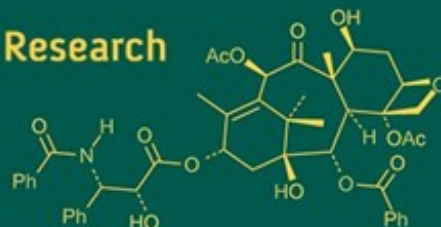
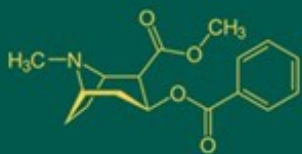


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693

ISSN Online: 2617-4707

NAAS Rating (2026): 5.29

Indexing: Embase

IJABR 2026; 10(10): 357-361

www.biochemjournal.com

Received: 05-08-2026

Accepted: 26-09-2026

Published: 09-10-2026

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Heat stress management in dairy cattle: A review

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i10e.10397>

ABSTRACT

Heat stress is one of the major environmental challenges limiting dairy cattle production in tropical and subtropical regions. Heat stress occurs when the total heat load imposed on an animal exceeds its capacity to dissipate body heat and maintain normal physiological function. Dairy cattle, particularly high-producing animals, are highly susceptible because of their high metabolic heat production. Heat stress results in increased respiration rate, rectal temperature, water intake and behavioural changes, accompanied by reductions in dry matter intake, milk yield, reproductive efficiency, immune function and animal welfare. The temperature-humidity index (THI) is widely used to monitor environmental heat load; however, breed, production level, climatic conditions and physiological measurements should also be considered when defining heat-stress thresholds. In India, crossbred and high-producing dairy animals may be particularly vulnerable during hot and humid seasons, while indigenous cattle generally possess greater thermotolerance. Management requires an integrated approach involving shade, suitable housing, ventilation, sprinklers, fans, adequate water availability, nutritional adjustment, reproductive management and selection for heat tolerance. Nutritional interventions including ration balancing, dietary fat, antioxidants, minerals, vitamins, yeast and betaine may provide supportive benefits, although responses vary with farm and animal conditions. Genetic selection for thermotolerance and precision monitoring using environmental and animal-based sensors represent promising long-term approaches. This review summarizes the mechanisms, assessment, effects and management of heat stress in dairy cattle, with particular emphasis on practical strategies applicable to Indian dairy production systems.

Keywords: Dairy cattle, heat stress, temperature-humidity index, cooling, nutrition, thermotolerance

1. Introduction

Dairy cattle require an appropriate thermal environment to maintain homeostasis, health and productive performance. Heat stress develops when environmental and internally generated heat exceed the animal's capacity for heat dissipation. Ambient temperature, relative humidity, solar radiation, air movement and metabolic heat associated with digestion and milk synthesis contribute to the total heat load. High-producing cows are particularly susceptible because increased milk production is associated with increased feed intake and metabolic heat production (Armstrong, 1994; Bouraoui *et al.*, 2002; West, 2003; St-Pierre *et al.*, 2003; Bernabucci *et al.*, 2010) [1, 2, 3, 4, 5]. Heat stress is increasingly important in dairy systems worldwide because of rising environmental temperatures and more frequent heat waves. It can reduce feed intake and milk production, impair reproduction, compromise immune function and negatively affect animal welfare (Baumgard *et al.*, 2013; Polsky *et al.*, 2017; Becker *et al.*, 2020; Jeelani *et al.*, 2019; Gujar *et al.*, 2023) [6, 7, 8, 9, 10]. India has a large and diverse dairy population comprising indigenous cattle, crossbred cattle and buffaloes, and dairy animals experience substantial seasonal heat loads across many regions. Indian evidence indicates that heat-stress thresholds vary with breed, production level and climatic conditions. For example, research on crossbred cattle in a subtropical region reported major physiological changes beginning around THI 74 and more pronounced disturbance at approximately THI 80 (Gayari *et al.*, 2024) [11]. Recent work has also emphasized genetic variation in heat tolerance and the potential use of climatic and animal records for identifying thermotolerant cattle (Chang-Fung-Martel *et al.*, 2021; Liu *et al.*, 2019) [12, 13]. Effective management therefore requires environmental monitoring, early identification of stressed animals, cooling, nutritional and reproductive management, and long-term genetic adaptation. This review summarizes current knowledge on heat stress in dairy cattle and evaluates practical approaches, with emphasis on Indian production systems.

2. Materials and Methods

This article was developed as a narrative review of peer-reviewed literature on heat stress in dairy cattle. Relevant literature was identified from scientific journal databases and publisher platforms, including PubMed, ScienceDirect, Springer, journal websites and Indian agricultural and veterinary research repository

ries. Search terms included combinations of “heat stress,” “heat stress in dairy cattle,” “temperature-humidity index,” “dairy cow cooling,” “heat stress nutrition,” “heat stress reproduction,” “heat stress immunity,” “thermotolerance,” “Indian dairy cattle,” “fans,” “sprinklers,” “shade,” and “genetic selection.” Priority was given to experimental studies, systematic reviews, *meta*-analyses and major review articles addressing physiological responses, production, reproduction, nutrition, welfare, environmental modification and genetic adaptation. As this was a narrative review, no quantitative *meta*-analysis or systematic risk-of-bias assessment was undertaken.

3. Results

3.1 Understanding heat stress in dairy cattle

Heat stress is a physiological condition in which cattle cannot adequately dissipate accumulated heat generated internally and received from the environment. External heat originates from solar radiation, air temperature and humidity, whereas internal heat is generated mainly through metabolism, physical activity and milk synthesis (St-Pierre *et al.*, 2003; Bernabucci *et al.*, 2010) [4, 5]. Cattle respond through increased respiration, sweating, peripheral vasodilation, reduced activity, increased water consumption and reduced feed intake. These responses help maintain thermal balance but redirect energy and nutrients away from production and reproduction. High-producing cows are generally more vulnerable because greater metabolic activity generates more heat (Bernabucci *et al.*, 2010) [5].

3.2 Assessment of heat stress

The temperature-humidity index is one of the most commonly used environmental indicators for evaluating heat stress because it combines ambient temperature and relative humidity (Armstrong, 1994; Bouraoui *et al.*, 2002; Tao *et al.*, 2018) [1, 2, 14]. A commonly used equation is:

$$\text{THI} = (1.8 \times T + 32) - [(0.55 - 0.0055 \times \text{RH}) \times (1.8 \times T - 26.8)]$$

where T is ambient temperature in °C and RH is relative humidity in %. Traditionally, values below approximately 68–72 have been considered relatively safe, but thresholds vary according to breed, production level, climate and measurement method (Gayari *et al.*, 2024; Tao *et al.*, 2018; De Rensis *et al.*, 2003; Roth, 2017) [11, 14, 15, 16]. Animal-based indicators should therefore be used together with THI. Important indicators include respiration rate, rectal or body temperature, panting score, water and feed intake, standing behaviour, lying time, rumination and milk production (Rhoads, 2023) [17].

3.3 Physiological and behavioural responses

Heat-stressed cattle show increased respiration, sweating, peripheral blood flow and water intake, together with reduced feed intake, activity, rumination and lying time and increased standing behaviour. These responses initially support thermal balance, but prolonged exposure results in physiological disturbance and reduced productivity (Bernabucci *et al.*, 2010; Becker *et al.*, 2020; Gujar *et al.*, 2023) [5, 8, 10]. Excessive standing may facilitate heat dissipation but can reduce resting time and compromise welfare.

3.4 Effects on feed intake and metabolism

Reduction in feed intake is an early production-related response to heat stress and decreases metabolic heat production. A global *meta*-analysis reported a strong negative relationship between THI and dry matter intake (Roth, 2017) [16]. However, reduced intake does not fully explain production losses. Heat stress can directly alter glucose metabolism, insulin responses, lipid metabolism and tissue nutrient utilization (Baumgard *et al.*, 2013; Polsky *et al.*, 2017) [6, 7]. Nutritional management should therefore maintain nutrient density, diet quality, rumen stability and water availability while avoiding excessive metabolic heat production.

3.5 Effects on milk production and milk composition

Milk production is strongly affected by heat stress through reduced feed intake, altered metabolism, endocrine changes and direct effects on mammary tissue (West, 2003; Baumgard *et al.*, 2013; Fabris *et al.*, 2019) [3, 6, 18]. Heat stress may alter milk fat, protein, lactose, somatic cell count and energy-corrected milk. The magnitude of loss depends on breed, stage of lactation, production level, and severity and duration of exposure. Research in Jersey crossbred cattle in India has reported significant changes in milk production and composition as THI increased (Bagath *et al.*, 2019) [19].

3.6 Effects on reproductive performance

Heat stress reduces estrus expression, increases silent estrus, lowers conception rate, alters follicular development, reduces oocyte quality, increases early embryonic loss and days open, and lowers pregnancy rate (Dahl *et al.*, 2016; Liu *et al.*, 2024; Ben-Ghedalia *et al.*, 2023; Schwartz *et al.*, 2009) [20, 21, 22, 23]. Oocytes and embryos are sensitive to elevated temperature, and reproductive consequences may persist after environmental conditions improve because follicles developing during heat stress may later produce compromised oocytes. Cooling before and after breeding, breeding during cooler periods where practical, improved estrus detection, suitable reproductive protocols, adequate nutrition and body-condition maintenance can reduce risk.

3.7 Effects on immune function and health

Heat stress can compromise immune function and increase disease susceptibility. Stress-related endocrine responses can influence cytokine production and immune-cell activity (Kim *et al.*, 2026) [24]. Potential consequences include increased susceptibility to mastitis, metabolic disorders, reproductive tract problems and other infectious diseases, as well as reduced vaccine responses. Late-gestation heat stress may also affect calf immune development and passive immune transfer (Shankpal *et al.*, 2018) [25].

3.8 Heat stress and animal welfare

Heat stress is an animal-welfare concern in addition to being a production problem. Panting, excessive respiration, salivation, shade-seeking, increased standing, reduced feeding and rumination, crowding around water, reduced lying behaviour and elevated body temperature are important signs of heat discomfort (Jeelani *et al.*, 2019) [9]. Heat-abatement programmes should therefore form part of good dairy welfare management.

3.9 Environmental management

Environmental modification is the first line of defence. Shade reduces solar radiation and can be provided by permanent roofs, shade cloth, trees and covered resting areas. Good ventilation increases convective heat loss and depends on adequate roof height, suitable building orientation, air inlets and outlets, avoidance of overcrowding and fans in high-risk areas. Sprinklers or soakers wet the hair coat and permit evaporative cooling; fans should operate simultaneously to improve evaporation (Malik *et al.*, 2024; Bohlouli *et al.*, 2013) [26, 27]. Additional early nighttime cooling can be beneficial when high night temperatures persist (Li *et al.*, 2020) [28].

3.10 Water management

Heat-stressed cows substantially increase water consumption because water is required for sweating, respiration, thermoregulation, milk production and fluid balance. Clean, fresh water should be continuously accessible, particularly near feeding areas, with adequate flow rate. Troughs should be cleaned regularly and positioned so dominant animals cannot restrict access by subordinate animals.

3.11 Nutritional management

Because feed intake often decreases during the hottest hours, a greater proportion of feed may be offered during cooler periods. Diets should maintain adequate effective fibre, fermentable carbohydrate, protein, minerals, appropriate dietary fat and buffers where required. Carefully formulated fat supplementation may help maintain energy

intake because fat has a lower heat increment than carbohydrate and protein fermentation, although excessive fat can impair intake and rumen fermentation. Heat stress may also disturb electrolyte and oxidative balance; sodium, potassium, magnesium, zinc, selenium, vitamin E and vitamin C may be considered within recommended nutritional limits. Yeast and betaine have been investigated as supportive strategies, with responses varying among studies (Ravagnolo *et al.*, 2000; Hansen, 2004; Collier *et al.*, 2017; Hammami *et al.*, 2013) [29, 30, 31, 32].

3.12 Genetic approaches

Long-term adaptation requires consideration of genetic thermotolerance. Indigenous cattle possess characteristics that can contribute to adaptation to hot climates, including sweating ability, skin characteristics, lower metabolic heat production and behavioural adaptation. Genetic selection can incorporate physiological traits, milk-yield response to THI and genomic markers (Chang-Fung-Martel *et al.*, 2021; Liu *et al.*, 2019; Allen *et al.*, 2015) [12, 13, 33]. Genotype × environment interaction is particularly relevant in India because cattle are maintained under diverse climatic conditions.

3.13 Precision livestock farming

Digital technologies can improve early detection through automated temperature sensors, respiration monitoring, activity sensors, rumination collars, infrared thermography, vaginal temperature sensors, automated THI monitoring, remote weather stations and artificial-intelligence-based prediction systems. Combining environmental data with animal-level information may improve heat-stress detection compared with THI alone (Rhoads, 2023; De Rensis *et al.*, 2015) [17, 34]. Low-cost sensors and mobile warning systems could be particularly useful for Indian dairy farms.

3.14 Economic considerations

Heat stress causes economic losses through reduced milk yield and quality, lower conception rates, increased days open, increased disease incidence and culling, higher veterinary, water and electricity costs, and reduced lifetime productivity (Turk *et al.*, 2015) [35]. The economic value of cooling depends on milk price, production level, local climate, water availability, electricity and equipment costs. For smallholder farms, shade, ventilation, adequate water, tree planting and modification of feeding time may be more feasible than expensive automated systems.

3.15 Challenges in India

Implementation is constrained by small herd size, limited financial resources, inadequate housing, limited water, high electricity costs, poor ventilation, lack of awareness, limited access to cooling equipment, regional climatic variation, breed differences, lack of farm-level THI monitoring and inadequate technical support. Recommendations developed in intensive dairy systems in temperate countries cannot always be transferred directly to Indian smallholder systems. Locally validated thresholds and management packages are needed for different breeds, production systems and agro-climatic regions.

3.16 Research gaps and future directions

Priority areas include breed-specific heat-stress thresholds; low-cost cooling systems that minimize water and electricity use; heat-resilient genetic selection; low-cost precision monitoring; evaluation of nutritional interventions under Indian conditions; improved management of dry cows and calves; and economic evaluation of combined shade, ventilation, sprinkling, nutrition and genetic interventions.

Tables

Table 1. Practical heat-stress management programme

Management area	Recommended measures
Environmental monitoring	Record temperature, relative humidity and THI
Shade	Provide permanent or natural shade
Housing	Improve ventilation and roof height
Air movement	Install fans in critical areas
Evaporative cooling	Use sprinklers/soakers with fans
Water	Provide continuous clean drinking water
Feeding	Increase feeding during cooler hours
Diet	Maintain nutrient density and fibre balance
Minerals	Ensure adequate electrolytes and minerals
Antioxidants	Use appropriate antioxidants such as vitamin E and selenium
Feed additives	Consider validated yeast, betaine and other additives
Reproduction	Provide cooling before and after breeding
Dry cows	Include dry and transition cows in cooling plans
Calves	Provide shade, water and ventilation
Genetics	Select animals with better thermotolerance
Monitoring	Use animal-based indicators along with THI

Table 2. Major approaches for heat-stress mitigation

Strategy	Primary mechanism	Major advantage	Important limitation
Shade	Reduces solar radiation	Low-cost and simple	Insufficient alone under severe heat
Fans	Increases air movement	Improves evaporative cooling	Requires electricity
Sprinklers	Wetting and evaporation	Strong cooling effect	Requires adequate water
Night cooling	Removes accumulated heat	Useful in persistent summer heat	Requires extended operation
Water availability	Maintains hydration	Essential and inexpensive	Poor trough access reduces benefit
Ration adjustment	Maintains nutrient supply	Supports production	Requires proper formulation
Antioxidants	Reduces oxidative stress	Supports cellular defence	Response varies

(continued on next page)

Strategy	Primary mechanism	Major advantage	Important limitation
Yeast	Supports rumen function	Potential nutritional benefit	Results are variable
Betaine	Osmoregulation and methyl donation	Useful nutritional tool	Cost and response vary
Genetic selection	Improves long-term resilience	Sustainable approach	Requires long-term breeding programme
Sensors	Early detection	Precision management	Initial investment and technical support

4. Discussion

The reviewed evidence indicates that heat stress should be managed as a multifactorial problem rather than by a single intervention. THI provides a useful basis for environmental monitoring, but individual response varies with breed, production level, physiological state and climate. Consequently, combining THI with respiration rate, body temperature, behaviour, feed intake and milk production provides a more practical basis for decision-making (Gayari *et al.*, 2024; Roth, 2017; Rhoads, 2023) [11, 16, 17]. Environmental interventions remain the most immediate and broadly applicable measures. Shade reduces solar radiation, while ventilation, fans and sprinklers increase sensible and evaporative heat loss. Water availability is fundamental and should be protected from competition among animals. Cooling may need to continue into the night where heat accumulated during the day is not dissipated. Nutritional interventions can help compensate for reduced intake and altered metabolism, but they should complement rather than replace environmental cooling. The variable responses to yeast, betaine and antioxidant supplementation indicate that additive selection should be based on diet, animal status, local conditions and evidence from relevant production systems (Ravagnolo *et al.*, 2000; Hansen, 2004; Collier *et al.*, 2017; Hammami *et al.*, 2013) [29, 30, 31, 32]. Reproductive management deserves particular attention because heat stress affects estrus expression, oocyte quality, embryo survival and conception, with effects potentially extending beyond the hottest period (Dahl *et al.*, 2016; Liu *et al.*, 2024; Ben-Ghedalia *et al.*, 2023; Schwartz *et al.*, 2009) [20, 21, 22, 23]. Similarly, dry cows and calves should be included in heat-abatement programmes because late-gestation heat stress can affect subsequent calf performance and immunity (Shankhpal *et al.*, 2018) [25]. For India, a major priority is adaptation of recommendations to smallholder systems and regional climates. Low-cost shade, improved ventilation, reliable water access and feeding during cooler hours are likely to provide the most accessible first-line measures. Long-term progress can be supported by selection for thermotolerance and precision monitoring, particularly when technologies become affordable and easy to operate. The most sustainable approach is therefore an integrated programme linking environmental monitoring, early detection, cooling, water, nutrition, reproductive management, health monitoring and genetic selection.

5. Conclusion

Heat stress is a major constraint to sustainable dairy production in tropical and subtropical environments. Its effects include reduced feed intake, altered metabolism, lower milk production, impaired reproduction, compromised immunity and reduced animal welfare. THI remains a useful environmental indicator, but it should be combined with animal-based measures because heat tolerance varies among breeds, production systems and climatic regions. For Indian dairy production, practical management should begin with adequate shade, ventilation, clean water and appropriate housing. Fans and sprinklers can provide additional cooling where resources permit. Nutritional strategies, including appropriate ration formulation, minerals, antioxidants, yeast and betaine, may support animals during heat load but should complement environmental cooling. Long-term resilience requires selection for thermotolerance, climate-adapted animals, improved housing and precision monitoring. Integrating environmental,

nutritional, genetic and management approaches provides a sustainable pathway for maintaining dairy productivity, health and welfare under increasing heat stress.

6. Acknowledgments

Conflict of interest: The authors declare that they have no conflict of interest.

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How to cite this article: Sathe PM, Tirpude SV, Sakhare AC, Rathore VS. Heat stress management in dairy cattle: A review. *International Journal of Advanced Biochemistry Research*. 2026;10(10):357-361. doi: <https://www.doi.org/10.33545/26174693.2026.v10.i10e.10397>