Effects of heat stress on ruminant physiological changes in dry arid regions: a review

OSAMA ANWER SAEED[1]*, NIDHAL KHALEEFA AHMED[2], HASSAN MUTHANA ALNORI[1] AND FARIS MAHMOUD ALI[3]

[1] Department of Animal Production, College of Agriculture, University of Anbar, Anbar, Ramadi, Iraq
[2] General Directorate for Education of Anbar, Ministry of Education, Anbar, Ramadi, Iraq
[3] Division of Al-Qaim Agriculture, Directory of Al-Anbar Agriculture, Ministry of Agriculture Ramadi, Iraq

SUMMARY

Heat stress in ruminants can have a profound effect on their bodies. Every part of the body is affected in some way, and it's an entirely caused systemic disorder. The characteristics of the animal, the environment, and the way the animal is managed all have an effect on the type and magnitude of the reaction. The development of effective measures to address heat stress (HS) has proven challenging due to the complex nature of the stress and the diverse array of ruminant production systems. The present matter has acquired significant urgency due to the ongoing expansion of the global economy and the concurrent rise in global temperatures. The objective of this study was to examine the physiological mechanisms employed by ruminant animals inhabiting arid and semi-arid regions in order to mitigate the effects of HS. The responses provided can be categorized into three distinct groups: the reduction of feed intake to decrease the production of metabolic heat, the enhancement of heat-loss capacity, and the activation of hormones, enzymes, and genes associated with heat tolerance. In light of HS, ruminant animals exhibit a decrease in their level of physical activity, feed consumption, and rumination, while concurrently increasing their water consumption, evaporative loss through sweating, respiration, panting, and rectal temperature (RT), in the specified sequence. The increased dissipation of heat caused by perspiration in ruminants would have made it unnecessary to have an elevated respiration rate. In order to meet the demands of perspiration and minimize the risk of respiratory alkalosis resulting from alveolar ventilation in the lungs, it is crucial to optimize the utilization of water and minerals in ruminant animals. Hormonal levels in the bloodstream are diminished due to HS, specifically affecting anabolic hormones like growth hormone, cortisol, triiodothyronine, and thyroxine. Ruminants exhibit discernible inclinations towards specific types of shade structures, contingent upon the characteristics of their immediate surroundings. Therefore, it is crucial to take these preferences into account when making well-informed decisions regarding heat mitigation strategies in agricultural environments. In conclusion, HS has a negative impact on ruminant physiology that reflects on productivity and welfare. With a better understanding of how HS affects livestock, researchers can come up with ways to manage it and show the need for more research on the topic of HS in livestock.

KEY WORDS

Enzymes, heat stress, ruminant, mitigation, physiological responses.

INTRODUCTION

Impacts of climate change include the deterioration of pasture and water resources, new pests and diseases that are more likely to be spread by livestock, an increase in drought periods, a rise in extreme weather events like heat waves, and an increase in financial burden for poor and marginal farmers. Ruminant species, namely cattle, sheep, and goats, play a crucial role in the establishment and maintenance of sustainable and ecologically responsible production systems in rural regions, particularly in areas characterized by extreme heat stress. Heat stress (HS) is a prevalent issue in various global regions, leading to detrimental effects on animal production and reproduction. The consequences encompassed by impaired production, reproduction, growth, milk quantity and quality, and the animal's innate immunity are the outcomes [1]. In the ruminant industry, HS can result in significant financial losses due to the negative effects it has on animal productivity, reproduction, health, and well-being [2]. Of particular concern is temperature, which is considered the main effective of HS. It has been observed that temperatures above 25 °C have a significant effect on feed intake and factor of physiological processes. The thermal comfort zone is influenced by various factors, including environmental humidity and air speed, genotype, physiological state, thermal susceptibility, acclimation, and diet. An animal's physiological and behavioral responses attempt to keep the temperature stable by increasing heat loss and decreasing heat production. During thermoneutral conditions, the core body temperature of cattle typically falls within the range of 38.0 to 39.3 °C [3], sheep from 38.5 to 39.5 °C [4], and goats from 38.3 to 40.0 °C [5].

Different animals have different physiological and behavioral responses to HS due to differences in their genes and the environment. These differences are caused by the interaction of many systems and organs, including the behavioral, cardiorespiratory, endocrine, and immune systems [6]. Because of

Corresponding Author:
Osama Anwer Saeed (osama_anwr85@uoanbar.edu.iq).

HS, the body's neuronal and neurohormonal systems are activated, including the immune system, to meet environmental demands. Both the severity of the stress response and its long-term health consequences depend on how well these systems are stimulated. That is to say, physiological and behavioral abnormalities are merely mechanisms by which animals adapt to a threat to their homeostasis. However, stress hormones and gene expression patterns are differentially regulated in ruminants so that they can recover from the harmful effects of HS. The hypothalamus plays a key role in the body's ability to deal with these conditions by coordinating a variety of physiological responses. Regrading, excessive sweating and increased peripheral circulation are two methods for dissipating heat from the skin [3]. Furthermore, endocrine system dysfunction can result from prolonged stress on the body's gene expression system [7]. Stressed animals undergo a cascade of physiological changes, including decreased feed intake and efficiency as well as altered mineral and nutrient balances, altered enzymatic activity as well as hormonal secretions, and blood metabolic products that ultimately lead to reduced reproductive and productive abilities [8]. With respect to thermoregulation, each species' unique characteristics and the critical role each agency's mechanisms play in maintaining production and ensuring its survival in the face of extreme heat. Therefore, the purpose of this review is to better understand the physiological responses of ruminants exposed to heat stress.

Climate in arid and semi-arid areas

In agriculture, weather conditions are extremely important. Changes in climate have put agriculture's productivity at risk, making it both economically and physically vulnerable. However, dryland areas (arid and semi-arid) make up more than 40% of the world's land area and support approximately 50% of livestock and 45% of food production [9]. About 15% of the Earth's land surface and 14.4% of the global population live in semi-arid regions [10], while the rest is represented by the arid regions. Additionally, a study has revealed that the arid and semi-arid regions constitute approximately 36% of the total land area on Earth [11]. Thermo-hygrometric indices are employed for evaluating the thermal conditions experienced by ruminant animals, taking into account the prevailing ambient temperature and relative humidity. The temperature-humidity index (THI) is a measure that represents the combined impact of air temperature and relative humidity on the thermal stress experienced by ruminant animals [12]. Semi-arid regions, commonly known as dry regions, are characterized by temperatures ranging from 30 to 45 ˚C during the hottest months [13]. The occurrence of thermal stress in animals can be attributed to various environmental factors, including air temperature, humidity, wind speed, and solar radiation. Ideal climatic conditions for livestock would include a temperature range of 13 to 20 °C, a wind speed ranging from 5 to 18 km/h, a relative humidity range of 55 to 65%, and a moderate level of sunshine [8]. Finally, it is plausible that regional land surface processes may also contribute to the accelerated warming observed in arid and semiarid regions.

Physiologic reactions to heat stress

Animals exhibit adaptive responses by altering their behavior and physiological processes to enhance their chances of survival in challenging environmental circumstances. Thermal dissipation serves as a crucial mechanism through which organisms uphold a consistent internal body temperature in the face of heat stress. Various physiological responses, such as perspiration, elevated respiratory rates, vasodilation resulting in heightened blood circulation to the skin, diminished metabolic rates, reduced dry matter intake (DMI), and modified water metabolism, collectively exert detrimental effects on the production and reproductive capabilities of cows [14]. Within the category of ruminants, the process of evaporative cooling is predominantly accomplished through the mechanisms of sweating and panting, with sweating being the more prominent of the two physiological responses. The phenomenon of heat stress promptly affects various physiological parameters, including respiration rate (RR), heart rate (HR), and rectal temperature (RT) [15,16]. Heat stress can cause an animal's RR to increase, allowing more heat to be dissipated into the atmosphere (Figure 1).

An instance of elevated ambient temperatures leads to an augmentation in the dissipation of surplus body heat in sheep and goats as a compensatory response to the excessive heat load [17]. Excess body heat is not dissipated due to the evaporation of water from the respiratory tract and skin surface, respectively, during respiration and perspiration. Sheep may also be able to adjust their body temperature and water deprivation every day by increasing their RR, HR, and panting score in the morning [18]. However, when an animal's physiological mechanisms are unable to compensate for an excessive heat load, the RT rises [19,20]. They may experience an increase in their RT under conditions of thermal stress [16]. Sejian et al. [21] stated that the Morada Nova ewes (acclimatized to Brazilian conditions) were able to maintain normal RR at an ambient temperature of 32°C as a result of their greater adaptability, but an increase in HR and RT were found in farm animals during the summertime. One degree above the threshold temperature of 21.3 was associated with an increase in the rate of breathing of approximately 4.3 breaths per minute above the baseline, which was equal to 60 breaths per minute [22]. Low respiration and HR during high THI conditions indicate that goats have a greater tolerance for HS than other ruminants [23]. As a consequence of what was mentioned above, an increase in both RR and RT are typical of the physiologic responses of ruminants to HS [24]. However, during HS a ruminant's insulation and ability to get rid of heat are affected by the length of its fleece, as well as its coat and skin. It is thought that wool sheep can't sweat as well if their fleeces are longer than 40 mm and that *Bos indicus* cattle can better control their body temperature than *Bos taurus* cattle because their hair coats are shorter and more blood flows to their skin [25]. The earlier studies focused on physiological indices through external performance. But it did not show how the body is doing, especially with regard to blood parameters, gene expression, and hormones.

Hematological responses

The dehydration resulting from HS can have an impact on animals through alterations in various hematological parameters, including red blood cell (RBC) count, white blood cell (WBC) count, hemoglobin (Hb) levels, lymphocyte count, neutrophil count, eosinophil count, monocyte count, granulocyte count, packed cell volume (PCV), and blood pH [19,26,27]. Several studies have shown that as environmental temperature rises, total blood hemoglobin (Hb) levels fluctuate [26,27]. The observed rise in oxygen demand under stressful conditions was attributed to the increase in Hb concentration in the animals [21]. The advantages of increased oxygen enhanced oxygen delivery to tissues and higher thermal tolerance may necessitate the development of new breathing techniques. Thermally stressed

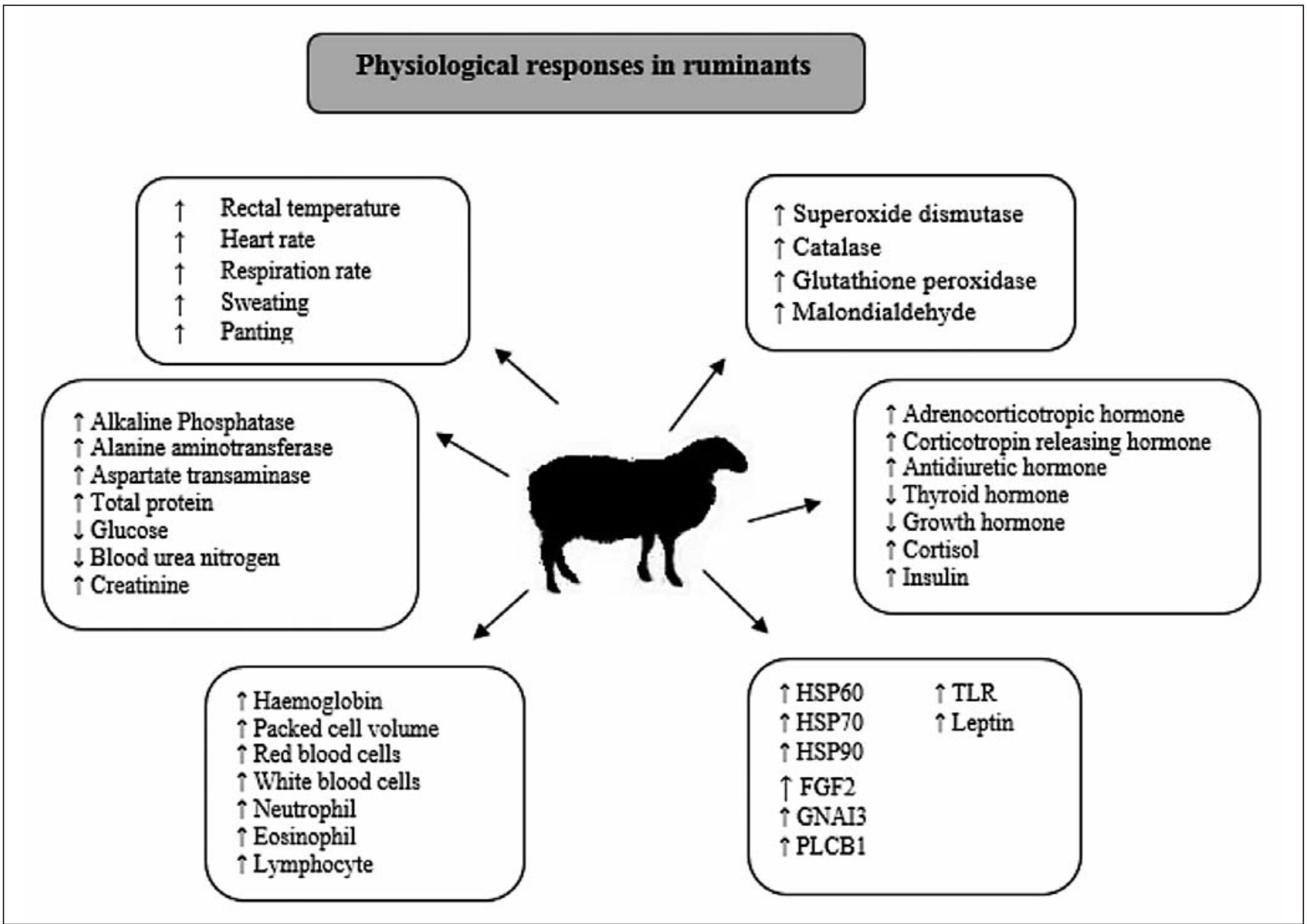

Figure 1 - Heat stress impacts on physiological status of ruminants adopted from [71] and [24].

Nigerian goats exhibited an elevated Hb value, which can be attributed to the heightened demand for hemoglobin to facilitate enhanced oxygen circulation during the process of panting [21, 28, 29]. Elevated PCV values serve as an adaptive mechanism in animals to facilitate the necessary water intake. This adaptation enables the transportation of a greater volume of water into the circulatory system, which is essential for facilitating evaporative cooling processes [28]. Carabaño et al. [30] confirmed that PCV could be a useful blood variable for assessing susceptibility to HS. Animals that are able to keep their PCV values stable despite being subjected to stressful conditions may be less susceptible to the effects of high temperatures. To enhance comprehension of the impact of HS on hematological variations, Alam et al. [31] observed that exposure of goats to HS resulted in elevated levels of RBC, PCV, Hb, WBC, neutrophils, eosinophils, lymphocytes, and monocytes.

Biochemical reactions

Heat stress has been found to have an impact on various biochemical parameters. These include alterations in alkaline phosphatase, alanine aminotransferase (ALT), aspartate transaminase (AST), lactate dehydrogenase, total protein, albumin, globulin, glucose, cholesterol, blood urea nitrogen, and creatinine levels [17, 19, 32]. The parameters under investigation were examined, and their findings did not yield conclusive results. However, our attention will be directed towards analyzing the most efficient outcomes. However, the lactating cow's metabolic response to the hot environment appears to be linked to an increase in creatinine levels in the serum at the peak of lactation [26]. Another study on Holstein cows by Koubkova et al. [33] found that total protein values increased significantly from 68.95 to 76.75 g/l during the hot period, then gradually decreased due to their rapid use in the process of gluconeogenesis. The same study also found that urea and glucose levels had significantly decreased. Low glucose levels may be attributed to a reduction in nutrient availability and a decreased rate of propionate synthesis. Alternatively, they may be a result of an elevated utilization of plasma glucose to meet the energy demands of muscles operating at a heightened metabolic rate, which is associated with an increased RR [32, 34, 35]. Probably, the decrease in glucose concentration in heat-stressed animals is a result of an increase in the concentration of circulating insulin at its basal level [34]. Contradictory results have been found in research on the effects of HS on glucose, cholesterol, and blood urea nitrogen. Under conditions of HS, there is a greater difference between the levels of glucose and cholesterol than there is in comfort zone [19]. Nevertheless, a recent investigation has unveiled an elevated concentration of AST in dairy cows during the summer dry period. This observation could potentially be attributed to the occurrence of oxidative stress. It is widely recognized that an increased concentration of AST in the blood serves as an indicator for the presence of postpartum hepatic steatosis 26. An elevation in the surrounding temperature is correlated with a rise in the process of lipid peroxidation. Thiobarbituric acid-reactive species (TBARS) and malondialdehyde (MDA) are commonly observed byproducts resulting from the peroxidation of polyunsaturated fatty acids. Previous studies have provided evidence that environmental heat stress has the potential to elevate the levels of TBARS and MDA in buffaloes and dairy cows. On the contrary, animals experience a decrease in glutathione, as well as vitamins E, C, and A, and ß-carotene. The observed decline can be attributed to the activation of cellular antioxidants, which serve to eliminate free radicals produced as a result of heat exposure and maintain stable levels of reactive oxygen species (ROS). Similarly, the high level of urea in heat-stressed animals may be the result of a low energy: protein ratio and gluconeogenesis caused by protein degradation under conditions of inadequate energy for growth [36].

Oxidative stress consequences

Reduced fertility is the result of oxidative stress and apoptosis, both of which are triggered by the accumulation of ROS in the cells brought on by HS [37]. The body produces antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx), which serve to safeguard against ROS that are generated during HS [38]. The antioxidants effectively eliminate both intracellular and extracellular superoxides while also inhibiting lipid peroxidation of the plasma membrane [39,40]. A study has indicated that the consequences of oxidative stress on various animal species are influenced by their unique thermal tolerances. The study observed variations in the production of SOD and erythrocytic lipid peroxidation (MDA) during the summer season[41]. The SOD converts superoxide to the less reactive form of hydrogen peroxide. Consequently, other enzymes (CAT and GPx) collaborated to eliminate the hydrogen peroxide produced by SOD and other potential sources [42]. However, thermal stress has been observed to have a negative impact on DMI, leading to a subsequent reduction in the production of antioxidants [43]. Consequently, the presence of antioxidants in the body is diminished relative to the levels of pro-oxidants, resulting in an imbalance between pro-oxidants and antioxidants. This imbalance ultimately gives rise to oxidative stress. The generation of oxidative stress relies not only on the augmentation of free radical production but also on the concurrent absence of a proportional increase in antioxidant production. In the event that the production of antioxidants fails to keep pace with the production of ROS [38], if the production of antioxidants remains stagnant, or even if it declines, the consequence will be the occurrence of oxidative stress. Several studies have demonstrated the significance of antioxidant supplementation in mitigating the effects of HS in ruminants [44-46]. Selenium is likely the most important trace mineral to support the cow's antioxidative defense during HS [43]. In another study conducted by Saeed and Khalaf [47], it was demonstrated that the RT of dairy cows can be safely maintained by inclusion 15% liquorice pulp to the concentrate diet.

Hormonal responses

Hormones are chemical messengers that the endocrine system uses to coordinate and control physiological processes. These are defined as chemicals that are produced by particular tissues and transported by the vascular system to act in any other tissue but that only act on target cells with particular receptors capable of responding to them [48]. There are a number of hormones involved in the process of thermal adaptation, some of which could serve as important stress indicators in animals. These include thyroxine (T_3), triiodothyronine (T_4), cortisol, leptin, and antidiuretic (ADH) hormones [47,49,50]. An adaptive response to HS is a decrease in T_3 levels, which affects the hypothalamo-pituitary-adrenal axis by decreasing thyrotropin-releasing hormone. This allows animals to lower their metabolic rates and heat production, as well as the amount of heat generated by their cells [19,28,51]. The anterior pituitary releases adrenocorticotropic hormone (ACTH) after the hypothalamo-pituitary-adrenal axis first releases corticotropin-releasing hormone (CRH) and ADH. The latter triggers the release of glucocorticoids from the adrenal cortex, which controls the level of the body's stress response, particularly cortisol. It also stimulates the adrenal medulla and sympathetic nerve terminals to secrete the hormones adrenaline and noradrenaline [52-54]. Plasma concentrations of T_3 decreased from 2.22 to 1.16 ng/ml in thermally acclimated cows, while T_4 decreased also [7]. This combination of decreased T_3 and plasma growth hormone has a synergistic effect on reducing heat production [49]. In ruminants, cortisol is the primary stress hormone, and activation of the hypothalamo-pituitary-adrenal axis may lead to increased production and release of cortisol [21]. However, Yousef et al. [55] reported that there was a lower level of plasma cortisol in calves housed under wooden-roofed sheds than in calves exposed to direct solar radiation. Furthermore, the distinct contrast between insulin levels under heat-stressed conditions and thermally neutral conditions suggests that the elevation in basal insulin levels is attributable to augmented pancreatic secretion rather than a reduction in insulin clearance from circulation[43].

Potential genes associated with heat stress

In response to elevated temperatures or various cellular stresses, both prokaryotes and eukaryotes exhibit the induction of a group of extensively conserved proteins referred to as heat shock proteins (HSPs). The cellular processes of gene transcription, RNA processing, and translation experience a decrease in their overall rates when cells are subjected to heat shock. The functionality of proteins that are produced is also modified, and there is a temporary increase in the expression of HSPs [8,50]. The cellular response encompasses the initiation of heat shock factors, upregulation of HSPs, enhanced oxidation of glucose and amino acids, decreased metabolism of fatty acids, and stimulation of the immune and endocrine systems via extracellular secretion of HSPs [56].

A variety of functions and cell locations distinguish the major mammalian HSPs, which include 60, 70, 90, and 100 that increase during HS [19,24]. Hooper et al. [57] reported that *HSP60* and *HSP70* gene expression was affected by solar radiation, indicating that these genes may have served as a defense mechanism against HS. In fact, *HSP70*'s typical biphasic expression pattern has the potential to both help animals withstand HS and serve as a biomarker for ruminant chronic HS [58]. The candidate genes *PGR* and *ASL*, *ACAT2* and *HSD17B7*, *ARL6IP1* and *SERPINE2*, and *ASL* and *PGR*, were identified as the genes that explained the most variation in RT, RR, and sweating rate, respectively [30]. While the *THR* gene is responsible for regulating the genomic actions of T_3 hormones in ruminants [59]. Kashyap et al. [60] reported an elevated blood expression of the *ATP1A1* gene in cattle breeds during the summer, suggesting a potential protective function against HS in cattle. Moreover, the aforementioned studies have indicated that the biological markers RR, RT, cortisol, *HSP70*, and *HSP90* gene expression could potentially serve as valuable tools for assessing the impact of various stressors on sheep and goats [21]. Several genes, including the thermo-tolerance genes *FGF2*, *GNAI3*, and *PLCB1*, have been linked to traits for adaptation to semi-arid and arid environments [61].

Table 1 - A selection of heat stress mitigation strategies for arid and semiarid regions.

Species	Region	Tools	Function	Authors
Cattle	Arid	Evaporative cooling regimes	Customizing cooling management to the thermal response of the cow can reduce heat stress.	Levit et al. [72]
Sheep	Semiarid	Shading facility	Improvements in reproductive efficiency and cooling pathways	Al-Dawood [73]
Goat	Arid and semiarid	Shade	Decreased respiratory rate and rectal temperature.	Aggarwal and Upadhyay [74]
Cattle	Arid and semiarid	Feeding management	18% is the upper limit for dietary crude protein during heat stress.	Huber et al. [75]
Cattle	Arid and semiarid	Roof height	Provide a minor influence on net radiation heat transfer.	Berman and Horovitz [76]
Cattle	Arid and semiarid	Sprinkler systems	Use huge water droplets to cool the cow, which reduces their reliance on the air's ability to hold water.	Collier et al. [77]
Sheep	Semiarid	Intensive system	Increase of heat tolerance and reduced the panting score.	Karthik et al. [78]
Goat	Arid	Feeding schedules	Modifications of rations can significantly assist in mitigating the detrimental effects of heat stress.	Sarangi [17]
Cattle	Arid and semiarid	Misters and fans	Cooled the vaginal temperature over the feed lines and stalls.	Weng et al. [79]
Sheep	Semiarid	Bedding	Reduce the moisture level in pens because of more urinate.	Collins et al. [80]
Livestock	Arid and semiarid	Wind protection	Assist ruminants' resistance in hot environments.	Hufana-Duran and Duran [81]
Sheep	Semiarid	Tree shade	Protection from direct sunlight exposure and a reduction in idle standing, panting when standing, and ruminating while standing.	De et al. [82]
Sheep	Arid	Type of breed	Select a breed that is more tolerant of heat stress situations than others.	Al-Thuwaini et al. [83]

Strategies of mitigation

Researchers have spent a lot of time and effort over the past few decades looking for HS management strategies that could reduce its effects. Stress mitigation has the potential to not only improve the economy of the livestock industry as a whole but also ensure the security of livelihoods for poor and marginal farmers. Therefore, it is absolutely necessary to have an understanding of the impact that environmental stress has on the production and reproduction of livestock. These efforts might help in identifying the appropriate targets in order to develop suitable strategies for mitigating their effects (Table 1). Consequently, in order to mitigate the adverse impacts of HS on ruminant production, practitioners have implemented a diverse range of strategies. These include the implementation of shading structures, adoption of specific feeding and grazing practices, ensuring adequate water availability, optimizing handling procedures, utilizing fans and evaporative cooling systems, as well as carefully selecting suitable locations for animal housing [19]. Schütz et al. [62] found that structures that provide shade, like trees, roofs, and fabric, can create microclimates that are better for ruminants because they block out more sunlight and cool the air around them. However, ruminants have distinct preferences for the type of shade structure based on environmental conditions, which must be taken into account when making decisions regarding heat mitigation on farms. Research has demonstrated that the provision of shade has a positive impact on the performance of animals in feedlots located in regions where the annual duration of temperatures exceeding 29.4 °C exceeds 700 hours. The effects in regions experiencing an annual solar radiation range of 500-700 hours are subject to variation and are contingent upon the specific year under consideration [63]. Kovács et al. [64] figured out that thermal variables correlated well with HS indicators in animals, and in the case of RT, all correlations were stronger in an unshaded thermal environment than in a shaded thermal environment.

As an essential molecule in the bodies of all vertebrates, water serves a variety of functions, including tissue tonicity, lubrication, thermoregulation, transport of nutrients, and excretion [43, 65]. Animals need constant access to adequate, clean, cool, and fresh water under HS conditions because their water needs are increased by HS conditions [19]. Under HS conditions, ruminants' feed intake and performance can be enhanced by diets designed for low metabolic heat increments [43]. There exist variations in the reactions of sheep and cattle towards thermal stress, as well as notable enhancements in the digestibility of dry matter and fiber constituents of alfalfa when provided to steers residing in an environment with a temperature of 32 °C, as opposed to 21 °C. Desert-adapted goats have a greater ability to digest high-fiber diets than goats from other environments [66]. Ruminants can be cooled in a variety of ways using the principles of convection, conduction, radiation, and evaporation [67]. The installation of fans will promote air movement, which will lower ambient temperatures, alleviate HS, and result in a reduction in RR, RT, and an increase in DMI; these benefits will be realized as a direct consequence of the installation of fans [68,69]. The heat generated by the movement of the muscles during the animal activity involved in handling and moving cattle raises the body temperature [63]. Although the act of relocating animals during the early morning hours has a negligible effect on heat load, it is advisable to refrain from doing so on days that are anticipated to have exceedingly high temperatures [70].

CONCLUSION

Elevated ambient temperatures exert detrimental effects on the physiological processes of ruminant animals. The impact of elevated relative humidity on thermal conditions amplifies the consequences of heat. Animals' biological processes, especially the production of anabolic hormones and enzymes, are severely impacted by prolonged exposure to high ambient temperatures. Ruminants have adapted defense mechanisms to buffer the blow to their health caused by these environmental stresses. Phenotypic responses, homeostatic responses to environmental change, and homeorhetic processes controlled by the endocrine system are all ways in which animals cope with stress. Researchers can help find solutions for controlling HS in livestock and raise awareness about the issue.

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Conflict of Interest
The authors declare that there were no conflicts of interest.

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