APPLIED VETERINARY RESEARCH

REVIEW ARTICLE
Published Online: March 7, 2025
https://doi.org/10.31893/avr.2024011

Response of dairy cattle to thermal stress: Implications for designing animal breeding strategies for sustainable productivity under changing climate

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Abstract The objective of this study was to review the response of dairy cattle to heat stress (HS) and assess breeding options for coping with sustainable productivity under a changing climate. High ambient temperature (AT) in combination with relative humidity affects most critical factors for livestock production, such as water availability, animal production, reproduction, and health. When the THI exceeds 72, cows will likely begin experiencing HS, and their in-calf rates will be affected. Several reports have shown the associations of SNPs in HSP genes with the thermal stress response and tolerance in farm dairy cattle. The association of polymorphisms in Hsp90 AB1 with heat tolerance has been reported in Thai native cattle, Sahiwal cattle, and Friesian cattle. Thus, ameliorating HS via physical modifications of the environment, nutrition management, genetic selection, and breeding is paramount. Compared with that of other livestock species, the effect of HS on dairy cattle is a serious problem. Therefore, intensive research under both controlled and on-farm trials is needed. From this review point of view, future research should focus on conservation strategies for locally adaptable breeds with optimum productivity. Moreover, a breeding strategy that considers disease resistance, environmental stress, and adaptation traits should be considered in the future. Furthermore, the regular prediction of environmental stress resulting from climate change and the design of pertinent response strategies are essential for reducing the adverse impacts of environmental stress to increase the resilience capacity of dairy cattle breeds. To promote the conservation of heat-tolerant native breeds, policies and incentives should be designed to address both environmental and economic challenges while recognizing the unique qualities of these breeds. By combining financial support, research, awareness, and market development, policies and incentives can create an environment where heat-tolerant native breeds thrive, contributing to more resilient agricultural systems in the face of climate change.

Keywords: amelioration, breeding options, changing climate, dairy cattle performance, heat stress

1. Introduction

Climate change affects livestock populations. As the temperature increased, the rainfall distribution patterns shifted. These factors indirectly affect ecosystems, such as changes in crop yield, alterations in the distribution of animal diseases, geographical restrictions on rare breed populations, and increased competition for resources (Kefyalew and Addis, 2016). HS is a reflexive reaction of animals in harsh environments and causes unfavorable consequences ranging from discomfort to death. An imbalance between metabolic heat production inside the animal body and heat dissipation to the surroundings results in HS under high AT and humid climates. The thermoneutral zone (TNZ) of dairy cattle ranges from 16°C to 25°C, within which they maintain a physiological body temperature of 38.4–39.1°C (Yousef, 1985). However, air temperatures above 20–25°C in a temperate climate and 25–37°C in a tropical climate such as India enhance heat gain beyond that lost from the body and induce HS (Sunil et al., 2011). Studies have shown that native/indigenous breeds survive and perform better than exotic breeds do and that their ability to cross under tropical environmental conditions may be due to the inability of exotic genes to be expressed/adapt under tropical conditions (Baumgard and Rhoads, 2013; Kumar et al., 2014). Furthermore, the sensitivity of dairy cattle to HS increases with increasing milk production (Sunil et al., 2011), which might be due to an increase in metabolic heat output with increased production levels in dairy animals. Thus, it is imperative to assess and organize information on HS and its impacts on dairy cattle and possible coping mechanisms for decision-makers as well as for scientific communities. Therefore, the objectives of this study were to review the impact of HS on dairy cattle performance and assess breeding options for coping mechanisms under environmental HS for sustainable productivity.

 Received: August 11, 2024 | Accepted: January 12, 2025

2. Climate Change and Variability

Alterations to the Earth's atmosphere that have occurred over much longer periods of decades to millennia are characterized as climate change. Although natural phenomena such as volcanic eruptions, variations in solar activity, tectonic movements, or changes in the Earth's orbital patterns can drive climate change, the term is most often associated with human-induced factors, particularly the rise in greenhouse gas emissions. The latest (Fifth) Assessment Report from the Intergovernmental Panel on Climate Change (IPCC, 2013), for example, revealed that, on average, global temperatures increased by approximately 0.85°C from 1880--2012 and concluded that more than half of the observed increase in global average temperatures was caused by elevated emissions of carbon dioxide and other greenhouse gases, whereas the climate tends to change quite slowly, which does not mean that we do not experience shorter-term fluctuations on seasonal or multiseasonal time scales. Many factors can cause temperature, for example, to fluctuate around the average without causing the long-term average itself to change. This phenomenon is known as climate variability, and when scientists talk about it, they usually refer to periods ranging from months to as many as 30 years (https://www.air-worldwide.com/blog/posts/2017/6/climate-variability-vs--climate-change-whats-the-difference/).

3. Livestock Production and Climate Change

For roughly one in three people around the globe, farming serves as the primary means of earning a living. Approximately 60% of the people rely on farming for their livelihood livestock. Nearly 800 million livestock keepers live on less than USD 2 a day (IMF and UNCTAD, 2011). Livestock production is a rapidly growing sector. It accounts for 40% of the global agricultural gross domestic product (GDP) and is crucial for food security in all regions. In sub-Saharan Africa, more than half of the population keeps livestock, and one in three of these livestock keepers can be considered poor (Food and Nations, 2012). Livestock make a necessary and important contribution to global calorie and protein supplies and important micronutrients. They produce 17% of the calories consumed globally and 33% of the protein. Livestock can increase the world's edible protein balance by transforming inedible protein found in forage into forms that people can digest. For example, in pastoral areas, livestock is the only option to turn a sparse and erratic biomass resource into edible products. On the other hand, livestock can also reduce the global edible protein balance by consuming large amounts of edible protein found in cereal grains and soybeans and converting it into small amounts of animal protein (Mottet and Tempio, 2017). The choice of livestock production systems, such as grass-based, integrated crop-livestock, and good management practices, is important for optimizing the protein output from livestock. Livestock is also a major asset among rural communities, providing a range of essential services, including savings, credit, and buffering against climatic shocks and other crises. In mixed systems, livestock consumes crop residues and byproducts (from agro-industrial processing) and produces manure used to fertilize crops. Cattle, camels, horses, and donkeys also provide transport and draught power for field operations, up to 81% in northern Africa (Gebresenbet and Kaumbutho, 1997). With all these services, the contribution of livestock goes beyond agriculture and food security and directly supports education and human health.

However, livestock need to be managed carefully to maximize the range of services they provide and reduce their vulnerability to the impacts of climate change and variability. Climate change poses serious threats to livestock production. Rising temperatures, alterations in rainfall patterns, more frequent extreme weather events, and the resulting increase in heat stress and decrease in water availability are anticipated to negatively impact livestock production and productivity on both direct and indirect levels globally. The most serious impacts are anticipated in grazing systems because of their dependence on climatic conditions and the natural resource base and their limited adaptation opportunities (Aydinalp and Cresser, 2008). The impacts are expected to be most severe in arid and semiarid grazing systems at low latitudes, where higher temperatures and lower rainfall are expected to reduce yields on rangelands and increase land degradation (Hoffman and Vogel, 2008). The direct impacts of climate change are likely to be more limited in nongrazing systems, mostly because the housing of animals in buildings allows for greater control of production conditions (FAO, 2009, Thornton and Gerber, 2010). Indirect impacts will be experienced through modifications in ecosystems; changes in yield, quality and type; the availability of feed and fodder crops; and greater competition for resources with other sectors (FAO, 2009, Thornton and Gerber, 2010). Climate change could lead to additional indirect impacts from the increased emergence of livestock diseases, as higher temperatures and altered rainfall patterns can alter the abundance, distribution, and transmission of animal pathogens (Baylis and Githeko, 2006). In nongrazing systems, indirect impacts from lower crop yields, feed scarcity, and higher feed and energy prices are more significant.

3.1. Impact of thermal stress on dairy cattle

When the AT exceeds 25°C, dairy cows are subjected to HS (Staples and Thatcher 2011). The first manifestation of HS is an increase in body temperature (BT) and the respiration rate (RR). As BT increases, there is a concurrent reduction in feed intake and a reduction in milk output (Staples and Thatcher 2011). The magnitude of reduced production is a function of the degree of heat load and the genetic value of the cow. According to Staples and Thatcher (2011), when the rectal temperature (RT) increases from 38.8 to 39.9°C, milk output decreases from 22.4 to 19.2 kg/day. Dry matter intake also decreased. There is evidence that higher-producing cows are more susceptible to HS than low-production cows are. Abera et al. (2021a) reported that the heart rate (HR) and RR increased by six beats per minute and four breaths per minute, respectively, when the THI increased from 66 to 78. The positive relationship between the THI and physiological parameters further confirmed that calves were good at thermoregulation at a THI value of 66. A large cattle population has died because of drought in the Borana Zone of Ethiopia in recent years, as shown in Figure 1.

Figure 1 Cattle population in the Borana Zone.

3.2. Temperature humidity index in cattle

Typically, the level of HS in cattle is estimated via the temperature–humidity index (THI), which was first introduced by (Thom, 1959). The THI is a useful and easy way to assess the risk of HS. This phenomenon is suggested to be an indicator of thermal climatic conditions. This index is widely used in hot areas worldwide to assess the impact of HS on dairy cows. An environment is generally considered stressful for cattle when the THI exceeds 72, and when the THI is at or above 72, adverse effects are expected(Broucek et al., 2009). This index has been adapted to describe the ambient temperature and humidity that cause HS in cattle (Dikmen and Hansen, 2009). Segnalini et al. (2013) divided the THI into six categories according to the level of HS in dairy cattle. However, THI values serve only as a rough measure of the HS effect on production (Polsky et al., 2017), and they call for necessary adjustments because the environmental stimulus includes other factors, such as wind speed and solar radiation (Mader et al., 2006). Moreover, the THI threshold for calves and heifers remains unknown because of the very limited information available related to the THI and HS of calves and heifers. More studies will help to quantify the THI for calves and heifers and even explore new indices to indicate the level of HS. The THI value of 66 can be considered optimal for high weight gain and normal physiological response to HS in Fogera cattle calves at Metekel Ranch (Abera et al., 2021).

3.3. Effect of heat stress on production performance

3.3.1. Milk production

A comparison study conducted by Staples and Thatcher (2011) revealed a difference in the HS response between high- and low-production cows, with high-production cows (32.6 kg milk/day) having a 4.7 kg/day decrease in milk production compared with a 2.7 kg reduction in low-production cows (19.0 kg milk/day). Compared with low-production cows (<20 kg), high-production cows (34.4 kg milk/day) presented a 2.3 kg/day reduction in milk yield, whereas there was no change in milk yield.

3.3.2. Feed intake

Feed intake begins to decline at air temperatures of 25–26°C in lactating cows and decreases more rapidly above 30°C in temperate climatic conditions, and at 40°C, it may decline by as much as 40% (Rhoads et al., 2013), 22–35% in dairy goats (Rhoads et al., 2013) or 8–10% in buffalo heifers (Hooda and Singh, 2010). Reducing feed intake is a way to decrease heat production in warm environments, as increasing heat consumption is an important source of heat production in ruminants (Kadzere et al., 2002). When the THI increased from 67 to 72, the birth and weaning weights of the calves decreased by 3.5 and 25 kg, respectively, due to a reduction in feed intake in Fogera cattle at the Metekel ranch (Abera et al., 2021b).

3.3.3. Effect of heat stress on growth performance

Temperatures ranging between 15°C and 29°C do not seem to have any effect on growth performance. The effects of high ambient temperature on growth performance are induced by a decrease in anabolic activity and an increase in tissue catabolism (Marai et al., 2007). This decrease in anabolism is essentially caused by a decrease in voluntary feed intake of the main nutrients. The increase in tissue catabolism occurs mainly in fat depots and/or lean body mass. Abera et al. (2021b) also reported that the birth weight of Fogera cattle significantly decreased over time from 2005--2019, which resulted in an increase in THI over these years that affected the dams and indirectly contributed to a decrease in the birth weight of the calves (Figure 2).

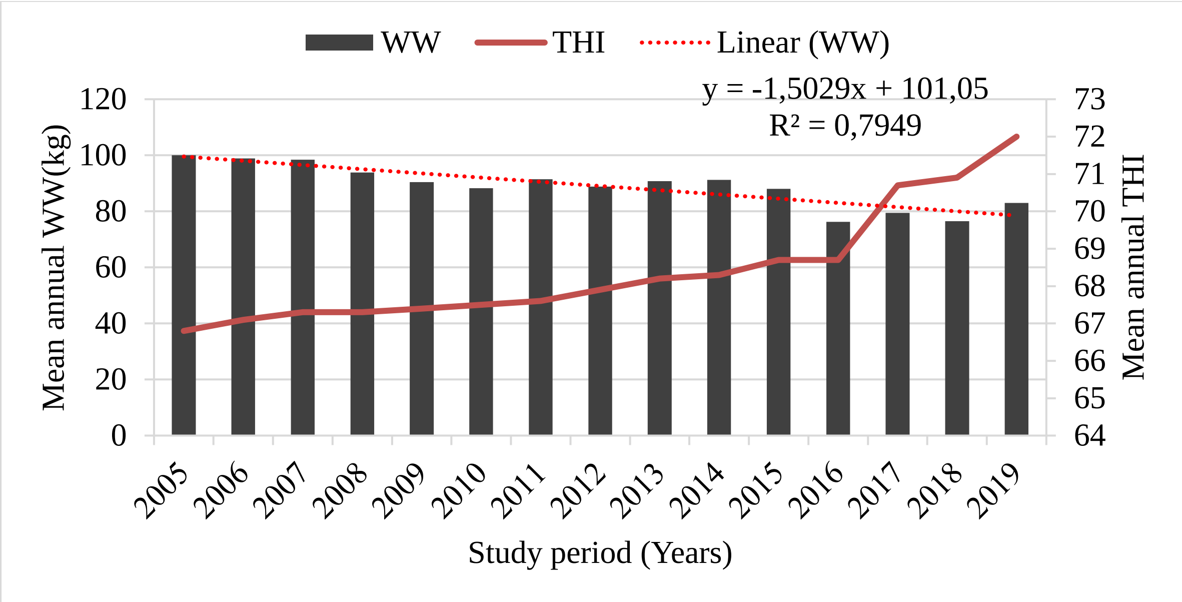

Figure 2 Trends in the mean annual weaning weight of Fogera cattle and the THI over the last 15 years.

4. Strategies for Ameliorating Heat Stress

4.1. Physical modifications of the environment

Among the acclimatization techniques, shading has an important role in reducing the radiant heat load on animals (Souza et al., 2010). Water sprinkling is also an important technique that aims to speed up heat exchange during the evaporation process (Cerutt et al., 2013). An adiabatic evaporative cooling system (AECS), which combines ventilation and air humidification via sprinklers, is a technique that has been used successfully in maintaining pen acclimatization and has shown satisfactory results in reducing the internal temperature of facilities and improving comfort conditions (Almeida et al., 2013). To validate an acclimatization strategy in the dairy industry, the AECS needs to benefit the animal environment, which can be assessed by thermal comfort indices (Kapa and Reddy, 2017). In this sense, the temperature–humidity index (THI), black globe temperature–humidity index (BGTHI) and radiant heat load (RHL) are the most commonly used thermal comfort indices and are highly correlated with physiological responses that indicate HS (Avila et al., 2013). When the THI exceeds 72, cows are likely to experience HS, and their in-calf rates are affected. When the THI exceeds 78, cow milk production is severely affected. When the THI increases above 82, very significant losses in milk production are likely, and cows show signs of severe stress and may ultimately die (Grandin, 2016).

4.2. Nutritional management

Rations should be greater than 18% protein on a dry basis, as overfeeding requires more energy to excrete excess nitrogen as urea. Optimizing undegraded protein in the rumen improves milk yield in hot climates (West, 1999). DMI and milk yield increased for cows fed diets containing 14% versus those fed diets containing 17% or 21% acid detergent fiber (ADF). However, milk yield was less sensitive to changes in dairy temperature for cows fed a 14% ADF diet (West, 2003). Increasing dietary fat content enhances milk production efficiency and yield in the warm season (Atrian and Shahryar, 2012). Compared with propionate, feed containing low fiber ratios during hot weather is logical since heat production is highly associated with the metabolism of acetate (Atrian and Shahryar, 2012). Heat stress in livestock, particularly in dairy cattle can significantly affect productivity, health, and overall welfare. Specific feed formulations and additives have been found to help mitigate the effects of heat stress by supporting metabolism, improving feed intake, or enhancing overall resilience. Probiotics can improve gut health, boost immune function, and help in nutrient absorption. Heat stress can lead to reduced appetite and digestion efficiency, but probiotics support gut flora and digestive processes. Studies shows that *Lactobacillus* spp. strains have been shown to help maintain rumen function and reduce the negative impacts of heat stress on dairy cows. *Saccharomyces cerevisiae* (yeast) supplementation in poultry has been shown to improve growth performance, feed intake, and gut health during heat stress periods. Moreover, Omega-3 fatty acids, such as alpha-linolenic acid (ALA), eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA), can help mitigate inflammation and oxidative stress that are elevated during heat stress. Additionally, omega-3s can improve the thermoregulatory processes of animals. Studies in dairy cattle show that adding sodium bicarbonate and potassium chloride to the diet during summer months helps mitigate heat stress, leading to improved milk yield and reduced incidence of metabolic disorders. For dairy cows, amino acids like methionine supplementation helps maintain milk protein content and overall milk production under heat stress conditions. Incorporating these feed additives and strategies into livestock management during periods of heat stress can significantly help maintain animal health, productivity, and overall welfare. The exact formulation and combination of additives depend on the species, environmental conditions, and specific farm needs.

4.3. Genetic selection and breeding

Differences in thermal tolerance exist between livestock species and provide clues or tools for selecting thermotolerant animals via genetic tools. Identifying heat-tolerant animals within high-performing breeds is only beneficial if these animals are able to sustain both high productivity and survivability under heat stress conditions. It is well known that Friesian Holstein milk reduces production when temperatures are consistently greater than 21°C (Ghosh et al., 2006), and fertility and longevity also decline (West, 2003; Santana et al., 2015; Carabaño et al., 2017). Cattle with shorter, thicker hairs and lighter coat colors demonstrate greater adaptability to hot climates compared to those with longer, thinner hairs and darker coats (Bernabucci et al., 2010). This phenotype has been characterized in *B. taurus* tropical cattle (Sene pol and Carona), and this dominant gene is associated with an increased sweating rate, lower RT, and lower RR in homozygous cattle under hot conditions (Mariasegaram et al., 2007). Florida Cow Project, initiated in the 1970s, focused on selecting dairy cattle for improved heat tolerance in the hot and humid conditions of Florida shows that through selective breeding, researchers focused on cows that showed better thermoregulation, reduced p anting, and more efficient heat dissipation. The program resulted in a herd of Holsteins with significantly better performance in terms of milk production and health during the summer months. The researchers found that there was a 10–15% increase in milk production compared to the general population of Holsteins in Florida. Moreover, the Australian Dairy Herd Improvement Scheme (ADHIS) includes heat tolerance as a key trait in breeding decisions. Researchers and breeders have focused on traits like the ability to sweat, reduced panting, and higher body temperature thresholds. Selection for heat tolerance also led to better overall animal health and reduced the occurrence of heat-related disorders such as mastitis. The Australian program has contributed to a 5-10% improvement in milk production in high-temperature environments.

4.4. Isolation and characterization of candidate genes for reducing heat stress

A heat shock gene related to thermotolerance was identified and is used as a marker in marker-assisted selection and genome-wide selection to develop thermotolerant bulls that are used in breeding programs. The major families of Hsps are Hsp100, Hsp90, Hsp70, Hsp60, and Hsp40. HSPs play a critical role in the recovery of cells from stress, in cytoprotection, and in guarding cells against subsequent insults. HSP gene expression under thermal stress conditions includes (i) activation of heat shock transcription factor 1 (HSF1); (ii) increased expression of Hsp genes and decreased expression and synthesis of other proteins; (iii) increased glucose and amino acid oxidation and reduced fatty acid metabolism; (iv) endocrine system activation of the stress response; and (v) immune system activation via extracellular secretion of heat shock proteins (HSPs). If stress persists, these gene expression changes lead to an altered physiological state referred to as “acclimation,” a process largely controlled by the endocrine system (Collier et al., 2008). The community of animal breeders must be able to drive the livestock population to conjugate quality and efficiency of production in different challenging environments under continuous evolution by using modern tools such as artificial intelligence, epigenomics, and possibly genome editing via a holistic and cost-effective approach (Maggiolino et al., 2020).

Emerging technologies like genome editing and epigenomics hold significant potential to accelerate the development of heat-tolerant dairy breeds. These technologies offer precise, targeted approaches to enhancing desirable traits such as heat tolerance, which is crucial in maintaining dairy productivity under the increasing pressures of climate change. Genome editing tools like CRISPR/Cas9 allow scientists to make precise changes to an organism's DNA, offering a powerful method for developing heat-tolerant cattle by directly editing genes associated with thermoregulation, sweat production, and stress response. Epigenomics involves the study of changes in gene expression or cellular phenotype caused by mechanisms other than changes in the DNA sequence itself. These epigenetic changes can be influenced by environmental factors like heat stress, and in turn, they could provide valuable insights into how animals adapt to their environments. By studying the epigenetic changes that occur in response to heat stress, researchers could identify epigenetic markers associated with heat tolerance. For example, methylation patterns on genes involved in stress responses or thermoregulation could provide targets for selective breeding or even direct manipulation. Heat stress can lead to changes in gene expression that help animals cope with temperature extremes. By understanding which epigenetic modifications are most beneficial for heat tolerance, breeders could select animals with favorable epigenetic profiles or use epigenetic editing to induce these changes. One of the fascinating aspects of epigenomics is that some epigenetic changes can be passed down to offspring, potentially leading to the development of heat-tolerant traits in future generations without altering the underlying DNA sequence. This could accelerate the adaptation of dairy breeds to changing climates. Heat tolerance may not only be an inherited trait but could also be influenced by the environment of the mother during pregnancy. By exploring epigenetic changes in response to maternal heat stress, breeders could identify ways to enhance the heat tolerance of offspring, even before birth. Unlike genetic modifications, epigenetic changes may not require altering the animal's DNA, which can be more palatable from a regulatory or ethical standpoint. Epigenomics provides a mechanism to understand how cattle adapt to environmental stressors, making it possible to identify and enhance traits that are beneficial for coping with heat stress.Epigenetic changes can occur rapidly in response to environmental conditions, offering a way to adapt cattle to changing climates faster than traditional breeding alone. Emerging technologies like genome editing and epigenomics offer transformative potential to accelerate the development of heat-tolerant dairy breeds. By leveraging these tools, breeders can target specific traits that improve thermoregulation, metabolic efficiency, and stress resilience. Combined with traditional breeding methods, these technologies could enable faster adaptation of dairy cattle to the challenges posed by climate change, ensuring the sustainability and productivity of dairy farming in increasingly hot environments.

The identification of SNP and the study of HSPs are crucial advancements in the field of animal breeding, particularly for enhancing heat tolerance in dairy cattle. These discoveries can be effectively integrated into marker-assisted selection (MAS) and genomic selection (GS) frameworks to accelerate the development of heat-tolerant breeds. SNPs are variations at a single base pair position in the DNA sequence, and they are the most common type of genetic variation in livestock. SNPs located in or near genes associated with heat tolerance can serve as powerful genetic markers in breeding programs. These SNPs can help identify animals with favorable alleles related to thermoregulation, stress response, and other heat-tolerant traits. On the other hand, HSPs are molecular chaperones that help protect cells from stress caused by high temperatures by facilitating the proper folding of proteins and preventing cellular damage. The expression of certain HSPs is critical for maintaining cellular function under heat stress, making them key to understanding heat tolerance in animals. The integration of SNP and HSP-related data into MAS and GS can provide a more holistic approach to selecting for heat tolerance in dairy cattle. By targeting both the genetic markers (SNPs) that influence thermoregulation and the molecular mechanisms (HSP expression) that protect cattle during heat stress, breeders can enhance the overall resilience of their herds. The findings on SNPs and HSPs offer powerful tools for improving heat tolerance in dairy cattle. By integrating these insights into MAS and GS, breeders can accelerate the development of cattle that are better suited to coping with the challenges of heat stress. SNPs provide precise genetic markers, while HSPs offer a functional mechanism to enhance cellular resilience during heat stress. Together, these approaches enable breeders to select for animals with both superior genetic potential and enhanced biological capacity to withstand heat, ensuring greater productivity and animal welfare in increasingly warm environments.

5. Implications for the Design of Animal Breeding Strategies

Exposing animals to an environment without any acclimatization inside a holding pen reflects negative responses to physiological variables, leading to a situation of HS. Therefore, for any improvement to be made in dairy cattle, environmental factors should be considered along with necessary amelioration activities. Several reports have shown the associations of SNPs in HSP genes with the thermal stress response and tolerance in farm animals. Therefore, identifying these genes associated with thermotolerance and using them as markers in breeding programs or for marker-assisted selection should be applied to identify animals adapted to thermal stress while considering genotype–environment interactions (G × E) and increased productivity. From this review point of view, future research should focus on conservation strategies for locally adaptable breeds with optimum productivity. Moreover, a breeding strategy that considers disease resistance, environmental stress, and adaptation traits should be considered in the future. Furthermore, the regular prediction of environmental stress resulting from climate change and the design of pertinent response strategies are essential for reducing the adverse impacts of environmental stress to increase the resilience capacity of dairy cattle breeds. Moreover, to promote the conservation of heat-tolerant native breeds, policies and incentives should be designed to address both environmental and economic challenges while recognizing the unique qualities of these breeds. By combining financial support, research, awareness, and market development, policies and incentives can create an environment where heat-tolerant native breeds thrive, contributing to more resilient agricultural systems in the face of climate change.

Ethical Considerations

Not Applicable.

Conflict of Interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

The author declares that the study was not supported by any organizations.

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