*, 2020). For many years, a THI of 68 was accepted as the point of heat stress in both lactating and dry cows, but this has recently been described as outdated (Perano *et al.*, 2015; Ouellet *et al.*, 2021). The THI values for different degrees of heat stress reported by different researchers (listed chronologically) are summarised in Figure 4. Unfortunately, these values do not correspond to the most recent literature, which indicates that cows experience heat stress at lower temperatures and thus lower THI values (Pontiggia *et al.*, 2023). Researchers agree that the higher the THI value, the larger the extent of stress and discomfort experienced by the cow (Herbut *et al.*, 2018). However, there is no consensus on the THI value at which production and behaviour will become altered.

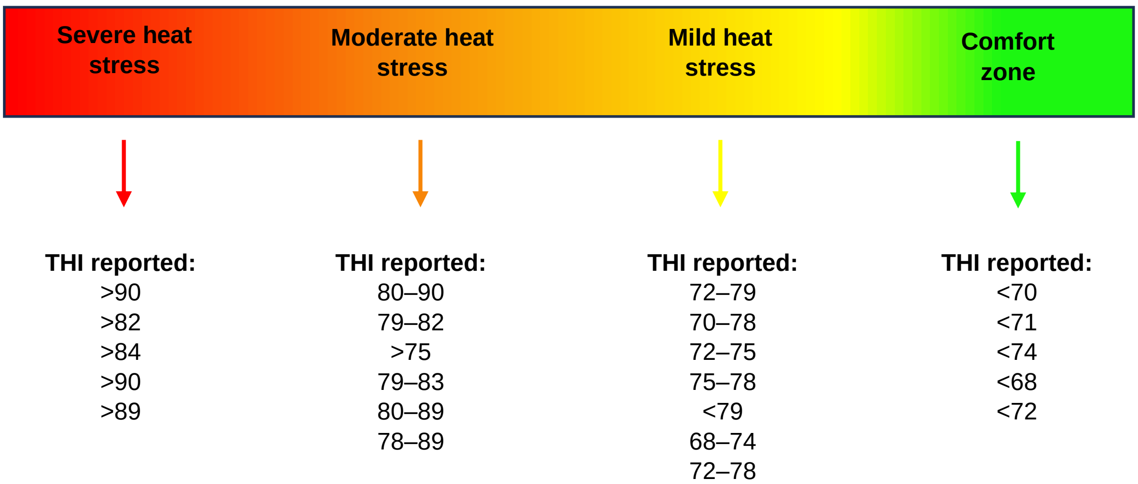

Figure 4 Spectrum of temperature-humidity index (THI) values assigned to different degrees of heat stress by various studies, compiled from Dikmen & Hansen (2009), Pinto *et al.* (2015), Archer *et al.* (2019), Yan *et al.* (2021), and Moore *et al.* (2024).

The THI simplifies complex environmental factors but omits vital abiotic and biotic elements that impact the effect of heat stress on dairy cows (Dikmen & Hansen, 2009; Moore *et al.*, 2024). Individual cow factors vary significantly and, as a result, biotic factors should be the focal point of heat stress measurements in order to obtain accurate and reliable results (Pontiggia *et al.*, 2023). Numerous thermal indices have been developed to evaluate the degree of heat stress experienced by cows during hot weather, as alternatives to the inadequate THI system, and these are summarised in Table 1 (Wang *et al.*, 2018; Cheruiyot *et al.*, 2022). These modern indices are not commonly employed at farm level because of their complexity, the need for specialised equipment to measure the necessary variables, and the unwillingness of dairy producers to use alternative measurements (Polsky & von Keyserlingk, 2017; Dado-Senn *et al.*, 2023). The THI therefore remains the thermal evaluation method of choice for dairy farmers, despite its limitations. Archer *et al.* (2021) thus suggested that the THI be used as a management tool to guide mitigation strategies and thereby ensure the optimal production of dairy cows.

Table 1 Different thermal indices designed to measure the degree of heat stress experienced by dairy cows, based on abiotic and biotic factors

Developed by	Abiotic factors included	Biotic factors included
Black globe-humidity index (BGHI)		
Buffington in 1981	Dry-bulb temperature Solar radiation Air movement	None
Equivalent temperature index (ETI)		
Baeta in 1987	Air temperature and relative humidity, Air velocity Solar radiation	None
Respiration rate index (RRI)		
Eigenberg in 2005	Air temperature Relative humidity Solar irradiance	Skin temperature Respiration rate
Heat load index (HLI)		
Gaughan in 2008	Black globe temperature Relative humidity Wind speed	None
Comprehensive climate index (CCI)		
Mader in 2010	Ambient temperature adjusted for relative humidity Wind speed Solar radiation	None
Index of thermal stress for cows (ITSC)		
Da Silva in 2015	Solar radiation Air temperature Wind speed Air partial vapour pressure	Rectal temperature Respiratory rate Convective heat load Skin surface evaporation
Equivalent temperature index for cattle		
Wang in 2018	Air temperature Relative humidity Air velocity Solar radiation	Respiratory evaporation Radiation heat gain Skin temperature Core temperature Respiration rate

The health, welfare, and overall productivity of dairy cows is severely affected by heat stress and, as a result, short-term amelioration strategies are employed to modify cows' microclimates through mechanical means (Ji *et al.*, 2020). However, dairy farms worldwide employ pasture-based systems, and many of the suggested mitigation strategies (both physical and nutritional) are regarded as impractical for these systems. Long-term, holistic strategies should thus be considered (Sesay, 2023). Nevertheless, dairy production systems remain focused on increasing production, despite the negative association between the level of production and heat tolerance and, as a result, researchers are striving to develop breeding values for heat tolerance that can be incorporated into selection indices (Cheruiyot *et al.*, 2022). Future research should focus on improving heat tolerance, to provide dairy cows with the greatest chance of surviving under increasingly harsh conditions.

Conclusion

Heat stress has become a focal point of research endeavours, livestock production industries, humanitarian organisations, animal welfare and conservation groups, and even broadcasting and media agencies. Even though heat stress is not a new challenge, it has become a severe threat to the future livelihood of Africa and its residents. Dairy cows are the most susceptible of livestock species to heat stress and, as a result, it is essential to consider and address the abiotic and biotic factors influencing the susceptibility of dairy cows to heat stress. Because of the large variation that exists within the use of thermal indices based on abiotic factors, it is essential to focus on cow-based factors to ensure accurate heat stress assessments.

Authors' contributions

L.M. Erasmus (ORCID: 0000-0002-2364-5886) wrote the initial draft of this manuscript; E. van Marle-Koster (0000-0002-3672-6976) designed the structure and edited drafts. Both authors have read and approved the finalised manuscript.

Conflict of interest declaration

The authors have no conflicts of interest to declare.

References

Adriaens, I., Van Den Brulle, I., D'Anvers, L., Statham, J.M.E., Geerinckx, K., De Vliegher, S., Piepers, S., & Aernouts, B., 2021. Milk losses and dynamics during perturbations in dairy cows differ with parity and lactation stage. J. Dairy Sci., 104(1), 405–418. doi 10.3168/jds.2020-19195

Aggarwal, A., Upadhyay, R., Aggarwal, A., & Upadhyay, R., 2013. Heat stress and hormones. In: Heat stress and animal productivity, 27–51.

Amamou, H., Beckers, Y., Mahouachi, M., & Hammami, H., 2019. Thermotolerance indicators related to production and physiological responses to heat stress of Holstein cows. J. Therm. Biol., 82, 90–98. doi 10.1016/j.jtherbio.2019.03.016

Anzures-Olvera, F., Véliz, F.G., De Santiago, A., García, J.E., Mellado, J., Macías-Cruz, U., Avendaño-Reyes, L., & Mellado, M., 2019. The impact of hair coat color on physiological variables, reproductive performance and milk yield of Holstein cows in a hot environment. J. Therm. Biol., 81, 82–88. doi 10.1016/j.jtherbio.2019.02.020

Archer, E.R.M., Landman, W.A., Malherbe, J., Maluleke, P., & Weepener, H., 2021. Managing climate risk in livestock production in South Africa: How might improved tailored forecasting contribute? Clim. Risk Manag., 32, 100312. doi 10.1016/j.crm.2021.100312

Avendaño-Reyes, L., Macías-Cruz, U., Sánchez-Castro, M.A., Anzures-Olvera, F., Vicente-Pérez, R., Mellado, M., Zamorano-Algándar, R., Robinson, P.H., Castañeda-Bustos, V.J., & López-Baca, A., 2023. Effects of parity, seasonal heat stress, and colostrum collection time postpartum on colostrum quality of Holstein cattle in an arid region. Int. J. Biometeorol., 1–8. doi 10.1007/s00484-023-02601-5

Balemi, T. & Negisho, K., 2012. Management of soil phosphorus and plant adaptation mechanisms to phosphorus stress for sustainable crop production: a review. J. Soil Sci. Plant Nutr., 12(3), 547–562. doi 10.4067/S0718-95162012005000015

Bang, N.N., Gaughan, J.B., Hayes, B.J., Lyons, R.E., & McNeill, D.M., 2022. Application of infrared thermal technology to assess the level of heat stress and milk yield reduction of cows in tropical smallholder dairy farms. J. Dairy Sci., 105(10), 8454–8469. doi 10.3168/jds.2021-21343

Becker, C.A., Collier, R.J., & Stone, A.E., 2020. Invited review: Physiological and behavioral effects of heat stress in dairy cows. J. Dairy Sci., 103(8), 6751–6770. doi 10.3168/jds.2019-17929

Berry, I.L., Shanklin, M.D., & Johnson, H.D., 1964. Dairy shelter design based on milk production decline as affected by temperature and humidity. Trans. ASABE, 7(3), 329–0331.

Biffani, S., Bernabucci, U., Vitali, A., Lacetera, N., & Nardone, A., 2016. Effect of heat stress on nonreturn rate of Italian Holstein cows. J. Dairy Sci., 99(7), 5837–5843. doi 10.3168/jds.2015-10491

Bojovic, M., & McGregor, A., 2023. A review of megatrends in the global dairy sector: what are the socioecological implications? Agr. Hum. Values, 40(1), 373–394. doi 10.1007/s10460-022-10338-x
Bonsma, J., 1983. Chapter 2: Livestock Ecology. In: Man must measure: livestock production. Applied Genetics Publishing Inc. Cody: Agri Books.
Broucek, J., Ryba, S., Dianova, M., Uhrincat, M., Soch, M., Sistkova, M., Mala, G., & Novak, P., 2020. Effect of evaporative cooling and altitude on dairy cows milk efficiency in lowlands. Int. J. Biometeorol., 64, 433–444. doi 10.1007/s00484-019-01828-5
Calamari, L., Abeni, F., Calegari, F., & Stefanini, L., 2007. Metabolic conditions of lactating Friesian cows during the hot season in the Po valley. 2. Blood minerals and acid-base chemistry. Int. J. Biometeorol., 52(2), 97–107. doi 10.1007/s00484-007-0097-4
Carmickle, A.T., Larson, C.C., Hernandez, F.S., Pereira, J.M., Ferreira, F.C., Haimon, M.L., Jensen, L.M., Hansen, P.J., & Denicol, A. C., 2022. Physiological responses of Holstein calves and heifers carrying the SLICK1 allele to heat stress in California and Florida dairy farms. J. Dairy Sci., 105(11), 9216–9225. doi 10.3168/jds.2022-22177
Cartwright, S.L., Schmied, J., Karrow, N., & Mallard, B.A., 2023. Impact of heat stress on dairy cattle and selection strategies for thermotolerance: a review. Front. Vet. Sci., 10, 1198697. doi 10.3389/fvets.2023.1198697
Cheruiyot, E.K., Haile-Mariam, M., Cocks, B.G., & Pryce, J.E., 2022. Improving genomic selection for heat tolerance in dairy cattle: Current opportunities and future directions. Front. Genet., 13, 894067. doi 10.3389/fgene.2022.894067
Collier, R.J., Collier, J.L., Rhoads, R.P., & Baumgard, L.H., 2008. Invited review: genes involved in the bovine heat stress response. J. Dairy Sci., 91(2), 445–454. doi 10.3168/jds.2007-0540
Collier, R.J., Dahl, G.E., & VanBaale, M.J., 2006. Major advances associated with environmental effects on dairy cattle. J. Dairy Sci., 89(4), 1244–1253. doi 10.3168/jds.S0022-0302(06)72193-2
Correa-Calderon, A., Armstrong, D., Ray, D., DeNise, S., Enns, M., & Howison, C., 2004. Thermoregulatory responses of Holstein and Brown Swiss heat-stressed dairy cows to two different cooling systems. Int. J. Biometeorol., 48, 142–148. doi 10.1007/s00484-003-0194-y
da Cruz, P.F.F., Monteiro, C.P., Guimarães, E.C., Antunes, R.C., & Nascimento, M.D.M., 2016. Physiological parameters, hair coat morphological characteristics and temperature gradients in Holstein-Gyr crossbred cows. Bioscience, 32(2), 471–477.
Dado-Senn, B., Ouellet, V., Lantigua, V., Van Os, J., & Laporta, J., 2023. Methods for detecting heat stress in hutch-housed dairy calves in a continental climate. J. Dairy Sci., 106(2), 1039–1050. doi 10.3168/jds.2022-22237
Dahl, G.E., Tao, S., & Laporta, J., 2020. Heat stress impacts immune status in cows across the life cycle. Front. Vet. Sci., 7, 116. doi 10.3389/fvets.2020.00116
De Abreu, A.S., Fischer, V., Thaler, A., Stumpf, M.T., Petronilho, F., Florentino, D.S., Hlavac, N.R., Uczay, M., Paludo, E., Weiss, P.H.E., & Vogel, C.I.G., 2020. Access to shade reduces DNA damage of Holstein cows under mild heat stress. Anim. Prod. Sci., 60(12), 1539–1546. doi 10.1071/AN19075
Dikmen, S. & Hansen, P.J., 2009. Is the temperature-humidity index the best indicator of heat stress in lactating dairy cows in a subtropical environment? J. Dairy Sci., 92(1), 109–116. doi 10.3168/jds.2008-1370
Dikmen, S., Khan, F.A., Huson, H.J., Sonstegard, T.S., Moss, J.I., Dahl, G.E., & Hansen, P.J., 2014. The SLICK hair locus derived from Senepol cattle confers thermotolerance to intensively managed lactating Holstein cows. J. Dairy Sci., 97(9), 5508–5520. doi 10.3168/jds.2014-8087
Dragovich, D., 1979. Effect of high temperature-humidity conditions on milk production of dairy herds grazed on farms in a pasture-based feed system. Int. J. Biometeorol., 23, 15–20. doi 10.1007/BF01553373
Dunshea, F.R., Leury, B.J., Fahri, F., DiGiacomo, K., Hung, A., Chauhan, S., Clarke, I.J., Collier, R., Little, S., Baumgard, L., & Gaughan, J.B., 2013. Amelioration of thermal stress impacts in dairy cows. Anim. Prod. Sci., 53(9), 965–975. doi 10.1071/AN12384
El-Ramady, H.R., Alshaal, T.A., Amer, M., Domokos-Szabolcsy, É., Elhawat, N., Prokisch, J., & Fári, M., 2014. Soil quality and plant nutrition. Sustain. Agric. Rev., 345–447. doi 10.1007/978-3-319-06016-3_11
Fabris, T.F., Laporta, J., Skibiel, A.L., Corra, F.N., Senn, B.D., Wohlgemuth, S.E., & Dahl, G.E., 2019. Effect of heat stress during early, late, and entire dry period on dairy cattle. J. Dairy Sci., 102(6), 5647–5656. doi 10.3168/jds.2018-15721
FAO, 2023. Dairy Market Review – Emerging trends and outlook in 2023. Rome.
Galán, E., Llonch, P., Villagrá, A., Levit, H., Pinto, S., & Del Prado, A., 2018. A systematic review of non-productivity-related animal-based indicators of heat stress resilience in dairy cattle. PloS One, 13(11), e0206520. doi 10.1371/journal.pone.0206520
Gebremedhin, K.G. & Wu, B., 1998. Sensible and latent heat losses from wet-skin surface and fur layer. In: *2001 ASAE Annual Meeting* (p. 1). American Society of Agricultural and Biological Engineers.
Godde, C.M., Mason-D'Croz, D., Mayberry, D.E., Thornton, P.K., & Herrero, M., 2021. Impacts of climate change on the livestock food supply chain; a review of the evidence. Glob. Food Sec., 28, 100488. doi 10.1016/j.gfs.2020.100488
Goselink, R.M.A., Klop, G., Dijkstra, J., & Bannink, A., 2015. Phosphorus metabolism in dairy cattle: literature study on recent developments and gaps in knowledge. Wageningen UR Livest. Res., 910 (36).

Hansen, P.J., 2020. Prospects for gene introgression or gene editing as a strategy for reduction of the impact of heat stress on production and reproduction in cattle. Theriogenology, 154, 190–202. doi 10.1016/j.theriogenology.2020.05.010

Haskell, M.J., March, M.D., & Carter, L.S., 2023. Effects of warm climatic periods on dairy cow behaviour and welfare in a maritime European climate. In: Joint International Congress on Animal Science 2023: Co-organised by the EAAP, WAAP and Interbull.

Herbut, P., Angrecka, S., & Walczak, J., 2018. Environmental parameters to assessing of heat stress in dairy cattle—a review. Int. J. Biometeorol., 62, 2089–2097. doi 10.1007/s00484-018-1629-9

Herbut, P., Hoffmann, G., Angrecka, S., Godyń, D., Vieira, F.M.C., Adamczyk, K., & Kupczyński, R., 2021. The effects of heat stress on the behaviour of dairy cows–a review. Ann. Anim. Sci., 21(2), 385–402. doi 10.2478/aoas-2020-0116

Hernández-Castellano, L.E., Nally, J.E., Lindahl, J., Wanapat, M., Alhidary, I.A., Fangueiro, D., Grace, D., Ratto, M., Bambou, J.C., & de Almeida, A.M., 2019. Dairy science and health in the tropics: challenges and opportunities for the next decades. Trop. Anim. Health Pro., 51, 1009–1017. doi 10.1007/s11250-019-01866-6

Hill, D.L., & Wall, E., 2015. Dairy cattle in a temperate climate: the effects of weather on milk yield and composition depend on management. Animal, 9(1), 138–149. doi 10.1017/S1751731114002456

Hill, S.R., Knowlton, K.F., Kebreab, E., France, J., & Hanigan, M.D., 2008. A model of phosphorus digestion and metabolism in the lactating dairy cow. J. Dairy Sci., 91(5), 2021–2032. doi 10.3168/jds.2007-0668

Hoffmann, G., Herbut, P., Pinto, S., Heinicke, J., Kuhla, B., & Amon, T., 2020. Animal-related, non-invasive indicators for determining heat stress in dairy cows. Biosyst. Eng., 199, 83–96. doi 10.1016/j.biosystemseng.2019.10.017

Hut, R.A. & Beersma, D.G., 2011. Evolution of time-keeping mechanisms: early emergence and adaptation to photoperiod. Philos. Trans. R. Soc. Lond., B, Biol. Sci., 366(1574), 2141–2154. doi 10.1098/rstb.2010.0409

Islam, M.A., Lomax, S., Doughty, A., Islam, M.R., Jay, O., Thomson, P., & Clark, C., 2021. Automated monitoring of cattle heat stress and its mitigation. Front. Anim. Sci., 2, 60. doi 10.3389/fanim.2021.737213

Jeelani, R., Konwar, D., Khan, A., Kumar, D., Chakraborty, D., & Brahma, B., 2019. Reassessment of temperature-humidity index for measuring heat stress in crossbred dairy cattle of a sub-tropical region. J. Therm. Biol., 82, 99–106. doi 10.1016/j.jtherbio.2019.03.017

Ji, B., Banhazi, T., Perano, K., Ghahramani, A., Bowtell, L., Wang, C., & Li, B., 2020. A review of measuring, assessing and mitigating heat stress in dairy cattle. Biosyst. Eng., 199, 4–26. doi 10.1016/j.biosystemseng.2020.07.009

Kadzere, C.T., Murphy, M.R., Silanikove, N., & Maltz, E., 2002. Heat stress in lactating dairy cows: a review. Livest. Prod. Sci., 77(1), 59–91. doi 10.1016/S0301-6226(01)00330-X

Keanthao, P., Goselink, R.M.A., Dijkstra, J., Bannink, A., & Schonewille, J.T., 2021. Effects of dietary phosphorus concentration during the transition period on plasma calcium concentrations, feed intake, and milk production in dairy cows. J. Dairy Sci., 104(11), 11646–11659. doi 10.3168/jds.2021-20488

Kovács, L., Kézér, F.L., Ruff, F., & Szenci, O., 2016. Cardiac autonomic activity has a circadian rhythm in summer but not in winter in non-lactating pregnant dairy cows. Physiol. Behav., 155, 56–65. doi 10.1016/j.physbeh.2015.11.031

Kusangaya, S., Warburton, M.L., Van Garderen, E.A., & Jewitt, G.P., 2014. Impacts of climate change on water resources in southern Africa: A review. Phys. Chem. Earth, 67, 47–54. doi 10.1016/j.pce.2013.09.014

Lees, A.M., Sejian, V., Wallage, A.L., Steel, C.C., Mader, T.L., Lees, J.C., & Gaughan, J.B., 2019. The impact of heat load on cattle. Animals, 9(6), 322. doi 10.3390/ani9060322

Liang, D., Wood, C.L., McQuerry, K.J., Ray, D.L., Clark, J.D., & Bewley, J.M., 2013. Influence of breed, milk production, season, and ambient temperature on dairy cow reticulorumen temperature. J. Dairy Sci., 96(8), 5072–5081. doi 10.3168/jds.2012-6537

Macmillan, K., Espinoza, O.S., & Oba, M., 2018. Case study: The effects of photoperiod on feeding behavior of lactating dairy cows in tie-stalls. Prof. Anim. Sci., 34(1), 103–107. doi 10.15232/pas.2017-01674

Magnone, D., Niasar, V.J., Bouwman, A.F., Beusen, A.H., van der Zee, S.E., & Sattari, S.Z., 2022. The impact of phosphorus on projected Sub-Saharan Africa food security futures. Nat. Commun., 13(1), 6471. doi 10.1038/s41467-022-33900-x

Martí-Herrero, J., Alvarez, R., Cespedes, R., Rojas, M.R., Conde, V., Aliaga, L., Balboa, M., & Danov, S., 2015. Cow, sheep and llama manure at psychrophilic anaerobic co-digestion with low cost tubular digesters in cold climate and high altitude. Bioresour. Technol., 181, 238–246. doi 10.1016/j.biortech.2015.01.063

Moore, S.S., Costa, A., Penasa, M., & De Marchi, M., 2024. Effects of different temperature-humidity indexes on milk traits of Holstein cows: A 10-year retrospective study. J. Dairy Sci., 107(6), 3669–3687. doi 10.3168/jds.2023-23723

Muller, C.J.C., 2017. Chapter 1: General introduction to dairy farming. In: The Dairy Farming Handbook. Elsenburg: Western Cape Department of Agriculture.

Müschner-Siemens, T., Hoffmann, G., Ammon, C., & Amon, T., 2020. Daily rumination time of lactating dairy cows under heat stress conditions. J. Therm. Biol., 88, 102484. doi 10.1016/j.jtherbio.2019.102484

Oettli, P. & Camberlin, P., 2005. Influence of topography on monthly rainfall distribution over East Africa. Clim. Res., 28(3), 199–212. doi 10.3354/cr028199

Oliveira, S.E.O., de Melo Costa, C.C., Chiquitelli Neto, M., Dalla Costa, F.A., & Maia, A.S.C., 2019. Effects of shade location and protection from direct solar radiation on the behavior of Holstein cows. Int. J. Biometeorol., 63, 1465–1474. doi 10.1007/s00484-019-01747-5

Ouellet, V., Negrao, J., Skibiel, A.L., Lantigua, V.A., Fabris, T.F., Marrero, M.G., Dado-Senn, B., Laporta, J., & Dahl, G.E., 2021. Endocrine signals altered by heat stress impact dairy cow mammary cellular processes at different stages of the dry period. Animals, 11(2), 563. doi 10.3390/ani11020563

Pal, P., Aggarwal, A., & Deb, R., 2022. Effects of photoperiod on reproduction of cattle: a review. Biol. Rhythm Res., 53(12), 1950–1960. doi 10.1080/09291016.2022.2102707

Perano, K.M., Usack, J.G., Angenent, L.T., & Gebremedhin, K.G., 2015. Production and physiological responses of heat-stressed lactating dairy cattle to conductive cooling. J. Dairy Sci., 98(8), 5252–5261. doi 10.3168/jds.2014-8784

Pinto, S., Hoffmann, G., Ammon, C., & Amon, T., 2020. Critical THI thresholds based on the physiological parameters of lactating dairy cows. J. Therm. Biol., 88, 102523. doi 10.1016/j.jtherbio.2020.102523

Polsky, L. & von Keyserlingk, M.A., 2017. Invited review: Effects of heat stress on dairy cattle welfare. J. Dairy Sci., 100(11), 8645–8657. doi 10.3168/jds.2017-12651

Pontiggia, A., Münger, A., Ammer, S., Philipona, C., Bruckmaier, R.M., Keil, N.M., & Dohme-Meier, F., 2023. Short-term physiological responses to moderate heat stress in grazing dairy cows in temperate climate. Animal, 17(3), 100718. doi 10.1016/j.animal.2023.100718

Pozzebon, M., Guldbrandtsen, B., & Sandøe, P., 2024. Gene editing cattle for enhancing heat tolerance: a welfare review of the "PRLR-SLICK cattle" case. Nanoethics, 18(2), 6. doi 10.1007/s11569-024-00455-8

Roffe, S.J., Fitchett, J.M., & Curtis, C.J., 2021. Quantifying rainfall seasonality across South Africa on the basis of the relationship between rainfall and temperature. Clim. Dyn., 56(7), 2431–2450. doi 10.1007/s00382-020-05597-5

Saizi, T., Mpayipheli, M., & Idowu, P. A., 2020. Heat tolerance level in dairy herds: a review on coping strategies to heat stress and ways of measuring heat tolerance. J. Anim. Behav. Biometeorol., 7(2), 39–51. doi 10.31893/2318-1265jabb.v7n2p39-51

Scharf, B., Carroll, J.A., Riley, D.G., Chase Jr, C.C., Coleman, S.W., Keisler, D.H., Weaber, R.L. & Spiers, D.E., 2010. Evaluation of physiological and blood serum differences in heat-tolerant (Romosinuano) and heat-susceptible (Angus) *Bos taurus* cattle during controlled heat challenge. J. Anim. Sci., 88(7), 2321–2336. doi 10.2527/jas.2009-2551

Scheffler, T.L., 2022. Connecting heat tolerance and tenderness in *Bos indicus* influenced cattle. Animals, 12(3), 220. doi 10.3390/ani12030220

Scholes, R. & Engelbrecht, F., 2021. Climate impacts in southern Africa during the 21st Century. Report for Earthjustice and the Centre for Environmental Rights. Global Change Institute, WITS.

Schüller, L.K., Burfeind, O., & Heuwieser, W., 2016. Effect of short-and long-term heat stress on the conception risk of dairy cows under natural service and artificial insemination breeding programs. J. Dairy Sci., 99(4), 2996–3002. doi 10.3168/jds.2015-10080

Schütz, K.E., Clark, K.V., Cox, N.R., Matthews, L.R., & Tucker, C.B., 2010. Responses to short-term exposure to simulated rain and wind by dairy cattle: time budgets, shelter use, body temperature and feed intake. Anim. Welf., 19(4), 375–383. doi 10.1017/S0962728600001858

Shehab-El-Deen, M.A.M., Fadel, M.S., Van Soom, A., Saleh, S.Y., Maes, D., & Leroy, J L., 2010. Circadian rhythm of metabolic changes associated with summer heat stress in high-producing dairy cattle. Trop. Anim. Health Pro., 42, 1119–1125. doi 10.1007/s11250-010-9534-1

Sesay, A.R., 2023. Effect of heat stress on dairy cow production, reproduction, health, and potential mitigation strategies. J. Appl. Adv. Res., 8, 13–25. doi 10.21839/jaar.2023.v8.8371

Shephard, R.W. & Maloney, S.K., 2023. A review of thermal stress in cattle. Aust. Vet. J., 101(11), 417–429. doi 10.1111/avj.13275

Smith, D.L., Smith, T., Rude, B.J., & Ward, S.H., 2013. Comparison of the effects of heat stress on milk and component yields and somatic cell score in Holstein and Jersey cows. J. Dairy Sci., 96(5), 3028–3033. doi 10.3168/jds.2012-5737

Suarez-Trujillo, A., Wernert, G., Sun, H., Steckler, T.S., Huff, K., Cummings, S., Franco, J., Klopp, R.N., Townsend, J.R., Grott, M., & Casey, T.M., 2020. Exposure to chronic light–dark phase shifts during the prepartum nonlactating period attenuates circadian rhythms, decreases blood glucose, and increases milk yield in the subsequent lactation. J. Dairy Sci., 103(3), 2784–2799. doi 10.3168/jds.2019-16980

Suthar, V.S., Burfeind, O., Patel, J.S., Dhami, A.J., & Heuwieser, W., 2011. Body temperature around induced estrus in dairy cows. J. Dairy Sci., 94(5), 2368–2373. doi 10.3168/jds.2010-3858

Tang, C., Liang, Y., Guo, J., Wang, M., Li, M., Zhang, H., Arbab, A.A.I., Karrow, N.A., Yang, Z., & Mao, Y., 2022. Effects of seasonal heat stress during late gestation on growth performance, metabolic and immuno-endocrine parameters of calves. Animals, 12(6), 716. doi 10.3390/ani12060716

Tucker, C.B., Rogers, A.R., & Schütz, K.E., 2008. Effect of solar radiation on dairy cattle behaviour, use of shade and body temperature in a pasture-based system. Appl. Anim. Behav., 109(2–4), 141–154. doi 10.1016/j.applanim.2007.03.015

Velasco, J.M., Reid, E.D., Fried, K.K., Gressley, T.F., Wallace, R.L., & Dahl, G.E., 2008. Short-day photoperiod increases milk yield in cows with a reduced dry period length. J. Dairy Sci., 91(9), 3467–3473. doi 10.3168/jds.2008-1028

Veissier, I., Van Laer, E., Palme, R., Moons, C.P., Ampe, B., Sonck, B., Andanson, S., & Tuyttens, F.A., 2018. Heat stress in cows at pasture and benefit of shade in a temperate climate region. Int. J. Biometeorol., 62, 585–595. doi 10.1007/s00484-017-1468-0

Walker, R.S., Martin, R.M., Gentry, G.T., & Gentry, L.R., 2015. Impact of cow size on dry matter intake, residual feed intake, metabolic response, and cow performance. J. Anim. Sci., 93(2), 672–684. doi 10.2527/jas.2014-7702

Wang, X., Bjerg, B.S., Choi, C.Y., Zong, C., & Zhang, G., 2018. A review and quantitative assessment of cattle-related thermal indices. J. Therm. Biol., 77, 24–37. doi 10.1016/j.jtherbio.2018.08.005

Williams, R., Scholtz, M.M., & Neser, F.W.C., 2016. Geographical influence of heat stress on milk production of Holstein dairy cattle on pasture in South Africa under current and future climatic conditions. S. Afr. J. Anim. Sci., 46(4), 441–447. doi 10.4314/sajas.v46i4.12

Yan, G., Liu, K., Hao, Z., Shi, Z., & Li, H., 2021. The effects of cow-related factors on rectal temperature, respiration rate, and temperature-humidity index thresholds for lactating cows exposed to heat stress. J. Therm. Biol., 100, 103041. doi 10.1016/j.jtherbio.2021.103041

Zeng, J., Cai, J., Wang, D., Liu, H., Sun, H., & Liu, J., 2023. Heat stress affects dairy cow health status through blood oxygen availability. J. Anim. Sci. Biotechnol., 14(1), 112. doi 10.1186/s40104-023-00915-3

Zhou, M., Huynh, T.T.T., Koerkamp, P.G., Van Dixhoorn, I.D.E., Amon, T., & Aarnink, A.J.A., 2022. Effects of increasing air temperature on skin and respiration heat loss from dairy cows at different relative humidity and air velocity levels. J. Dairy Sci., 105(8), 7061–7078. doi 10.3168/jds.2021-21683