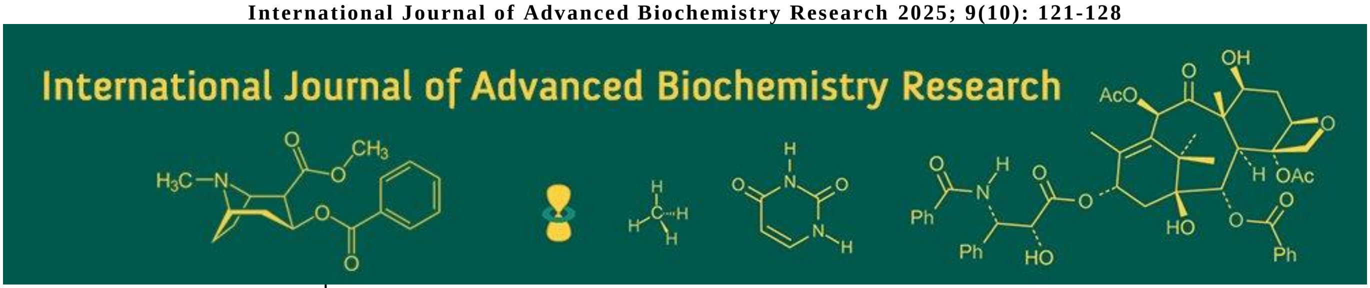
International Journal of Advanced Biochemistry Research 2025; 9(10): 121-128



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2025): 5.29
IJABR 2025; 9(10): 121-128
www.biochemjournal.com
Received: 25-08-2025
Accepted: 27-09-2025

SB Mohad
Department of Animal Husbandry and Dairy Science, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

AT Lokhande
Department of Animal Husbandry and Dairy Science, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

DK Kamble
Department of Animal Husbandry and Dairy Science, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

SH Mane
Department of Animal Husbandry and Dairy Science, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

PN Puram
Department of Animal Husbandry and Dairy Science, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

JB Shedge
Department of Animal Husbandry and Dairy Science, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

SL Shingade
Department of Animal Husbandry and Dairy Science, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

Corresponding Author:
SB Mohad
Department of Animal Husbandry and Dairy Science, Mahatma Phule Krishi Vidyapeeth, Rahuri, Maharashtra, India

Effect of global climate change on livestock sector and its ameliorative measures: A review

SB Mohad, AT Lokhande, DK Kamble, SH Mane, PN Puram, JB Shedge and SL Shingade

DOI: https://www.doi.org/10.33545/26174693.2025.v9.i10b.5926

Abstract
Global climate change, characterized by long-term shifts in temperature, rainfall, and extreme weather events, poses significant challenges to livestock production, a critical sector for food security, livelihoods, and the economy. Livestock systems are particularly vulnerable to heat stress, water scarcity, altered feed availability, and emerging diseases, which compromise animal health, welfare, productivity, and reproductive performance. Physiological responses to heat stress include elevated respiration rate, rectal temperature, sweating, and altered blood flow, while metabolic changes involve reduced feed intake, shifts in nutrient utilization, and electrolyte imbalances. Hormonal dysregulation, behavioral modifications, impaired rumen function, and increased susceptibility to hyperthermia, dehydration, and immune suppression further exacerbate the impacts on growth, milk yield, meat quality, and fertility. Mitigation strategies encompassing environmental management, nutritional supplementation, genetic selection for heat tolerance, and automated real-time monitoring offer effective avenues to enhance resilience. Integrating these approaches is essential to sustain livestock productivity, ensure animal welfare, and support global food security under intensifying climate change.

Keywords: Global climate change, livestock sector, heat stress, animal productivity

Introduction
Climate change, defined as long-term alterations in average weather patterns caused by natural and human-induced factors, is reshaping ecosystems worldwide (UNFCCC, 1992; Visschers, 2018) [94, 96]. Unlike short-term weather variations, climate change involves persistent shifts in temperature, rainfall, and extreme events (Stephenson *et al*., 2008; IPCC, 2021) [90, 44]. Livestock production is particularly vulnerable, as it depends on stable water, feed, and disease control, and climate extremes such as droughts, floods, and heatwaves disproportionately affect livestock-dependent regions, especially in developing countries (FAO, 2018; Eckstein *et al*., 2021) [25, 24]. Livestock also contributes approximately 14.5% of global anthropogenic greenhouse gas emissions, creating a feedback loop that exacerbates global warming and threatens animal health, productivity, and sustainability (Gerber *et al*., 2013; IPCC, 2021) [33, 44].

Heat stress is a primary concern for livestock under climate change, causing physiological, metabolic, and behavioral disruptions. Elevated temperatures overwhelm thermoregulation, resulting in oxidative stress, reduced feed intake, altered metabolism, and intestinal barrier dysfunction, which collectively impair growth, reproduction, milk yield, and meat quality (Getachew, 2016; Tharinda *et al*., 2024) [34, 92]. Traditional monitoring methods, such as visual observation or weather-based indices, are limited due to farm scale, individual variability, and microclimatic conditions, highlighting the need for real-time, autonomous monitoring systems to detect and manage heat stress effectively (Islam *et al.*, 2021) [46].

Nutritional and management strategies are essential to mitigate the impacts of heat stress. Heat stress increases reactive oxygen species (ROS), which damage cell membranes and polyunsaturated fatty acids, but enzymatic antioxidants (superoxide dismutase, catalase, glutathione peroxidase) and non-enzymatic antioxidants (vitamins A, C, E, albumin, glutathione), along with minerals like zinc and chromium, can help counteract oxidative damage and support productivity (Anamika *et al*., 2024) [8].

Integrated approaches combining genetic selection for heat tolerance, dietary interventions, environmental management (shade, cooling systems), and automated monitoring are critical to sustain livestock health, productivity, and food security in a warming climate.

Impact of global climate change on Livestock

1. Physiological Responses

A. Impact on Respiration Rate

Heat stress in cattle is characterized by a sharp rise in respiration rate (RR) as a primary thermoregulatory response, with significant increases observed at temperatures above 25 °C (Gaughan *et al.*, 2012) [31]. Elevated RR and heart rate support evaporative cooling but may alter pulmonary ventilation and blood acid-base balance, leading to respiratory alkalosis (Polsky & von Keyserlingk, 2017) [68]. Breed differences are evident, as *Bos indicus* cattle generally maintain lower RR under heat stress compared to *Bos taurus*, reflecting adaptive traits (Sejian *et al*., 2018) [80]. Studies also show that changes in physiological parameters such as RR and rectal temperature (RT) occur in a phasic pattern, with buffaloes exhibiting earlier onset of heat stress than cattle (Sharma *et al*., 2023) [82]. Thermal humidity index (THI) strongly influences skin temperature and RR, with significant seasonal variation; for instance, RR was higher in late summer than in early monsoon (Velayudhan *et al*., 2023; Amamou *et al*., 2019) [95, 6].

B. Impact on Core (Rectal) body temperature

Several studies have established rectal temperature (RT) as a key indicator of heat stress in cattle, closely linked with declines in milk yield and productivity. In dairy and feedlot cattle, heat stress consistently elevates RT, respiration rate, and metabolic strain, leading to reduced performance and health challenges (Bouraoui *et al*., 2002; West, 2003; Collier *et al.,* 2006; Brown-Brandl *et al*., 2006; Gantner *et al*., 2011; Schuller *et al*., 2014) [16, 97, 20, 18, 27, 78]. Breed differences have been noted, with Bos indicus showing greater thermal tolerance than Bos taurus (Pires *et al*., 2022) [67]. Comparative studies further reveal species-specific thresholds, with buffaloes exhibiting RT increases at lower THI values than cattle, indicating earlier onset and greater severity of heat stress (Sharma *et al*., 2023) [82]. While most studies confirm RT as a reliable marker, some findings suggest it may remain stable under mild climatic stress (Velayudhan *et al.,* 2023) [95]. These results highlight the physiological, welfare, and productivity implications of rising RT in heat-stressed cattle and the importance of effective mitigation strategies.

C. Increased Sweating

Sweating, though limited in cattle due to fewer sweat glands, is a key thermoregulatory response that aids heat dissipation through evaporative cooling but also causes water and electrolyte loss (Beede & Collier, 1986; West, 2003) [12, 97]. Its effectiveness depends on airflow and declines under high humidity, reducing cooling efficiency (Kadzere *et al.,* 2002) [48]. Research shows that heat stress elevates sweating rates but often overwhelms this mechanism, leading to higher body temperatures, dehydration, and reproductive as well as performance challenges (Ravagnolo *et al*., 2000; Mader *et al*., 2006; Gaughan *et al.,* 2010) [70, 57, 29]. These findings emphasize that while sweating is vital for thermoregulation, its limitations under severe stress highlight the importance of targeted management strategies to safeguard cattle health, reproduction, and productivity.

D. Altered blood flow

Heat stress induces marked alterations in cattle blood parameters, reflecting physiological and metabolic strain. Studies consistently report elevated cortisol, hematocrit, and hemoglobin levels, indicating stress responses, dehydration, and hemoconcentration, along with electrolyte imbalances and shifts in glucose and protein metabolism (Hahn, 1999; Marai *et al*., 2000; Silanikove *et al*., 2000; Bernabucci *et al*., 2002; West, 2003; Itoh *et al.*, 2003; Lacetera *et al*., 2006; Nardone *et al*., 2010; Sejian *et al*., 2018) [36, 58, 87, 13, 97, 47, 54, 63, 80]. These changes contribute to oxidative stress, impaired milk production, and reduced productivity, with breed-specific differences highlighting varied resilience to thermal loads. Collectively, the findings underscore the critical role of blood biomarkers in assessing heat stress and the need for tailored antioxidant, nutritional, and management strategies to safeguard cattle health and performance under rising temperatures.

2. Metabolic Changes

Heat stress induces significant alterations in metabolic processes to reduce internal heat production and manage energy balance.

A. Reduced Feed Intake

Heat stress has been widely documented to reduce dry matter intake (DMI), nutrient utilization, and overall productivity in cattle, with significant consequences for growth, milk yield, and reproduction. Early studies highlighted the importance of nutritional strategies in mitigating these effects, emphasizing dietary adjustments to counter reduced intake and absorption (Beede *et al*., 1986; West, 1999; NRC, 2001) [12, 98, 64]. Research consistently shows that heat stress lowers feed intake, leading to declines in milk production, altered feeding behavior, impaired health, and reproductive challenges (Holter *et al*., 1997; Kadzere *et al.,* 2002; Abeni *et al.,* 2007; Kargar *et al.,* 2015) [42, 48, 1, 50]. Nutritional interventions such as supplemental yeast cultures, vitamins, and dietary modifications have proven beneficial in improving feed intake and sustaining milk yield under heat stress (Shwartz *et al.,* 2009; Rhoads *et al*., 2013) [84, 73]. Moreover, studies on metabolism reveal that reduced intake disrupts energy balance and nutrient metabolism, further aggravating productivity losses (Baumgard *et al.,* 2013) [10]. Collectively, these findings underline the critical role of feed and nutritional management in supporting cattle health, productivity, and reproduction during periods of thermal stress.

B. Shift in Nutrient Utilization

Heat stress has profound effects on nutrient metabolism, feeding behavior, and productivity in dairy animals. Studies have shown that high temperatures alter feeding patterns, reduce dry matter intake (DMI), and impair immune function, leading to decreased milk yield and overall health challenges (Sevi *et al*., 2001; Kadzere *et al*., 2002) [81, 48]. Heat stress also accelerates protein catabolism, as evidenced by increased 3-methylhistidine and blood urea nitrogen levels, indicating muscle protein breakdown and reduced nitrogen balance (Kamiya *et al*., 2006; Gao *et al*., 2017) [49, 28]. These changes highlight the need for nutritional strategies to support protein metabolism under thermal stress. Moreover, carbohydrate metabolism is significantly altered, with heat-stressed cows relying more on glucose than fatty acids to meet energy demands, a shift that reduces internal heat production but compromises energy efficiency (Baumgard *et al*., 2011; Baumgard & Rhoads, 2013) [9, 10]. Dietary interventions such as monensin supplementation and yeast culture have been shown to improve glucose metabolism, sustain feed intake, and support milk production under heat stress (Shwartz *et al*., 2009; Baumgard *et al*., 2011) [84, 10]. Collectively, these findings emphasize that targeted nutritional and metabolic management is essential to alleviate the negative impacts of heat stress on dairy cattle health, metabolism, and productivity.

C. Impact on Electrolyte balance

Heat stress has been consistently shown to disrupt electrolyte balance in ruminants, particularly reducing sodium, potassium, and chloride levels, which impairs feed intake, digestion, immune function, and overall productivity (Morrison, 1983; Silanikove, 1992; Smith *et al*., 2000; Kumar *et al*., 2010) [62, 85, 89]. Studies across cattle and sheep reported significant electrolyte losses through sweating and increased respiration, with consequences on physiological and metabolic stability (Beatty *et al*., 2006; Gaughan & Mader, 2014) [11, 32]. Bos indicus breeds demonstrated superior adaptive mechanisms compared to Bos taurus in maintaining electrolyte balance (Beatty *et al*., 2006) [11], while elevated temperature-humidity index (THI) values were strongly correlated with electrolyte depletion (Dikmen & Hansen, 2009) [23]. Reviews further emphasized that electrolyte imbalance under heat stress compromises immune responses, metabolic functions, and long-term livestock sustainability under climate change (Nardone *et al*., 2010; Ganaie *et al*., 2013) [63, 26]. Collectively, these findings highlight the importance of adaptive management strategies such as adequate water provision, shade, cooling systems, and targeted electrolyte supplementation to safeguard health, productivity, and resilience in livestock during thermal stress.

3. Hormonal Changes

Heat stress induces profound hormonal alterations in cattle, significantly affecting metabolism, growth, reproduction, immunity, and overall productivity. Elevated cortisol, reduced thyroid hormones (T_3 and T_4), impaired insulin sensitivity, and disrupted reproductive hormones such as progesterone, estrogen, LH, and FSH are consistently reported under thermal stress. These changes lead to reduced feed intake, altered energy metabolism, compromised milk yield and composition, impaired immune responses, decreased fertility, increased embryonic mortality, and prolonged calving intervals (Lamb *et al*., 1985; Wolfenson *et al*., 2000; Silanikove, 2000; Ronchi *et al*., 2001; Rensis & Scaramuzzi, 2003; Lacetera *et al*., 2003; Hansen, 2007; Bernabucci *et al*., 2010) [55, 99, 87, 86, 75, 72, 53, 37-38, 14]. Studies across different breeds and production systems have shown that heat stress elevates cortisol and suppresses thyroid and reproductive hormones, with detrimental effects on growth and reproduction (Hooda *et al*., 2011; Alhidary *et al*., 2012; Omontese *et al*., 2014) [41, 4, 65]. Interestingly, native breeds in harsh climates demonstrate better adaptability in maintaining hormonal balance compared to high-yielding exotic breeds (Silanikove & Güler, 2020) [88]. Collectively, these findings emphasize that hormonal dysregulation is a central mechanism through which heat stress compromises livestock productivity and highlight the importance of genetic selection, adaptive management, and nutritional strategies to alleviate these impacts.

4. Behavioural changes

High-producing dairy cows are particularly vulnerable to heat stress, with disturbances in thermoregulation reflected through behavioral changes such as reduced feed intake, increased standing time, shade-seeking, panting, and altered lying behavior, which serve as important indicators of welfare. Studies consistently show that access to shade and cooling interventions, such as water misting, significantly improve comfort, reduce panting and body temperature, and enhance feed intake and performance (Blackshaw *et al*., 1994; Mitlöhner *et al*., 2001; Brown-Brandl *et al*., 2005; Schutz *et al*., 2008) [15, 61, 17, 61]. Behavioral responses such as increased water consumption, reduced activity, and prioritization of shade over lying highlight the critical role of environmental management in mitigating heat stress and maintaining cattle health and productivity (Chen *et al*., 2013) [19].

5. Impact on rumen functioning

Heat stress markedly disrupts rumen physiology, impairing nutrient-energy balance by reducing dry matter intake, decreasing ruminal motility and contractions, altering fermentation patterns, lowering volatile fatty acid (VFA) production, and decreasing fiber digestibility, ultimately compromising productivity. Several studies have demonstrated these effects: high temperatures reduce ruminal pH, VFA production, and feed intake (Tajima *et al*., 2007; Zhao *et al*., 2010) [91, 100], alter fermentation and fiber digestion (Rhoads *et al*., 2009; Abeni & Galli, 2017) [74, 2], and increase the risk of subacute ruminal acidosis (Hernandez *et al*., 2011) [73]. Provision of shade and cooling improves feed intake, rumen pH, and fermentation efficiency (Gaughan *et al*., 2010) [30], while seasonal studies also confirm summer heat stress disrupts microbial balance, fiber digestion, and milk production (Mazzullo *et al*., 2014) [59]. More recent evidence highlights that heat stress alters the rumen microbiome itself, impairing fermentation efficiency and nutrient utilization, emphasizing the importance of dietary and management interventions to support rumen health under thermal stress (Allen *et al*., 2015; Pereira & De Souza, 2020) [5, 66].

6. Impact on Health

A. Hyperthermia: Severe heat stress can cause hyperthermia, which is life-threatening if not managed promptly (West, 2003; Kadzere *et al*., 2002; Baumgard & Rhoads, 2013) [97, 10]. Hyperthermia can result in organ failure and death if not addressed (West, 2003) [48].

B. Dehydration: Excessive water loss through sweating and respiration can result in dehydration, impacting organ function (Beede & Collier, 1986; Kadzere *et al*., 2002; Nardone *et al*., 2010) [12, 48, 63]. Dehydration can lead to electrolyte imbalances and reduced blood volume, affecting cardiovascular health (Kadzere *et al*., 2002) [48].

C. **Immune Suppression:** Chronic heat stress weakens the immune system, making animals more susceptible to diseases (Baumgard & Rhoads, 2013; West, 2003) [97, 10]. Immune suppression can increase the incidence of infections and reduce overall health.

7. Impact on Reproductive ability
Heat stress has a profound negative impact on cattle reproduction, primarily by reducing conception rates due to heat-induced changes in the uterine environment that impair sperm viability and embryo development (De Rensis & Scaramuzzi, 2003; Hansen, 2009) [22, 39]. Elevated temperatures also increase embryonic mortality, particularly during early pregnancy, by disrupting normal embryonic growth (Wolfenson *et al*., 2000; Sartori *et al*., 2002) [99, 77]. Moreover, heat stress alters estrous cycles, leading to irregularities in estrous behavior and reduced success of both natural mating and artificial insemination (Wolfenson *et al*., 2000; Hansen, 2009) [99, 39]. Hormonal imbalances, especially reductions in progesterone and estradiol, further compromise fertility and pregnancy maintenance (De Rensis & Scaramuzzi, 2003; Sartori *et al.*, 2002) [22, 77]. Additionally, heat stress impairs luteal function, resulting in reduced progesterone production, which weakens pregnancy support mechanisms and increases the risk of early embryonic loss (Wolfenson *et al*., 2000) [99].

8. Impact on Production ability
Heat stress markedly reduces productivity in cattle, with dairy cows showing a 10-25% decline in milk yield during hot periods due to reduced feed intake, impaired nutrient absorption, and diversion of energy toward thermoregulation instead of lactation (West, 2003; Kadzere *et al*., 2002) [97, 48]. Milk composition is also compromised, as elevated temperatures decrease fat and protein content, lowering both quality and quantity of milk (Collier *et al*., 2006) [20]. In beef cattle, heat stress diminishes growth performance by reducing weight gain, largely because of decreased feed intake and higher energy demands for cooling (Brown-Brandl *et al*., 2006) [18, 57].

Approaches for mitigating Heat Stress in Livestock
Shelter Management
Environmental and management interventions are crucial to mitigating heat stress in cattle. Providing shade, especially with high solar protection, significantly improves cattle comfort and is widely utilized even under moderate radiation levels (Shearer *et al*., 1991; Tucker *et al.*, 2008) [83, 93]. Effective strategies include natural or artificial shade, improved ventilation, evaporative cooling (fans, foggers, misters, cooling pads), and water-based methods such as sprinklers, wallows, and cooling ponds, with the best results achieved through combined approaches. Adjusting feeding times, ensuring proper airflow, and selecting heat-tolerant breeds further enhance resilience (Hansen, 2007; Aggarwal *et al.*, 2013) [37-38].

Nutritional management
Heat stress in cattle necessitates dietary and nutritional adjustments to maintain nutrient intake, optimize energy efficiency, and support thermoregulation. Reduced dry matter intake (DMI) during hot weather limits nutrient availability, making it essential to increase dietary nutrient density while balancing energy, protein, and fiber to avoid metabolic disorders (West, 1999) [98]. Supplementation with antioxidants such as vitamin E and selenium has been shown to improve oxidative status, reduce cellular damage, and support intestinal integrity under heat stress (Gupta *et al*., 2005; Liu *et al*., 2016) [17, 56]. At the cellular level, heat stress induces the expression of heat shock proteins (HSP70, HSP90, HSP27) via heat shock factors, providing protection to denatured proteins, with HSP70 identified as a reliable biomarker for heat stress in livestock (Archana *et al.*, 2017) [7]. Nutritional strategies, including enhanced dietary energy, protein, essential amino acids, and adequate mineral supply, alongside sufficient water availability, are critical for maintaining fiber digestibility, feed intake, and overall physiological resilience during high-temperature conditions (Conte *et al.*, 2018) [21].

Genetic modification
Advances in molecular biotechnology and genomics offer new opportunities to enhance heat stress tolerance in livestock. Genetic and genomic selection, epigenetic regulation, and thermal imprinting can improve thermotolerance while maintaining productivity (Renaudeau *et al.*, 2012) [71]. Functional analyses of over 19,600 genes in cattle, sheep, goats, and horses revealed pathways related to growth, stress response, immune function, metabolism, and behavior, highlighting targets for selection and multi-omics approaches (McManus *et al*., 2022) [60]. Studies on heat shock-regulated genes in peripheral blood mononuclear cells showed that both heat shock, oxidative stress, and immune response genes are affected in different cattle breeds, such as Hariana and Vrindavani (Sajjanar *et al*., 2023) [76]. Genetic modifications, including the SLICK gene mutation affecting the prolactin receptor, have demonstrated promising results by improving body temperature regulation and reducing heat stress in cattle adapted to hot climates (Pozzebon *et al.*, 2024) [69].

Automated monitoring of cattle heat and its mitigation
Automated phenotyping technologies, including on-animal sensors and IoT-based environmental controls, offer new opportunities to monitor and manage heat stress in livestock by providing real-time, individualized data on body temperature, panting, and movement (Koltes *et al.*, 2018; Islam *et al*., 2020, 2021) [45, 46]. These technologies can help identify heat-tolerant and susceptible animals, enabling targeted mitigation and genetic selection to enhance thermal resilience, while overcoming the limitations of visual observation and weather-based indices. Grouping animals by genotype or coat color and prioritizing resources for heat stress management can further improve productivity in commercial operations. In the broader context of climate change, livestock face multiple challenges, including heat stress, limited feed and water, increased disease incidence, and reduced reproductive performance. Addressing these challenges requires an integrated approach combining genetic selection for heat tolerance, nutritional strategies to support metabolic resilience, improved management practices such as shade and water provision, and enhanced disease and water management. Collaborative efforts among researchers, farmers, and policymakers are essential to implement these strategies effectively, ensuring sustainable and productive livestock systems.

Conclusion

Climate change poses a significant threat to livestock health, productivity, and sustainability, primarily through heat stress, which disrupts physiological, metabolic, hormonal, and behavioral homeostasis. Heat stress elevates respiration rate and core body temperature, alters blood parameters and electrolyte balance, reduces feed intake by 10-25%, impairs rumen function, and compromises reproductive performance and milk yield, while increasing embryonic mortality (West, 2003; Kadzere *et al*., 2002; Wolfenson *et al.*, 2000) [97, 48, 99]. Breed differences are evident, with Bos indicus and native breeds demonstrating greater resilience compared to high-yielding Bos taurus cattle (Silanikove & Güler, 2020) [88]. Mitigation strategies integrating environmental management (shade, ventilation, evaporative cooling), nutritional interventions (enhanced dietary energy, protein, minerals, antioxidants, and water supply), genetic selection (heat-tolerant breeds, SLICK gene), and automated monitoring technologies (on-animal sensors, IoT-based systems) have proven effective in sustaining productivity under thermal stress (Hansen, 2007; Koltes *et al.,* 2018; Pozzebon *et al*., 2024) [37-38, 51, 69]. A multidisciplinary approach combining genetics, nutrition, management, and technology is therefore essential to safeguard livestock systems against the escalating impacts of climate change while maintaining animal welfare, productivity, and food security.

References

1. Abeni F, Calamari L, Stefanini L. Effects of heat stress on milk traits and feeding behavior of grazing dairy cows. Animal Science Journal. 2007;78(6):664-671.
2. Abeni F, Galli A. Heat stress and the alteration of bovine rumen function: An overview. Journal of Animal Science and Biotechnology. 2017;8:37.
3. Aggarwal A, Upadhyay R. Shelter management for alleviation of heat stress in cows and buffaloes. In: Heat Stress and Animal Productivity. New Delhi: Springer; 2013.
4. Alhidary IA, Shini S, Al Jassim RA, Gaughan JB. The effect of restricted feed intake and heat stress on live weight gain and some blood variables in growing male *Holstein* calves. Animal Production Science. 2012;52(7):646-651.
5. Allen JD, Hall LW, Collier RJ, Smith JF. Effect of core body temperature, time of day, and climate conditions on feed intake of lactating dairy cows. Journal of Dairy Science. 2015;96(1):377-387.
6. Amamou H, Yves B, Mokhtar M, Hammami H. Thermotolerance indicators related to production and physiological responses to heat stress of *Holstein* cows. Journal of Thermal Biology. 2019;82:90-98.
7. Archana PR, Aleena J, Pragna P, Vidya MK, Niyas APA, *et al*. Role of heat shock proteins in livestock adaptation to heat stress. Journal of Dairy Veterinary Animal Research. 2017;5(1):00127.
8. Anamika, Ratwan P, Dalal DS, Magotra A. Impact of heat stress on tropical livestock and various approaches for mitigation. 2024;7(6):84-86.
9. Baumgard LH, Wheelock JB, Sanders SR, Moore CE, Green HB, Waldron MR, Rhoads RP. Postabsorptive carbohydrate adaptations to heat stress and monensin supplementation in lactating *Holstein* cows. Journal of Dairy Science. 2011;94(11):5620-5633.
10. Baumgard LH, Rhoads RP. Effects of heat stress on postabsorptive metabolism and energetics. Annual Review of Animal Biosciences. 2013;1:311-337.
11. Beatty DT, Barnes A, Taylor E, Pethick D, McCarthy M, Maloney SK. Physiological responses of *Bos taurus* and *Bos indicus* cattle to prolonged, continuous heat and humidity. Journal of Animal Science. 2006;84(4):972-985.
12. Beede DK, Collier RJ. Potential nutritional strategies for intensively managed cattle during thermal stress. Journal of Animal Science. 1986;62(2):543-554.
13. Bernabucci U, Ronchi B, Lacetera N, Nardone A. Markers of oxidative status in plasma and erythrocytes of transition dairy cows during hot season. Journal of Dairy Science. 2002;85(9):2173-2179.
14. Bernabucci U, Basiricò L, Morera P. Impact of hot environment on colostrum and milk composition. Cellular and Molecular Biology. 2010;56:69-82.
15. Blackshaw JK, Blackshaw AW, McCowan B. Shade-seeking and lying behaviour in *Bos indicus* crossbred cows and calves in a tropical climate. Applied Animal Behaviour Science. 1994;39(2):159-168.
16. Bouraoui R, Lahmar M, Majdoub A, Djemali M, Belyea R. The relationship of temperature-humidity index with milk production of dairy cows in a Mediterranean climate. Animal Research. 2002;51(6):479-491.
17. Brown-Brandl TM, Eigenberg RA, Nienaber JA, Hahn GL. Dynamic responses of heat-exposed cattle to shade and no-shade conditions. Transactions of the ASAE. 2005;48(2):749-755.
18. Brown-Brandl TM, Eigenberg RA, Nienaber JA, Hahn GL. Environmental effects on heat stress in feedlot cattle. Journal of Animal Science. 2006;84(3):712-719.
19. Chen JM, Stookey JM, Arnone B. Behavioral changes of beef cattle in response to heat stress. International Journal of Biometeorology. 2013;57(5):669-674.
20. Collier RJ, Dahl GE, VanBaale MJ. Major advances associated with environmental effects on dairy cattle. Journal of Dairy Science. 2006;89(4):1244-1253.
21. Conte G, Ciampolini R, Cassandro M, Lasagna E, Calamari L, Bernabucci U, *et al*. Feeding and nutrition management of heat-stressed dairy ruminants. Italian Journal of Animal Science. 2018;17(3):604-620.
22. De Rensis F, Scaramuzzi RJ. Heat stress and seasonal effects on reproduction in the dairy cow—a review. Theriogenology. 2003;60(6):1139-1151.
23. Dikmen S, Hansen PJ. Is the temperature-humidity index the best indicator of heat stress in lactating dairy cows in a subtropical environment? Journal of Dairy Science. 2009;92(1):109-116.
24. Eckstein D, Künzel V, Schäfer L, Winges M. Global Climate Risk Index 2021. Bonn (Germany): Germanwatch; 2021.
25. Food and Agriculture Organization of the United Nations (FAO). The future of food and agriculture: Alternative pathways to 2050. Rome: FAO; 2018.
26. Ganaie AH, Shanker G, Bumla NA, Ghasura RS, Mir NA, Wani SA, *et al*. Biochemical and physiological changes during thermal stress in bovines. Journal of Veterinary Science and Technology. 2013;4(1):126.
27. Gantner V, Mijić P, Kuterovac K, Solić D, Gantner R. Temperature-humidity index values and their

significance on the daily production of dairy cattle. Mljekarstvo: Journal for Dairy Production and Processing Improvement. 2011;61(1):56-63.
28. Gao ST, Guo J, Quan SY, Nan XM, Fernandez MS, Baumgard LH, Bu DP. The effects of heat stress on protein metabolism in lactating *Holstein* cows. Journal of Dairy Science. 2017;100(6):5040-5049.
29. Gaughan JB, Bonner SL, Loxton I, Mader TL, Lisle A, Lawrence R. Effect of shade on body temperature and performance of feedlot steers. Journal of Animal Science. 2010;88(12):4056-4067.
30. Gaughan JB, Mader TL, Holt SM, Sullivan M. Heat stress and the implications for feed intake, digestion, and performance. Journal of Animal Science. 2010;88(12):2311-2321.
31. Gaughan JB, Mader TL. Heat stress and livestock. Animal Frontiers. 2012;4(3):24-31.
32. Gaughan JB, Mader TL. Body temperature and respiratory dynamics in unshaded beef cattle. International Journal of Biometeorology. 2014;58(7):1443-1450.
33. Gerber PJ, Steinfeld H, Henderson B, Mottet A, Opio C, Dijkman J, *et al*. Tackling climate change through livestock: A global assessment of emissions and mitigation opportunities. Food and Agriculture Organization of the United Nations; 2013.
34. Getachew Bekele Fereja. The impacts of climate change on livestock production and productivities in developing countries: A review. International Journal of Research - Granthaalayah. 2016;4(8):181-187.
35. Gupta S, Gupta HK, Soni J. Effect of vitamin E and selenium supplementation on concentrations of plasma cortisol and erythrocyte lipid peroxides and the incidence of retained fetal membranes in crossbred dairy cattle. Theriogenology. 2005;64(6):1273-1286.
36. Hahn GL. Dynamic responses of cattle to thermal heat loads. Journal of Animal Science. 1999;77(Suppl 2):10-20.
37. Hansen PJ. Exploiting genetic and physiological diversity to enhance fertility under heat stress conditions. Theriogenology. 2007;68(1):1-5.
38. Hansen PJ. Physiological and cellular adaptations of *Bos indicus* cattle to thermal stress. Theriogenology. 2007;68(Suppl):S242-S249.
39. Hansen PJ. Effects of heat stress on mammalian reproduction. Philosophical Transactions of the Royal Society B: Biological Sciences. 2009;364(1534):3341-3350.
40. Hernandez L, Benedito JL, Abuelo A, Castillo C. Ruminal acidosis in feedlot: From aetiology to prevention. The Scientific World Journal. 2011;11:766-777.
41. Hooda OK, Upadhyay RC, Singh SV. Physiological responses, growth rate and blood metabolites under feed restriction and thermal exposure in kids. Journal of Stress Physiology & Biochemistry. 2011;7(4):324-331.
42. Holter JB, West JW, McGilliard ML. Predicting ad libitum dry matter intake and yields of Jersey cows. Journal of Dairy Science. 1997;80(2):307-313.
43. West JW. Nutritional strategies for managing the heat-stressed dairy cow. Journal of Animal Science. 1999;77(Suppl 2):21-35.
44. IPCC. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press; 2021.
45. Islam MA, Lomax S, Doughty AK, Islam MR, Clark CEF. Automated monitoring of panting for feedlot cattle: Sensor system accuracy and individual variability. Animals. 2020;10:1518.
46. Islam MA, Lomax S, Doughty A, Islam MR, Jay O, Thomson P, *et al*. Automated monitoring of cattle heat stress and its mitigation. Frontiers in Animal Science. 2021;2:737213.
47. Itoh F, Obara Y, Rose MT, Fuse H, Hashimoto H. Heat stress increases plasma vitamin C in lactating cows. Journal of Animal Science. 2003;81(5):1117-1122.
48. Kadzere CT, Murphy MR, Silanikove N, Maltz E. Heat stress in lactating dairy cows: A review. Livestock Production Science. 2002;77(1):59-91.
49. Kamiya M, Kamiya Y, Tanaka M, Oki T, Nishiba Y, Shioya S. Effects of high ambient temperature and restricted feeding on urinary and plasma 3-methylhistidine in lactating Holstein cows. Animal Science Journal. 2006;77(2):201-207.
50. Kargar S, Ghorbani GR, Fievez V, Soto S, Brisaert M. Interaction between feed intake, heat stress, and reproductive performance in high-producing dairy cows. Journal of Dairy Science. 2015;98(11):8888-8897.
51. Koltes JE, Koltes DA, Mote BE, Tucker J, Hubbell DS. Automated collection of heat stress data in livestock: New technologies and opportunities. Translational Animal Science. 2018;2:319-323.
52. Kumar B, Manuja A, Ahuja P, Mahajan V. Impact of heat stress on immune responses of livestock: A review. Journal of Animal Science. 2010;88(7):2337-2350.
53. Lacetera N, Bernabucci U, Ronchi B, Nardone A. Physiological and productive consequences of heat stress: The case of dairy ruminants. Proceedings of the 12th International Conference on Production Diseases in Farm Animals (ICPD); 2003 Jul; Leipzig, Germany. p. 45-56.
54. Lacetera N, Bernabucci U, Scalia D, Ronchi B, Kuzminsky G, Nardone A. Heat stress elicits different responses in peripheral blood mononuclear cells from Brown Swiss and Holstein cows. Journal of Dairy Science. 2006;89(12):4606-4612.
55. Lamb RC, Barker HD, Oltenacu EA. Effect of environmental temperature on composition of Holstein milk. Journal of Dairy Science. 1985;68(6):1466-1470.
56. Liu F, Cottrell JJ, Furness JB, Rivera LR, Kelly FW, Wijesiriwardana U. Selenium and vitamin E together improve intestinal epithelial barrier function and alleviate oxidative stress in heat-stressed pigs. Experimental Physiology. 2016;101(7):801-810.
57. Mader TL, Davis MS, Brown-Brandl TM. Environmental stress and performance of feedlot cattle. In: Proceedings of the 2006 Kansas State University Beef Cattle Conference; 2006.
58. Marai IFM, Haeeb AAM. Buffalo's biological functions as affected by heat stress—A review. Livestock Science. 2010;127(2-3):89-109.
59. Mazzullo G, Caccamo M, Rifici C, Zumbo A. Effect of seasonal variations on rumen function in lactating dairy cows. Veterinary World. 2014;7(8):559-564.
60. McManus C, Maranhão AQ, Pimentel D, Pimentel F, de Macedo Brigido M. Genetic adaptation of livestock

to heat stress challenges. In: Sejian V, Chauhan SS, Devaraj C, Malik PK, Bhatta R, editors. Climate Change and Livestock Production: Recent Advances and Future Perspectives. Singapore: Springer; 2021. p. 1-20. https://doi.org/10.1007/978-981-16-9836-1_21
61. Mitlöhner FM, Morrow JL, Dailey JW, Wilson SC, Galyean ML, Miller MF, McGlone JJ. Shade and water misting effects on behavior, physiology, performance, and carcass traits of heat-stressed feedlot cattle. Journal of Animal Science. 2001;79(9):2327-2335.
62. Morrison SR. Ruminant heat stress: Effect on production and means of alleviation. Journal of Animal Science. 1983;57(1):159-168.
63. Nardone A, Ronchi B, Lacetera N, Ranieri MS, Bernabucci U. Effects of climate changes on animal production and sustainability of livestock systems. Livestock Science. 2010;130(1-3):57-69.
64. National Research Council. Nutrient Requirements of Dairy Cattle: Seventh Revised Edition, 2001. Washington, DC: The National Academies Press; 2001. https://doi.org/10.17226/9825
65. Omontese BO, Rekwot PI, Ate IU, Rwuaan JS, Kawu MU, Ayo JO. Seasonal variations in reproductive hormones of cattle in tropical climates. Tropical Animal Health and Production. 2014;46(6):1101-1106.
66. Pereira AMF, De Souza BB. Rumen microbiome and heat stress in dairy cattle: A review. Animal Microbiome. 2020;2:26.
67. Pires BV, Ana C, Freitas B, John LK, Thaise PM, Nedenia BS, Claudia CP. Meta-analysis and meta-regression of core body temperature in taurine and zebuine cattle under different environmental conditions. Livestock Science. 2022;265:105104.
68. Polsky L, von Keyserlingk MAG. Effects of heat stress on dairy cattle welfare. Journal of Dairy Science. 2017;100(11):8645-8657.
69. Pozzebon M, Guldbrandtsen B, Sandøe P. Gene editing cattle for enhancing heat tolerance: A welfare review of the "PRLR-SLICK cattle" case. Nanoethics. 2024;18:6. https://doi.org/10.1007/s11569-024-00455-8
70. Ravagnolo O, Misztal I. Effect of heat stress on reproduction parameters of dairy cattle. Journal of Dairy Science. 2000;83(2):212-218.
71. Renaudeau D, Collin A, Yahav S, de Basilio V, Gourdine JL, Collier RJ. Adaptation to hot climate and strategies to alleviate heat stress in livestock production. Animal. 2012;6(5):707-728.
72. Rensis FD, Scaramuzzi RJ. Heat stress and seasonal effects on reproduction in the dairy cow—a review. Theriogenology. 2003;60(6):1139-1151.
73. Rhoads RP, Baumgard LH, Suagee JK, Sanders SR. Nutritional interventions to alleviate the negative consequences of heat stress. Journal of Animal Science. 2013;91(2):104-114.
74. Rhoads ML, Rhoads RP, VanBaale MJ, Collier RJ, Sanders SR, Weber WJ, *et al*. Effects of heat stress and plane of nutrition on lactating Holstein cows: I. Production, metabolism, and aspects of circulating somatotropin. Journal of Dairy Science. 2009;92(5):1986-1997.
75. Ronchi B, Stradaioli G, Verini Supplizi A, Bernabucci U, Lacetera N, Accorsi PA, *et al*. Influence of heat stress on milk production, immune functions, and plasma hormones in Holstein cows. Journal of Dairy Science. 2001;84(4):629-637.
76. Sajjanar B, Aalam MT, Khan O, *et al*. Genome-wide expression analysis reveals different heat shock responses in indigenous (*Bos indicus*) and crossbred (*Bos indicus* × *Bos taurus*) cattle. Genes and Environment. 2023;45:17.
77. Sartori R, Sartor-Bergfelt R, Mertens SA, Guenther JN, Parrish JJ, Wiltbank MC. Fertilization and early embryonic development in heifers and lactating cows in summer and lactating and dry cows in winter. Journal of Dairy Science. 2002;85(11):2803-2812.
78. Schüller LK, Burfeind O, Heuwieser W. Effects of short-term heat stress on blood parameters in lactating dairy cattle. Animal. 2014;8(8):1288-1296.
79. Schütz KE, Cox NR, Matthews LR. How important is shade to dairy cattle? Choice between shade or lying following different levels of lying deprivation. Applied Animal Behaviour Science. 2008;114(3-4):307-318.
80. Sejian V, Bhatta R, Gaughan JB, Dunshea FR, Lacetera N. Adaptation of animals to heat stress. Animal. 2018;12(s2):s431-s444.
81. Sevi A, Annicchiarico G, Albenzio M, Taibi L, Muscio A, Dell'Aquila S. Effects of solar radiation and feeding time on behavior, immune response and production of lactating ewes under high ambient temperature. Journal of Dairy Science. 2001;84(3):629-640.
82. Sharma S, Sharma V, Konwar D. A comparative study on effect of heat stress on physiological and cellular responses of crossbred cattle and riverine buffalo in subtropical region of India. International Journal of Biometeorology. 2023;6(4):24-31.
83. Shearer JK, Beede DK, Bucklin RA, Bray DR. Heat stress. Part 3. Environmental modification to reduce heat stress in dairy cattle. 1991;19922274881.
84. Shwartz G, Rhoads ML, VanBaale MJ, Rhoads RP, Baumgard LH. Effects of a supplemental yeast culture on heat-stressed lactating Holstein cows. Journal of Dairy Science. 2009;92(3):935-942.
85. Silanikove N. Effects of water scarcity and hot environment on appetite and digestion in ruminants: A review. Livestock Production Science. 1992;30(3):175-194.
86. Silanikove N. Effects of heat stress on the welfare of extensively managed domestic ruminants. Livestock Production Science. 2000;67(1-2):1-18.
87. Silanikove N, Koluman N, Shapiro F. Mechanisms that limit milk production in dairy cows exposed to extreme heat loads. Journal of Animal Science. 2000;78(Suppl_3):26-35.
88. Silanikove N, Koluman N, Güler M. The physiological and behavioral basis of the productivity of ruminants in Mediterranean and Middle Eastern climates: The advantages of the native breeds. Small Ruminant Research. 2020;185:106090.
89. Smith JF, Harner JP, Armstrong DV. Managing heat stress in dairy cattle. Journal of Dairy Science. 2000;83(6):1043-1051.
90. Stephenson DB, Diaz HF, Murnane RJ. Definition, diagnosis, and origin of extreme weather and climate events. Climatic Extremes and Society. 2008;340:11-23.
91. Tajima K, Nonaka I, Higuchi K, Takusari N, Kurihara M, Takenaka A, *et al*. Influence of high ambient

temperature and restricted feeding on rumen fermentation and blood metabolites in beef cattle. Animal Science Journal. 2007;78(2):173-178.
92. Tharinda D, De Silva, Subhani A, Sarada, Mailvaganam P, Wimal A, Perera. Effect of heat stress on cattle: A review. Advanced Technologies. 2024. https://doi.org/10.31357/ait.v3i2.7339
93. Tucker CB, Rogers AR, Schütz KE. Effect of solar radiation on dairy cattle behaviour, use of shade and body temperature in a pasture-based system. Applied Animal Behaviour Science. 2008;109:141-154.
94. UNFCCC. Definitions of climate change. 1992. https://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf
95. Velayudhan SM, Brugemann K, Alam S, Yin T, Devaraj C, Sejian V, *et al*. Molecular, physiological and hematological responses of crossbred dairy cattle in a tropical savanna climate. Biology. 2023;12:26.
96. Visschers VH. Public perception of uncertainties within climate change science. Risk Analysis. 2018;38:43-55.
97. West JW. Effects of heat-stress on production in dairy cattle. Journal of Dairy Science. 2003;86(6):2131-2144.
98. West JW. Nutritional strategies for managing the heat-stressed dairy cow. Journal of Animal Science. 1999;77(Suppl_2):21-35.
99. Wolfenson D, Roth Z, Meidan R. Impaired reproduction in heat-stressed cattle: Basic and applied aspects. Animal Reproduction Science. 2000;60-61:535-547.
100. Zhao LY, Fan ZY, Xue B, Wang L, Hou ZP. Effects of heat stress on rumen fermentation and physiological indices in Holstein heifers. Journal of Animal and Veterinary Advances. 2010;9(11):1570-1573.