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FEED ADDITIVES SUPPLEMENTATION: A POTENTIAL STRATEGY TO AMELIORATE HEAT STRESS IN SHEEP – A REVIEW

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Abstract

Given a significant climate-flexible and socio-economic role in developing nations, environmental heat stress imposes a major financial impact on sheep production systems globally, endangering their production, reproduction, and growth. In this regard, the adverse effects of heat stress on sheep production systems have to be addressed through adoption of effective heat alleviation measures like animal management, nutritional management and genetic interventions of which the nutritional interventions seem to be the most cost effective way to alleviate heat stress. Nutritional manipulation for heat stress alleviation in sheep involves the use of antioxidant supplements (vitamin B; vitamin E and selenium; selenium; zinc sulphate and folic acid; vitamin C, vitamin E, selenium and zinc; naringin; *Opuntia ficus-indica* f. *inermis*; açai oil and brown seaweed like *Ascophyllum nodosum* and *Sargassum latifolium*). Further, electrolyte supplements (dietary electrolyte balance (DEB); sodium bicarbonate and potassium bicarbonate; sodium hydroxide) have a beneficial effect on thermal responses, respiratory activities, gas exchange parameters, rumen fermentation, blood buffering capacity and acid-base balance. The mineral mixture supplements (mineral blocks; mineral mixture and antioxidants; chromium; zinc) play a crucial role in increasing the efficiency of antioxidant defence system, immunity-related parameters, production, reproduction, feed digestibility and insulin sensitivity. Probiotic supplements (*Lactobacillus acidophilus*, *Saccharomyces cerevisiae*, *Propionibacterium freudenreichii*, *Lactobacillus casei*, *Enterococcus faecium*, *Lactobacillus lactis*, *Bacillus subtilis*, *Propionibacterium freudenreichii*, *Pediococcus cerevisiae*, *Megaspha eraelsdenii*, *Bacillus licheniformis*, *Aspergillus oryzae*, *Schizochytrium limacinum*, and *Trichoderma reesei)* improve lactational performance, dietary energy utilization and productivity. The probiotics (live *Saccharomyces cerevisiae*) and prebiotics (mannan oligosaccharide plus ß-glucans) used in heat stress alleviation improve dietary energy utilization. Furthermore, the vital role of herbal supplements (rosemary, cinnamon, turmeric, clove, naringin, chestnut tannins, giloy stem powder, curcumin, rocket oil (watercress oil), flaxseed, cornus, oregano, thyme, chamomile flowers, *Moringa oleifera*, betaine) has been highlighted to promote feed intake, antioxidant status, growth performance, feed utilization, reproductive performance and immune response. Effective adoption of nutritional strategies can thus ensure sustainable sheep production in this changing climate scenario.

Key words: climate change, feed supplements, heat stress, mitigation approach, sheep husbandry, sustainability

Climate change has been well established to be a concerning issue impacting the livestock sector alarmingly. This global climate emergency leads to multiple stress in livestock animals and is likely to increase in the future. Heat stress is reported to be the main stressor that has a detrimental impact on livestock productivity among them (Sejian et al., 2018). Heat stress challenges and strains the thermoregulatory system, which negatively influences the production of the animals. As per the United Nations population estimates and projections, the World Population Prospects 2019 reports that the global population is expected to reach 9.7 billion by 2050 and 10.9 billion by 2100 (UN, The World Population Prospects 2019) and in order to ensure food security in this population explosion scenario, strategic and systematic improvements are crucial to increase the efficiency of livestock production systems. In this regard, as a measure to address the chaotic demand imposed by the growing human population on livestock sector in this climate-challenging scenario, the small ruminant sector is emerging and widely accepted to be a sustainable solution. The small ruminants including the ovines and caprines are known for their efficiency to produce quality animal products using restricted resources; potent adaptive nature across diverse zones of agro-ecology; immense climate resilience and negligible eco-footprint (Sejian et al., 2021). Sheep in particular has been a fundamental livestock species that has been reared providing sustainable financial security to the rural community. By supplying varied products like meat, milk, wool, skin, horn, fibre, manure for fertilizer, and dung for fuel, they contribute significantly to the global economy. Sheep farming contributes to risk reduction and adaptation to climate variability in India, where more than 60% of the geographical area is covered by arid and semi- arid regions prone to drought and famine (Shinde and Sejian, 2013). Even though this species has the ability to sustain optimal production under heat stress conditions, the sheep industry is similarly vulnerable to its negative effects. Thus, a major interest of researchers around the globe is inclined towards improving knowledge of the adaptive mechanisms. Moreover, there is a significant rise in studies to frame efficient solutions using various approaches for heat stress mitigation in sheep. In particular, the nutritional intervention in amelioration of the adverse consequences of heat stress in sheep has been taken up. Hence, this review attempts to collate novel nutritional strategies employed in heat stress mitigation in sheep. The feed supplements adopted in diverse sheep production systems will be summarized to provide appropriate recommendations and farmer-friendly solutions.

Importance of small ruminants from farmer's perspective

Sheep and goats are opportunistic and have long served as key protein sources across the world. The value of sheep and goats extends beyond the obvious economic reasons. The economic role of small ruminants have been well established because they offer the simplest and most easily accessible form of credit for meeting urgent social and financial responsibilities of the resource poor producers. In this regard, small ruminant rearing plays a significant role in the livelihood of producers in developing nations and smallholder farmers, especially women. Small ruminants are extremely important for landless people, especially women, as evidenced by the tendency of their overall income share to be inversely correlated with the extent of land holding. Further, raising small ruminants would serve as a supplementary vocation to provide revenue and employment, as women are frequently denied the right to own property in certain cultural contexts and because agriculture (crop production) only offers seasonal work (Oluwatayo and Oluwatayo, 2012). Small ruminants thus ensure food, financial security and employment for rural women in addition to being the primary means of subsistence for the landless producers.

Small ruminants are raised in various agro-ecological systems and are typically regarded as a valuable resource for smallholders, playing an important cultural and economic role (Wodajo et al., 2020). Sheep and goats utilize a wide range of marginal land resources to produce a number of goods like meat, milk, wool, hair, hide and manure, which allows them to contribute efficiently to economic diversification. In addition, small ruminants have an efficient water conserving mechanism and have developed an effective water economy that allows them to continue producing and consuming dry matter even at high temperatures in periods of water scarcity. Small ruminants are equipped with water-saving mechanisms like reduced panting and respiration rate that contributes in minimizing water loss, boosting their capacity to survive dry periods (Jaber et al., 2013). More than half of all small ruminant populations worldwide are found in dry areas, demonstrating the tolerance and plasticity of small ruminants under such conditions and their potential suitability for future relocation to areas projected to experience rising temperatures (Monteiro et al., 2018).

There are several benefits that small ruminants have over large ruminants, which render them extremely significant. In addition to their broad adaptation to a variety of agro-ecological zones and their many distinctive qualities such as their high digestive efficiency for coarse roughages, water metabolism, greater tolerance to tannins, and resistance to disease, they also ensure food security and survival, which contributes to their socio-economic role. In addition, the small ruminants contribute to economic and ecological niche in small-scale farm systems and agriculture (Devendra, 2001). These ruminant species during dry seasons or semi-arid areas also have the capacity to excavate the soil in order to utilize underground portions of perennial plants and shoots to consume, suggesting efficient use of rearing systems (Sejian et al., 2017 a; Monteiro et al., 2018). Small ruminants have a distinct advantage in the livestock sector due to their size, prolificacy and low cost of production. Moreover, it has been considered that small ruminant livestock production can be utilized to promote policy reforms, development, and marketing channels, as well as serve as the focal point of value-added enterprises (Blackburn, 1992). Thus, it can be established to be a vehicle for economic and ecological growth and hence the potential for the rural community to exploit these animals are numerous in ecological and socio-economic aspects.

Small ruminants appear to be of significant importance from farmer's viewpoint and stand to be a promising sector due to their low cost of production, resistance to diseases, short generation interval, prolificacy, adaptability to small holdings, ability to use crop residues effectively, and resistance to extreme weather conditions compared to large ruminants. Furthermore, small ruminants serve as the primary source of sustenance and survival ensuring economic and food security for the resource depleted farmers. Thus, the small ruminants fulfil the social, economic, ecologic and cultural demands of the farmers and act as a relevant choice of sustainable livelihood resource in this climate change scenario.

Climate change as the most significant factor affecting sheep production

It is well established that climate change and the associated climate-related shocks pose to be a global threat.

According to the fifth assessment report by the Intergovernmental Panel on Climate Change (IPCC), Agriculture, Forestry and Other Land Use (AFOLU) sector accounts for about a quarter (~10–12 $GtCO_2eq/yr$) of the net anthropogenic greenhouse gas (GHG) emissions mainly from deforestation, agricultural emissions from soil and nutrient management and livestock (IPCC, 2014). In addition to being a contributing factor in the phenomena of climate change, the livestock production system, a subsector of agriculture is also vulnerable to its negative effects. The global climate change phenomenon intensifies and increases the frequency of extreme weather events, thereby amplifying the likelihood of climate disasters with serious effects on the agricultural systems. In this regard, the productivity of natural resources is declining due to climate change, which has major implications on agriculture sector (Marshall et al., 2016). It has been reported that climate change threatens livestock productivity by affecting feed crop and forage quality, water availability, animal and milk production, livestock diseases, animal reproduction and biodiversity (Rojas-Downing et al., 2017).

Global climate change is projected to alter air temperature, precipitation, water availability, and carbon dioxide levels in the atmosphere, affecting the productivity of meat and dairy systems (McManus et al., 2020). The predictions reveal that the global mean surface temperature would rise from 3.7°C to 4.8°C in 2100 compared to pre-industrial levels under baseline scenarios, excluding additional mitigation (IPCC, 2014). In this alarming scenario, it is reported that high ambient temperature will be the primary and important negative phenomenon of climate change affecting the sheep production sector. Other elements that will impact sheep husbandry include cyclones, droughts, exorbitant rains, weather fluctuations, and diseases (Gowane et al., 2017). The alteration in the weather variables cause several constraints that the sheep must cope as a means of survival and it includes heat and cold stress, water scarcity, low forage quality and quantity, parasite, pest, and disease prevalence that varies by ecological zone.

Climate change can affect sheep husbandry through changes in breed composition, population, feed and fodder scarcity, grazing land shrinkage, disease spread, market trends for wool and meat, reproductive and productive disorders, poor performance, and consumer demand (Shinde and Sejian, 2013). Animal productivity, including milk, meat, and reproduction, is greatly impacted by climate change and it can be attributed to the internal redirection of energy resources towards adaptation (Wanjala et al., 2023). Of the several environmental conditions that sheep experience in this climate change scenario, heat stress appears to significantly impair the animals' ability to produce, jeopardizing their growth, meat, milk and wool production (Sejian et al., 2017 a). Animals under heat stress conditions tend to restrict heat production by decreasing feed intake, which has a negative impact on production and reproduction (McManus et al., 2020). Thus, heat stress is becoming a significant limiting factor affecting sheep production in many parts of the world.

Economic consequences of heat stress on sheep production

Agriculture and animal husbandry employ more than 1.3 billion people and account for 40% of global Gross Domestic Product (GDP) and in the climate change associated population explosion scenario, the demand for livestock products is predicted to double by 2050 (Rojas-Downing et al., 2017; Wankar et al., 2021). By the year 2100, an increase in global surface temperature of 3.7–4.8°C has been anticipated (IPCC, 2014) and the extreme climatic circumstances caused by climate change will impose multiple stresses on sheep husbandry, negatively impacting their production capacity paving way to economic crisis.

Sheep husbandry is an important socio-economic activity in many nations globally, involving sheep rearing for protein and fibre resources (Lees et al., 2017). Given a significant socio-economic role in developing nations, environmental heat stress imposes a major financial impact on sheep production systems globally, endangering their productivity, reproduction, growth, and wellbeing (Slimen et al., 2019 a). Unprecedented weather variations in the past several years, such as persistently high temperatures and humidity, heat waves, and solar flares, have caused the milk and meat industries to suffer billion-dollar losses (Wankar et al., 2021). A study examined the effects of temperature on the level of GDP and revealed that each additional degree increase in temperature is associated with a statistically significant reduction of 8.9 percentage points of per capita GDP (Dell et al., 2009). The importance of drastic fluctuation in this weather variable is thus projected to be taken into serious consideration.

Heat stress in sheep triggers the peripheral thermal receptor, which transmits a suppressive nerve impulse to the hypothalamic appetite centre, resulting in a reduction in feed intake as an adaptive change to produce less body heat (Indu and Pareek, 2015). The study also reports that when ewes attempt for ways to adapt to heat stress, their development and physiological performances get compromised and this was evidenced as significant changes in body weight, body condition score, respiration rate, pulse rate and rectal temperature. This can therefore lead to decreased milk production, decreased reproductive efficiency, altered immune system function, and death (Cheng et al., 2022).

In this changing climate associated heat stress conditions, the extreme temperatures demand an increase in energy for sustenance of the animal, but the inadequate supply of forage with a compromised quality in grazing lands restricts the energy intake leading to energy crisis, nutritional stress and loss of production (Shinde and Sejian, 2013). Additionally, the concomitant and negative impact of climate change on disease incidence, parasite infection, and decreased pasture availability aggravates the efficiency of animals to produce meat, milk, and wool (Singh et al., 2012). Thus, heat stress has been identified as the primary impediment to animal productivity, causing significant economic harm by destabilizing production efficiency of the animals. These monetary losses are the result of long-term mortality as well as performance and productivity disruptions. Since the poorer segments of society own the majority of sheep, a decline in production might cause severe economic challenges in rural regions with serious implications on the national economy.

Impact of heat stress on sheep production

Heat stress is an intriguing component that impairs livestock production and reproductive performance. Globally, sheep livestock producers face a substantial financial burden due to heat stress associated production losses. Exposure to high ambient temperature causes a variety of dramatic alterations in animal biological systems. Heat stress affects ruminant animals by a combination of environmental conditions like high ambient temperature, relative humidity, high solar radiation, low wind speed, and precipitation (Al-Dawood, 2017). Exposure of animals to high ambient temperatures augments attempts to dissipate body heat, resulting in an increase in respiratory rate, body temperature, and water consumption, as well as a decrease in feed intake (Marai et al., 2007). Heat stress is one of the most destructive factors, affecting growth, productivity, reproductive performance, milk quantity and quality, and natural immunity, rendering animals more vulnerable to diseases and even death (Berihulay et al., 2019; Lacetera, 2019).

The negative impacts of heat stress in sheep are reflected evidently by causing impairment of various production traits. Their productive performance gets hampered as the animals attempt to adjust to the harsh climatic conditions, mostly as a result of the high energy required for adaptation processes (Indu et al., 2014). Animals experiencing heat waves endure severe changes in their biological processes, including reduced feed intake efficiency and utilization, imbalances in water, protein, energy, and minerals, enzymatic reactions, hormonal secretions, and blood metabolites, as a result of their physiological systems' inability to manage the extreme heat (Marai et al., 2007). Moreover, a heat stressed animal in its productive stage (growth, lactation) will show a drastic decrease in growth parameters due to a decrease in feed intake and internal heat generation (Silanikove, 2000). It has been reported that reduced anabolic activity and increased tissue catabolism are the effects of higher ambient temperature on growth performance. The primary reason of this decline in anabolism is a reduction in the voluntary feed intake of essential nutrients (Marai et al., 2007).

Environmental factors including heat stress have a negative impact on the immune system of the animals. It is widely reported that heat stress reduces animal immunity by causing the adaptive immune system to switch from cell-mediated to humoral immunity (Lacetera et al., 2005). Further, it has been suggested that the hypothalamo-pituitary-adrenal (HPA) axis is the primary mechanism by which the stress signal modulates the immunological response (Inbaraj et al., 2016). In this respect, evidences suggest that high ambient temperatures have a detrimental impact on sheep immunological functions (Sevi and Caroprese, 2012). Thus, the changes in immune status of the animal drives in serious health complications leading to compromised production in sheep.

Heat stress has a significant economic impact on the global dairy industry. Lactating sheep may have physiological and productive issues if the temperature rises beyond the critical threshold. Heat stress negatively impacts not only the milk quantity, but also the milk composition and quality (Finocchiaro et al., 2005). It is reported that heat stress decreases milk fat and protein content. In addition, high ambient temperatures can also result in plasma mineral imbalance, mainly due to the loss of sodium, potassium, calcium, and phosphorus and the increase in chloride concentration (Sevi and Caroprese, 2012).

It is well established that the sheep meat industry incurs production losses due to the negative impact of heat stress on meat production. According to research on Hu sheep, heat stress caused alterations in the rumen microbiota and the gene expression profiles of muscle, which hampered growth performance, carcass features, and meat quality (Zhang et al., 2024). Recent studies report that heat stress affects the carcass and meat quality traits likely by changing the rate and degree of post-mortem muscle glycolysis and the resulting pH (Zhang et al., 2020). These evidences strongly suggest that heat stress in sheep adversely affects its production performance and maintaining animals under hot and humid climatic conditions in the future will more likely require application of efficient heat abatement strategies.

Impact of heat stress on sheep adaptation

In comparison to large ruminants, small ruminants, are known to be highly suited to a variety of climatic conditions. Furthermore, the higher survival rates of sheep in harsh weather conditions such as drought or famine indicate that sheep will be an ideal animal for climate change adaptation in the coming years. In an attempt to survive the stressor, sheep adapts to negative environmental stresses like heat stress through morphological, behavioural, endocrine, blood biochemical, and cellular changes (Sejian et al., 2017 b). The combination of behavioural, morphological, and physiological adaptability plays a critical role in livestock for maintaining thermal and water balance (Cain et al., 2008).

The main behavioural responses of animals to adapt to the hot environmental condition include altered feeding, defecating and urinating frequency, water intake, lying time, standing time, shade seeking behaviour (Athira et al., 2017), open-mouthedpanting and increased salivation (Marcone et al., 2021). The behavioural responses of an animal to heat stress are crucial in influencing an animal's tolerance to temperature variations. Even though these behavioural changes appear voluntary, they are directed by specific changes in the internal environment of an animal (Sejian et al., 2017 b).

Morphological adaptations are physical alterations that take place in animals over many generations to improve their fitness in a particular environment (Berihulay et al., 2019). These include allometric features of the body such as body size and form, extremity design, skin characteristics (colour, thickness, distribution of sweat glands), and features of the hair coat (colour, thickness, absorption and reflectivity, and angle of hair arrangement to skin) (Sejian et al., 2017 b). These anatomical features also control the amount of heat lost from the animal body. Moreover, the primary morphological adaptations in sheep are body shape and size, coat and skin colour, hair type, and fat storage (Chedid et al., 2014). Compared to small sized animals, larger sized animals acquire heat more slowly and have a lower metabolic rate. Animals with long, slender appendages decrease radiant heat gain but enhance convective heat loss and these factors have a significant impact on an animal's rate of heat gain and loss (Berihulay et al., 2019).

According to Sejian et al. (2012 a), ewes subjected to three different types of stress – heat, nutrition and walking have elevated physiological parameters such rectal temperature, pulse rate, respiration rate, and sweating rate. These changes are the result of thermoregulatory adaptations made to maintain homeostasis. Dissipation of excess body heat is accomplished by evaporation of water from the respiratory tract and skin surface via panting and sweating, respectively. Because the sheep have a wool coat, their ability to sweat is significantly reduced. The ears and legs lose a significant amount of heat as the temperature rises to 36°C. Moreover, the rectal temperature rises when the animal's physiological systems are unable to counteract the high heat load (Marai et al., 2007). This rise in body temperature may be the cause of changes in the blood circulation system (Rashid et al., 2013). Rectal temperature in sheep also serves as an indication of several stressors (Sejian et al., 2017 b). In addition, feeding and rumination time can also be a significant physiological indicator in heat stressed sheep (Rashid et al., 2013). Increased pulse rate and skin temperature in heat stressed animals may be caused by skin capillary bed vasodilatation, which increases blood flow to body surface regions to aid in heat dissipation. Higher respiratory rate may be an adaptive process of heat loss (Wojtas et al., 2014).

It is well established that the cellular components in blood and other metabolites show significant alterations under heat stress conditions. Many studies in sheep have reported that blood cellular components such as haemoglobin level, PCV value, WBC count, and RBC counts were all increased in response to elevated temperature (Rashid et al., 2013; Aatish et al., 2007). During heat stress conditions, the combined effects of the limited water intake and increased evaporative loss result in haemoconcentration, which in turn leads to elevated levels of packed cell volume (PCV) and haemoglobin in ewes (Sejian et al., 2017 b). A considerable alteration in blood metabolites such as blood urea nitrogen, uric acid, plasma glucose, and aspartate aminotransferase levels in heat stressed sheep has been reported (Rashid et al., 2013).

It has been reported in sheep that increased energy expenditure and reduced feed accessibility altered blood biochemical markers including albumin, glucose, cholesterol, protein, and globulin (Sejian et al., 2017 b). Similarly, other studies suggested that a reduction in feed consumption in heat stressed animals is the cause of decrease in cholesterol and glucose levels (Rashid et al., 2013; Indu et al., 2014). The higher levels of serum ALT and AST that were seen under heat stress conditions might be attributed to either an increase in gluconeogenesis or to some deleterious effect of heat stress on liver function (Rashid et al., 2013; Wojtas et al., 2014). In addition, the endocrine profile is also subjected to variations under heat stress conditions and the primary indicators of changes in the hormonal profile are a decrease in anabolic and an increase in catabolic hormones (Bernabucci et al., 2010).

The cellular adaptation of the animal is varied and it has been demonstrated that heat stress impairs the integrity and fluidity of cellular membranes and prevents the function of transmembrane transport proteins and receptors. In fact, research has demonstrated that heat stress alters the structure of the cytoskeleton in a number of ways, affecting the cell shape, the mitotic apparatus, and intra-cytoplasmic membranes like lysosomes and the endoplasmic reticulum (Belhadj Slimen et al., 2016). These changes alter many molecular functions in heat stressed animals. Moreover, according to Li et al. (2019 a), heat stress in sheep promotes organ damage, inhibits biogenesis, increases ROS production, weakens the antioxidant system, compromises innate immunity, and triggers apoptosis. Other responses include release of heat shock proteins (HSPs), which typically enter the blood circulation following tissue injury (Abdelnour et al., 2019).

The above discussed adjustments can thereby make it easier for the sheep to adapt to the elevated temperature and harsh environmental conditions. Thus, comprehending the adaptation efforts of animals to heat stress might aid in understanding the mechanisms involved in successful production situations.

Different approaches for relieving heat stress in sheep

Ruminants fail to maintain homeostasis under heat stress, even if their thermoregulation systems are highly developed. Regardless of breed or adaption stage, there is unquestionable proof that hyperthermia is detrimental to production. As a result, heat stress causes significant financial losses, underscoring the need for effective mitigation strategies.

Genetic strategies

Management and nutritional strategies are short-term heat stress mitigation options and are production system-specific depending on the profitability. However, the genetic manipulation contrastingly is a long-term solution and is suggested to be more rewarding as it modifies animal flocks and herds in a way that is cumulative and permanent (Osei-Amponsah et al., 2019). Under rising pressures and a changing climate, genetic improvements in sheep for climate-stress-related tolerance or resistance will be a key component in the implementation of sustainable sheep production systems (Li et al., 2019 b).

Following the advancement of biotechnological tools characterizing gene expression and identifying important cellular responses to heat stress are made possible. Genetic and bioinformatic tools are creating opportunities to identify and improve the thermo-tolerant capability of heat stressed animals. The identification of sheep breeds appropriate to agro-ecological zones can aid in providing local farmers with the best possible economic return through climate-resilient breed dissemination. Further, as reported in studies using goats, the novel next generation sequencing technologies like skin metagenomics, skin transcriptomics and skin epigenetic changes can aid in identifying climate resilient animals (Silpa et al., 2022). It has been reported that one sustainable way to reduce the impact of climate change on ruminant production is through genetic selection and the breeding of thermotolerant animals (Osei Amponsah et al., 2019). Thus, these advanced technologies can be adopted effectively in bringing genetic improvements in this climate change scenario and ensure sustainable sheep production.

Management

Alternative management strategies have been developed to mitigate heat stress impacts and to improve production. It has been suggested that the production capacity of the flock under heat stress conditions can be improved by implementing efficient management techniques, such as housing, animal care, and climate monitoring (Lees et al., 2017). Management measures such as shearing of wool prior to onset of summer; provision of clean, fresh and cool water; access to shade with good ventilation regimes; stall feeding; feed administration in late afternoon and provision of sprinklers and cooling devices can be simple and effective in alleviating heat stress in sheep (Caroprese et al., 2012; Lees et al., 2017). Further, it has been reported that in barns and comparable buildings, it is essential to install fans or other cooling devices (Sejian et al., 2015). Thus, appropriate microclimate facility for the sheep has to be set up in production systems in order to ensure optimal production.

The other animal management practice that is suggested to be adopted is proper handling of the animal (transport, shearing, sorting) as it exerts a considerable influence on the productivity of the animal (Beatty et al., 2008). Reproductive management practice through effective utilization of advanced techniques to lessen the effect of heat stress on fertility, such as timed mating programmes during summer can be adopted (Al-Dawood, 2017). It is also important to select appropriate breeds based on thermo-tolerant ability and it is crucial to acknowledge the influence of wool colour and coat characteristics associated with the thermo-tolerance of sheep (Lees et al., 2017).

Long-term protective benefits will result from careful selection of the housing location to emphasize elements that maximize heat dissipation, such as low radiation, air temperature and humidity, and maximal air velocity (Sejian et al., 2015). According to Gaughan et al. (2008), it is suggested that developing a few thermal indices and forecasting climatic conditions, mitigation measures for heat stress- related issues can be implemented. Mitigation of the adverse impact of heat stress on animal production can be achieved by adopting effective farmer-friendly management practices. Better management of heat stressed animals may reduce the initiation of thermoregulatory mechanisms, allowing for better energy utilization for growth and/or production.

Nutritional intervention

It is crucial that animals must be protected from the stress by providing optimal nutrition as these conditions have the potential to either directly increase nutritional requirements or decrease the availability of high-quality feed (Soren, 2012). The adaptive mechanisms such as sweating, respiration, hormone production, and cellular defence used to deal with elevated core temperatures can also lead to an increase in energy needs in heat stressed sheep (DiGiacomo et al., 2022). Reduced feed intake under heat stress increases the need for energy and micronutrients, which can cause micronutrient shortages and altered metabolism, which in turn reduces growth performance (Dunshea et al., 2017). Moreover, heat waves compromise the availability of quality feed in addition to water shortage and it is crucial to consider these indirect adverse effects as feed and water restrictions aggravate the heat stress responses in animals (Slimen et al., 2019 a).

A number of recent studies provided data that shed light on the many nuances of nutritional interventions aimed at reducing the negative effects of heat stress in sheep (Table 1). There are many economically viable dietary modification strategies that can be adopted for effective heat stress abatement. It has been reported that changes in feeding schedules (feeding at cool hours, feeding intervals), grazing time, ration composition (dietary fibre adjustment, use of high-quality fibre forage, increased energy density (supplemental protected fat) and the use of feed additives, such as yeast culture, niacin, buffers (sodium bicarbonate), and fungal culture can all significantly lessen the harmful effects of heat stress (Al-Dawood, 2017). It has been suggested that an effective dietary approach for countering the lower dry matter intake in regions with high temperatures is to consume more protein, energy-dense foods, and essential amino acids (Conte et al., 2018).

Table 1. Applications of different types of feed supplements for heat stress amelioration in sheep

Type of feed supplement	Breed	Age group	Dose	Beneficial effect	Reference
1	2	3	4	5	6
Antioxidant supplements					
A. Vitamin B	Adult Ossimi rams	13–14 months	Vitamin B_1 – 100 mg Vitamin B_6 – 40 mg Vitamin B_{12} – 1000 µg	■ Improved rectal and scrotal skin temperature; libido; semen quality and fertility	(El-Darawany, 1999)
B. Selenium (sodium selenate)	Australian Merino wethers	9 months	5 mg/week	■ Alleviates heat stress effects on rectal temperature and body weight loss	(Alhidary et al., 2012)
C. Selenium (inorganic and organic)	Farafra and Saidi sheep	2–4 years	Inorganic Se: 0.3 mg/kg diet sodium selenite	■ Alleviates heat stress effects on physiological responses	(Hayder et al., 2016)
			Organic Se: 0.3 mg/kg diet selenium yeast	■ Improves reproductive performance	
D. Selenium enriched with *Saccharomyces cerevisiae* yeast	Ewes	-	0.3 mg Se/kg	■ Reverses the reduced antioxidant capability and immune function	(Ashrafi et al., 2024)
E. Vitamin E and selenium	Australian Merino wethers	7 months	0.8 mg/kg – Se; 150 mg/kg – vitamin E	■ Improved heat tolerance in terms of body weight, enzymatic profile and antioxidant status	(Alhidary et al., 2015)
F. Vitamin E and selenium	Damani and Balkhi	3–4 years	0.3 mg – Se; 50 mg/kg – vitamin E	■ Improves antioxidant status, physiological and hormonal profile	(Qureshi et al., 2017)
G. Vitamin E and selenium	Crossbreed finisher lambs	7 months	Vitamin E as α-tocopherol acetate – 228 mg/kg DM; Se – 1.16 mg/kg DM	■ Improves average daily feed intake, average daily gain and preserves oxidative balance	(Chauhan et al., 2016)
H. Vitamin E and selenium	Crossbred (Merino × Border Leicester) × (Dorset) lambs	7 months	Vitamin E as α-tocopherol acetate – 228 mg/kg DM; Se – 1.16 mg/kg DM	■ Increases final live lamb weight and hot carcass weight ■ Reduces lipid oxidation of aged meat	(Chauhan et al., 2020)
I. Vitamin E and selenium	Baladi ewes	1–2 years	0.3 mg – Se; 50 mg/kg – vitamin E	■ Improves reproductive performance and growth ■ Improves blood metabolite-related protein metabolism and thyroxin hormone concentrations	(El-Shahat and Abdel, 2011)
J. Vitamin E and selenium	Merino × Poll Dorset	10–12 months	1.2 mg/kg DM – Se; 100 IU/kg DM – vitamin E as α-tocopherol acetate	■ Improves ability to mitigate adverse effects of heat stress	(Chauhan et al., 2015)
K. Vitamin E and selenium	Damani and Balkhi	–	0.3 mg – Se; 50 mg/kg – vitamin E	■ Improves physiological, hormonal and antioxidant status	(Shakirullah et al., 2017)
L. Antioxidant and mineral mixture	Malpura ewes			■ Alleviates heat stress effects on productive and reproductive efficiency	(Sejian et al., 2014 a)
M. Vitamin C, vitamin E, selenium and Zinc	Mandya	3–5 years	Vitamin E as α-tocopherol acetate – 250 mg/animal/day; vitamin C – 2 g/animal/day; zinc – 150 ppm/animal/day; selenium – 0.1 mg/animal/day	■ Reduces heat stress and maximizes reproductive performance	(Sathisha et al., 2020)

Table 1 – contd.

1	2	3	4	5	6
N. Zinc sulphate and folic acid			Zinc – 0.4 mg/kg body weight; folic acid – 0.02 mg/kg body weight	■ Improves reproductive functioning like testicular dynamics and semen quality	(Fadl et al., 2022)
O. Naringin	Awassi male lambs	4 months	14 g/week	■ Improves body weight and feed efficiency ■ Reduces heat stress effects on antioxidant system and immune functions	(Alhidary and Abdelrahman, 2016)
P. *Opuntia ficus-indica* f. *inermis*	Barbarine sheep	-	Betaine – 100 µg/ml; α-tocopherol – 10 µg/ml	■ Thermo-protection of lymphocytes	(Slimen et al., 2019 b)
Q. Açai oil	Lacaune sheep	2–3 parity	2% açai oil in concentrate (0.65% of total diet on DM basis)	■ Improves antioxidant capacity and milk production	(Dos Santos et al., 2019)
R. Brown seaweed (*Ascophyllum nodosum*)	Dorset × Rambouillet × Finn	-	1% of diet	■ Improves immune system function and reduces heat stress associated oxidative stressors	(Saker et al., 2004)
S. Brown seaweed (*Sargassum latifolium*)	Barki sheep	-	4% of diet	■ *Enhances* antioxidant defense system ■ Modulates thermo-respiratory processes and inflammatory responses	(Ellamie et al., 2020)
Electrolyte supplements					
A. Dietary electrolyte balance (DEB)	Farafra mature rams	2–3 years	300 meq/kg of DM	■ Beneficial effects on the thermal responses, respiratory activities and gas exchange parameters ■ Regulation of blood buffering capacity and acid-base balance	(Saleh et al., 2020)
B. Sodium bicarbonate and potassium bicarbonate	Farafra mature ewes Farafra mature rams	2.5–3.5 years 2.0–3.0 years	1% sodium bicarbonate (G1), 1% potassium carbonate (G2), 0.5% sodium bicarbonate + 0.5% potassium carbonate (G3) and 1% sodium bicarbonate + 1% potassium carbonate (G4)	■ Sodium or potassium or both to the diet of animals during summer (the hot season) led to alleviate heat stress in terms of controlling the blood metabolites	(El-Moty et al., 2010)
C. Sodium hydroxide (NaOH)	Merino × Poll Dorset wethers	-	3% NaOH-treated wheat plus forage	■ Decreases heat released following rumen fermentation, enhancing the thermo-tolerant capability	(Gonzalez-Rivas et al., 2017)
Mineral mixture supplements					
A. Mineral block	Tibetan sheep	-	13.09 g per day per sheep	■ Increases efficiency of antioxidant defence system and immunity-related parameters	(Wang et al., 2016)
B. Mineral mixture and antioxidants	Malpura ewes	2–4 years	20 g of mineral and antioxidant mixture per kg feed	■ Improves productive and reproductive efficiency	(Sejian et al., 2014 a)
C. Zinc	Awassi lambs	8 months	6 ml/day (72 mg)	■ Improves feed digestibility	(Abbi and Qasim, 2024)
D. Nano chromium picolinate (nCrPic)	Merino × Poll crossbred ewes and wethers	9 months	400 or 800 µg/kg Cr as nCrPic	■ Enhances insulin sensitivity preventing cells from progressing towards apoptotic pathways during heat stress	(Hung et al., 2023)
E. Chromium-methionine	Kermani male lambs	8–9 months	1.5 or 3 mg of Cr/kg DM	■ Improves antioxidant status and feed to gain efficiency	(Seifalinasab et al., 2022)

Table 1 – contd.

1	2	3	4	5	6
F. Chromium-methionine and chromium nanoparticles	Pregnant Afshari ewes	–	3 mg Cr as chromium-methionine per kg DM and 3 mg Cr as chromium nanoparticles per kg DM	■ Better body condition score during transition period of ewes under heat stress conditions	(Asadi et al., 2024)
Probiotic supplements					
A. *Bacillus subtilis* with essential oils	Pelibuey × Katahdin non-castrated male lambs	–	2 g probiotic (2.2 × 10^8 CFU/g *Bacillus subtilis*)	■ Promotes dry matter intake and weight gain	(Escobedo-Gallegos et al., 2023)
B. *Schizochytrium limacinum*	Male Merino lambs	5 months	5 g/day	■ Improves dietary energy utilization and productivity	(Sucu et al., 2017)
C. *Trichoderma reesei* and *Aspergillus oryzae* with dry live baker's yeast (*Saccharomyces cerevisiae*) and mixed culture fortified with herbal medicine plants (Effective microorganisms with medicinal herbs – EMMH)	Farafra and Saidi ewes	2–4 years	3 kg EMMH/ton	■ Improves lactational performance of ewes and performance of suckling lambs	(Saleh and Gomaa, 2016)
D. *Saccharomyces cerevisiae* and raisin flour	Awassi male lambs	2–3 months	5 g *Saccharomyces cerevisiae* as baker's yeast daily	■ Boosts blood pH and decreases cortisol	(Mahdi et al., 2020)
Prebiotic supplements					
A. Probiotics (live *Saccharomyces cerevisiae* and prebiotics (mannan oligosaccharide plus ß-glucans)	Pelibuey × Katahdin lambs	–	3 g of live *Saccharomyces cerevisiae*, 3 g of mannan oligosaccharide plus ß-glucans	■ Improves dietary energy utilization	(Estrada-Angulo et al., 2021)
Herbal products					
A. Phytogenic-rich herbal mixture (PRHM) supplementation, including cinnamon, turmeric, rosemary, and clove buds	Male Afshari × Chaal lambs	11−12 months	2% PRHM in diet	■ Promotes feed intake, serum and liver antioxidant status, and improves growth performance	(Hashemzadeh et al., 2022)
B. Naringin	Awassi male lambs	4 months	7 or 14 g	■ Improves performance traits, antioxidant status and immune response	(Alhidary and Abdelrahman, 2016)
C. Chestnut tannins (CT)	Male Ujumqin lambs	4 months	5 g and 10 g of CT/kg	■ Improves meat quality, stress parameters and antioxidant system	(Liu et al., 2016)
D. Amla and giloy stem powder	Magra lambs	3–4 months	1.5 g/kg body weight	■ Antioxidant properties and immune-boosting benefits	(Joshi et al., 2023)
E. Curcumin nano-micelles (C-NM)	Crossbred male lambs [Île-de-France × (Dalagh × Romanov)]	4–5 months	40 and 80 mg per head per day	■ Improves growth performance, immunological response, and antioxidant status	(Bokharaeian et al., 2023)

Table 1 – contd.

1	2	3	4	5	6
F. Rocket oil (watercress oil)	Crossbred ram lambs (1/2 Finnish Landrace × 1/2 Rahmani)	3–4 months	2 mg rocket oil/kg live body weight	■ Improves body weight gain, growth performance at puberty, reproductive ability and feed efficiency	(El-Badawy et al., 2018)
G. Flaxseed	Late-lactation Sarda ewes	-	Whole flaxseed	■ Enhances humoral immune and thermoregulatory responses	(Caroprese et al., 2012)
H. Cornus plant extract supplementation, with or without oregano and thyme essential oil	Chios crossbred ewes	-	0.5 g cornus extract, 0.01 g oregano and 0.005 g thyme essential oil per kg of concentrate	■ Improves feed utilization and productivity	(Kalaitsidis et al., 2021)
I. Chamomile flowers	Farafra ewes	2–4 years	1.0 gm chamomile flower /10 kg LBW/day	■ Promotes reproductive performance ■ Increases physiological responses to heat stress with no detrimental impacts on blood metabolites	(Saleh and Abozed, 2018)
J. *Moringa oleifera*	Ewes (local breed in the Al-Ahssa)	2.5–3 years	50 and 100 g	■ Modulates thermo-tolerance response parameters, metabolites, liver and kidney functions	(Al Mufarji et al., 2022)
K. Curcumin	Male Hu sheep	4 months	450 and 900 mg (per sheep)	■ Promotes lipid metabolism ■ Improves antioxidant status and immune ability ■ Improves the reproductive performance and prevents testicular cell apoptosis	(Jiang et al., 2019)
L. Betaine	Merino sheep	8– 10 months	2 and 4 g/day	■ Ameliorates and improves physiological responses	(DiGiacomo et al., 2016)
M. Phytogenic-rich herbal mixture (PRHM) – 50% rosemary leaves (*Rosemarinus officinalis*), 20% cinnamon barks (*Cinnamomum zeylanicum*), 20% turmeric roots (*Curcuma longa*), and 10% clove buds (*Eugenia caryophyllata* Thunb.).	Male Afshari × Chaal lambs	11–12 months	Diet supplemented with 1% and 2% PRHM	■ Affects expression of genes related to insulin metabolism ■ Increases efficiency of glucose utilization	(Hashemzadeh et al., 2023)

A meta-analysis report enlists the feed supplements used as heat relieving strategy in sheep which includes antioxidants like vitamin E, vitamin C, selenium; proteins-rich food like fish meal, urea, L-tyrosine; fat supplements like polyunsaturated fatty acids, *Ascophyllum nodosum*, olive pulp, flaxseed; energy- rich grain diet, concentrate; fibre-rich acacia, lucerne hay, wheat straw and mineral supplements (Slimen et al., 2019 a).

The oxidative state and physiological reactions that are adversely affected in heat stressed sheep may be mitigated through supplementing the animal with antioxidants at supranutritional doses (Chauhan et al., 2014). According to many studies, supplementing sheep with vitamin E, selenium, or both aids in mitigating heat stress (Alhidary et al., 2015; Chauhan et al., 2014). Another major study finding in sheep reports that nano chromium picolinate reduces the adverse effects of heat stress on rectal temperature, respiration rate and average daily feed intake resulting in proper weight gain (Hung et al., 2021). Given that water affects animal thermoregulation, it is considered as a critical nutrient that is essential for managing heat stress in ruminants. Supplementing with whole flaxseed has been reported to improve humoral immunological and thermoregulatory responses throughout high ambient temperature conditions (Caroprese et al., 2012).

In addition, mineral supplementation in severe heat stress conditions must ensure balanced supply of all nutrients arising from altered turnover in addition to buffer needs (Conte et al., 2018). A study in Malpura ewes supplemented with minerals and antioxidants ameliorated the heat stress effects on feed intake, water intake, body condition score, respiration rate and rectal temperature in the afternoon, oestrus duration, estradiol, progesterone, Hb, PCV, plasma glucose, total protein, cortisol, T_3 and T_4 levels reflecting its efficacy (Sejian et al., 2014 a). Other dietary interventions studied in sheep include the use of wheat grains treated with a commercial starch binding agent, Bioprotect™ in heat stressed Merino lambs which reported that treated wheat grains had a positive impact on the physiological responses like respiratory and heart rate of heat stressed animals (Prathap et al., 2022). These evidences suggest strongly that concerted efforts in manipulation of animal nutrition can be an effective heat abatement strategy.

Different nutritional strategies

In particular, the use of feed supplements is a significant, persuasive, adaptable, and cost-effective technique to relieve heat stress in sheep. The following section attempts to summarize the recent advances in nutritional manipulation of heat stressed sheep herds, reporting useful recommendations. Figure 1 describes the various feed supplements used for ameliorating heat stress in sheep.

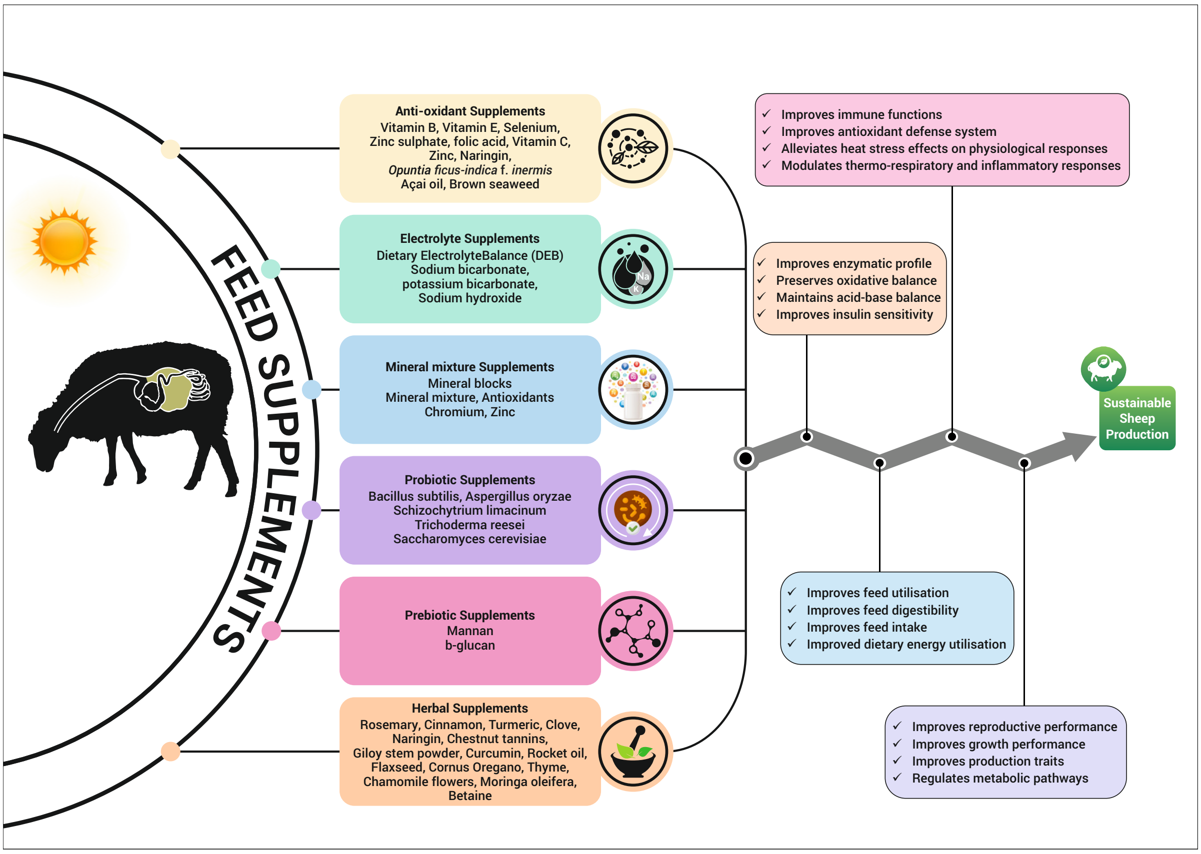

Figure 1. Feed supplements used for ameliorating heat stress in sheep

Antioxidant supplements

It is well established that an added stressor associated with heat stress in animals is the oxidative stress. Several studies documented that increased ambient temperature results in oxidative stress, as evidenced by a reduction in selenium content, increased superoxide dismutase (SOD) activity, a high oxidative stress index, increased protein oxidation, reactive oxygen species generation, and malondialdehyde (MDA) levels (Slimen et al., 2019 a; Nisar et al., 2013). In addition, heat stress has been linked with elevated or induced oxidative stress (Sivakumar et al., 2010; Chauhan et al., 2021). Moreover, the physiological response in sheep like increased respiration under heat stress conditions acts as a secondary source of free radical production (Slimen et al., 2019 a). In this regard, it has been proposed by many researchers that supplementing diets with antioxidants can improve immune function and oxidative state of heat stressed animals (Chauhan et al., 2014; Alhidary et al., 2015; Lees et al. 2017).

To prevent oxidative tissue deterioration, antioxidant nutrients such vitamins E, A, and C as well as the trace minerals selenium, copper, zinc, and manganese are crucial (Salles et al., 2008). Antioxidant nutrients, such as vitamin B, vitamin E and selenium, have been demonstrated to reduce the deleterious effects of heat stress by improving/maintaining the oxidative state of the animal (El-Darawany, 1999; Alhidary et al., 2015). It has been reported that administration of selenium at higher doses can alleviate the impacts of thermal stress in sheep with a positive effect on rectal temperature and body weight loss (Alhidary et al., 2012). Moreover, different types of selenium (organic and inorganic) supplemented to two breeds of sheep under heat stress conditions showed a mitigating effect on physiological response and also improved the reproductive capability (Hayder et al., 2016). Selenium-enriched *Saccharomyces cerevisiae* yeast supplement in heat stressed sheep diet has been disclosed to reverse the reduced antioxidant capability and immune function caused by heat stress (Ashrafi et al., 2024).

A combination of vitamin E and selenium supplemented to Damani and Balkhi sheep subjected to heat stress has been proved to improve the antioxidant status, physiological and hormonal profile (Qureshi et al., 2017). Similarly, a study reported that supplementation of high levels of dietary vitamin E and selenium increased average daily feed intake and average daily gain, as well as preserved oxidative balance in finisher lambs subjected to heat stress (Chauhan et al., 2016). Vitamin E and selenium are vital minerals that act as antioxidants, reducing cellular damage caused by endogenous peroxides. A study has validated that supplementing Baladi ewes with vitamin E and selenium throughout the summer season boosted reproductive performance and lamb growth rates (El-Shahat and Abdel Monem, 2011). In addition, the study established that supplementing with more than one antioxidant improves blood metabolite-related protein metabolism and thyroxin hormone concentrations. In addition, antioxidants (vitamin E and selenium) supplemented at supranutritional levels increase final live lamb weight and hot carcass weight in addition to reducing the lipid oxidation of aged meat (Chauhan et al., 2020). A study in heat stressed ewes supplemented with supranutritional dietary Se or vitamin E reports positive effects in heat stress alleviation. However, the study also validates that the two antioxidants work more effectively together to increase their ability to mitigate the adverse effects of heat stress in sheep (Chauhan et al., 2015).

Study results report that a combination of antioxidant and mineral mixture supplementation to heat stressed Malpura ewes aids in alleviating the adverse effect of heat stress on the productive and reproductive efficiency (Sejian et al., 2014 a). A study in Damani and Balkhi sheep proved the positive impact of vitamin E and Se in improving the physiological, hormonal and antioxidant status under heat stress conditions (Shakirullah et al., 2017). Further, a combination of vitamin C, vitamin E, selenium and zinc antioxidant nutrients supplemented to heat stressed Mandya sheep has been effective in reducing heat stress and in maximizing reproductive performance of the animals (Sathisha et al., 2020). Fadl et al. (2022) reported that the combined use of potent antioxidants, zinc sulphate and folic acid in summer diet of rams exerted positive effects on reproductive functioning as testified by improved testicular haemodynamics and semen quality.

A study described the effect of using naringin, a flavanone glycoside, on the antioxidant defences in heat stressed lambs (Alhidary and Abdelrahman, 2016). The study pointed out a significant decrease in thiobarbituric acid reactive substances (TBARS), a by-product of lipid oxidative damage, which testifies to the improved antioxidant capacity of the animal. The high antioxidant property of the components of mesocarps of *Opuntia ficus-indica* f. *inermis* and cladodes with enriched betacyanins and betaxanthins has also been reported to protect and maintain the sheep lymphocytes viability under heat stress conditions, thus preventing hyperthermia-induced lymphocyte death (Slimen et al., 2019 b). A study reported that the use of açai oil in heat stressed dairy sheep diet improved the antioxidant capacity in serum and milk (Dos Santos et al., 2019). The high antioxidant role of brown seaweed (*Ascophyllum nodosum*) treated forage fed to heat stressed wether lambs has proved to improve the immune system function and also to reduce the adverse effects of heat stress associated oxidative stressors (Saker et al., 2004). Similarly, Barki sheep's diet containing brown seaweed (*Sargassum latifolium*) has been proved to be efficient in protecting animals from heat stress by enhancing the antioxidant defense system in addition to modulating thermo-respiratory processes and inflammatory responses (Ellamie et al., 2020).

Enhancing the health and performance of animals under heat stress may be possible with a strong antioxidant network that may stop oxidative damage to biological components. Thus, these evidences suggest that applications of antioxidant supplements are viable options that can be crucial and effective in preventing and reversing some of the adverse consequences of heat stress in sheep.

Electrolyte supplements

An imbalance in the acid-base state caused by increased perspiration and respiratory rate accounts for a portion of the detrimental effects of heat stress on performance (Kadzere et al., 2002). Additionally, it has been suggested that the increased panting brought on by heat stress may result in respiratory alkalosis and possible compensatory metabolic acidosis during the night time cooling (Sanchez et al., 1994). There will be loss of electrolytes in the sweat, with the amount lost varying across species and perhaps among breeds, with other animal factors like acclimatization to heat also impacting the composition of the electrolytes (Barnes et al., 2004), reflecting that significant quantities of electrolytes are lost when ruminants make efforts to maintain homeostasis. Previous study findings and interpretations of fundamental physiological responses to heat stress imply that replenishing lost electrolytes may be beneficial. The use of electrolyte supplements may thus aid in relieving and mitigating the negative impacts of heat stress.

Various studies carried out in different species like poultry (Majekodunmi et al., 2012), cattle (Al-Qaisi et al., 2020), buffaloes (Kumar et al., 2010), goats (Jamal et al., 2021) and pigs (Haydon et al., 1990) described the beneficial effects of electrolyte supplement in relieving heat stress. Electrolytes used in combination with ascorbate have been suggested to relieve heat stress associated oxidative stress and aid in boosting cell mediated immunity in buffaloes (Kumar et al., 2010). A study reports that electrolyte modification in diet of growing-finishing swine during high ambient temperature conditions improves feed intake and weight gain due to enhanced blood buffering capacity (Haydon et al., 1990). Moreover, reports have suggested supplementation of electrolytes aid in adjusting the acid-base imbalance and in minimizing the heat stress effects on growth performance in poultry and swine (Aguiar et al., 2015). The supplementation of sodium bicarbonate has proved to improve dry matter intake in sheep and goats (Kawas et al., 2007; Jamal et al., 2021) and this has been attributed to increased rumen pH and stable rumen environment as a result of the electrolyte's buffering capability (Tripathi et al., 2004).

A study in heat stress exposed rams supplemented with different levels of dietary electrolyte balance (DEB) demonstrated that electrolyte supplementation has positive effects on the thermal response, respiratory function and gas exchange parameters (Saleh et al., 2020). A study in sheep revealed that dietary electrolytes improve the total protein levels in blood, having a positive effect on acid-base balance. The role of proteins has been attributed to its reserve buffering capacity with a crucial role in action of intracellular buffers in body tissues. Moreover, the study reported that an increase in sodium and potassium salts in diet improved the DEB and in addition increased thyroid hormone levels that may be a sign of improved glucose, protein, and fat metabolism, consequent to heat stress alleviation (El-Moty et al., 2010). The effect of sodium hydroxide supplementation was studied in grain-fed Merino × Poll Dorset wethers. This study revealed that heat stressed wethers fed with 3% NaOH-treated wheat plus forage had lower respiration rate and flank temperature than those fed wheat grain plus forage. The improved heat tolerance in sheep fed with 3% NaOH-treated wheat plus forage were attributed to the decreased rate of rumen fermentation of 3% NaOH-treated wheat plus forage, thereby reducing rumen heat released during feed fermentation. These evidences strongly suggest that dietary electrolyte additions might play a crucial role in heat stress alleviation in sheep.

Mineral mixture supplements

Minerals are essential to every biological process. Minerals have received particular attention among the nutrients that can be changed in diets designed for feeding animals in hot weather because of their significance as a structural component of tissues and because they are involved in the synthesis and activity of enzymes connected to oxidative metabolism (Sejian et al., 2014 b; Vinod, 2015). It is well known that modifications in mineral metabolism occur in animals raised in a hot environment. The increased respiration will result in excessive water losses, consequently lowering mineral concentrations (Sejian et al., 2012 b). In addition, heat stress causes a substantial decrease in dry matter intake as well as an increase in excretion of urine and sweat containing minerals, hence heat stressed animals must be supplemented with mineral resources in order to replenish their negative mineral balance (Marai et al., 2008). It is reported that loss of magnesium may be due to reduced intake alongside exploitation of Mg for lipolytic enzymes and Mg transport across rumen during heat stress (Caroprese et al., 2012). Hence, these losses can be replenished by supplementation with mineral mixture. Moreover, in sheep, selenium, manganese, zinc, copper, sulphur, vitamin E and vitamin A have been found to play a crucial and synergistic role in antioxidant defence mechanisms, thereby modulating the oxidative stress (Masters, 2018). Moreover, a study in Tibetan sheep validates that mineral blocks have protective effects, which can be attributed to the increased efficiency of antioxidant defence system, as well as an increase in the advantages of immunity-related parameters (Wang et al., 2016).

It is dictated that the mineral content of the pasture fluctuates according to season. Seasonal fluctuation can have a significant impact on dietary mineral intake due to variations in composition, growth stage, pasture availability, and soil moisture content. In addition, it was reported that minerals are the most variable nutritional component of pasture and fodder (Khan et al., 2007). Dietary mineral variability on marginal rangelands has made precision mineral supplementation of sheep to be a challenging husbandry practice. Knowledge of plant variations, plant phenology temporal shifts, metabolic mineral antagonism, and soil geochemical mapping can help forecast site-specific mineral deficiencies (Stewart et al., 2021). A study reported that the concentration of P and N in the entire vegetation is often considerably lower than the physiological requirements of grazing animals on summer range (Li et al., 2009). Therefore, factors like climate, agronomic measures, technologies in feed processing and genetic variations need to be considered during mineral mixture preparation, due to their possible fluctuating effects on the nutritive content of feed (Khan et al., 2007) and also in meeting the physiological demands of the animals under heat stress.

It has been reported that supplementing heat stressed lactating Friesian cows with mineral mixture and urea is a simple and safe method to improve dairy cow performance during high summer temperatures (Kamal et al., 1989). The urea molasses mineral block (UMMB) is found to be a vital feed component for ruminants as it is a combination of energy, protein, and minerals in the ruminant diet that allows animals to sustain themselves until pasture conditions recover after extreme environmental conditions (Dubey and Anjora, 2021). In this regard, a sheep study indicated that use of molasses-urea block (MUB) for supplementing trace minerals resulted in enhanced weight gain (Forsberg et al., 2002). Similarly, research efforts can warrant the potential use of urea molasses mineral block under heat stress conditions in sheep production systems.

Several studies reported that administration of minerals to heat stressed animals improves their ability to dissipate body heat load (Conte et al., 2018; Del Río-Avilés et al., 2021). During the hot summer months, a certain ratio and quantity of a particular mineral may help with dry matter intake by modifying blood chemistry in animals (El-Moty et al., 2010). Lambs supplemented with organic or inorganic trace minerals had increased dry matter intake, growth rate, and feed conversion efficiency in comparison to a non-supplemented counterpart (Samarin et al., 2022).

A study in heat stressed Malpura ewes supplemented with mineral mixture and antioxidants revealed their effective role in counteracting the adverse heat stress effects on the productive and reproductive efficiency (Sejian et al., 2014 a). It has been suggested that potassium, sodium, magnesium, copper, selenium, zinc, and phosphorus should be supplied in a balanced manner in the feed (Sejian et al., 2012 b). The role of zinc supplementation in heat stress mitigation has also been highlighted in a study using growing Awassi lambs during hot season that reports an improved feed digestibility in addition to effective alleviation of heat stress (Abbi and Qasim, 2024).

A recent study disclosed that chromium supplementation increased insulin sensitivity in sheep and reduced the adverse effects of heat stress (DiGiacomo et al., 2022). Moreover, similar views have been echoed reporting that dietary chromium can reverse the detrimental effects of heat stress in sheep attributed to improving insulin sensitivity (Dunshea et al., 2017). In parallel, the results of another experiment demonstrated that sheep under heat stress upon dietary supplementation with nano chromium picolinate (nCrPic) showed greater insulin sensitivity. The enhanced sensitivity of insulin suggests that glucose is being used more efficiently or preferentially to produce less heat during metabolism under heat stress conditions. In addition, the same study disclosed that the enhanced insulin sensitivity prevented the cells progressing towards apoptotic pathways during heat load conditions (Hung et al., 2023). Chromium supplemented in the diet of finishing lambs during summer has been demonstrated to improve antioxidant status and the feed to gain efficiency without any negative impact on the health and metabolism of sheep (Seifalinasab et al., 2022). The results of a study recommend the use of chromium, particularly in the form of chromium-methionine and chromium nanoparticles for ewes in transition period to evidence a better body condition score under heat stress conditions (Asadi et al., 2024). Thus, chromium supplements in the diet act as a promising nutritional strategy to reduce the adverse heat stress impacts in sheep.

The potential use of fertilizers as pasture amendment and dietary supplementation of ruminants with a specifically tailored mineral mixture is crucial for livestock farmers and environmentalists alike, given that their use might enhance forage nutritional quality and, in turn, meet the nutritional needs of animals under heat stress conditions (Khan et al., 2007). In addition, precision trace-mineral nutrition for sheep grazed under extensive production systems necessitates further research in order to customize area-specific mineral mixture for effective heat stress management. Thus, mineral mixture supplementation can be adopted as an effective nutritional intervention in minimizing the effects of heat stress in sheep.

Probiotic and prebiotic supplements

Probiotics are naturally occurring microbes that, when administered, enhance the animal's health by competing with harmful microbes and by increasing nutrient utilization by positively influencing intestinal microbiota. Moreover, probiotics have been extensively explored for their positive effects on the rumen environment and ruminant performance by influencing microbial activity, fermentative and digestive processes in the rumen (Khalid et al., 2011). A study in Nellore brown rams demonstrated that supplementation of probiotics in diet enhanced feed utilization efficiency and daily weight gain (Rao et al., 2003). Another study in Barki lambs reports that probiotics have positive impact on rumen parameters, growth, digestibility and economic efficiency (Soliman et al., 2016). A study reports the efficiency of natural feed additive combination of essential oil and probiotics over antibiotics. The results revealed the effect of probiotics in promoting dry matter intake and weight gain of feedlot lambs under heat stress conditions (Escobedo-Gallegos et al., 2023).

Probiotics that are commonly known as direct-fed microbials (DFM) have been extensively used in ruminants to enhance dry matter intake and hence productivity, particularly in animals under stressful environmental conditions (Khattab et al., 2020). Many evidences suggest the role of probiotics in stress amelioration in livestock animals. For instance, dietary supplementation of probiotics in beef bulls enhanced the digestibility of nutrients, growth and physiological response to heat stress, having a positive impact on the blood parameters (Kassab et al., 2017). Similarly, in feedlot cattle, yeast probiotic supplements mitigated adverse effects of heat stress as demonstrated by decrease in respiratory rate and vaginal temperature along with increased water intake (Broadway et al., 2020). Similarly, a study found that introducing *Saccharomyces cerevisiae* and *Clostridium butyricum* to the diets of heat stressed goats substantially alleviated heat stress by increasing rumen fermentation efficiency and growth performance (Cai et al., 2021). Furthermore, microalgae (*Schizochytrium limacinum*) supplement in the diet of lambs during summer season has been suggested to improve the dietary energy utilization and the productivity of the animals under stress (Sucu et al., 2017).

As evidenced in other species, probiotics have been exploited as they have a positive impact on heat stress mitigation in sheep. A study demonstrates that probiotics have a favourable role in enhancing physiological responses of animals under heat stress and were suggested to ameliorate the negative effects of heat stress and also to improve the lactational performance of ewes as well as the performance of suckling lambs (Saleh and Gomaa, 2016). Their effects on heat stress mitigation can be attributed to a reduction in blood cortisol concentrations as concluded in a study where treated heat stressed lambs demonstrated a trend towards decreased cortisol concentrations (Vosooghi-Poostindoz et al., 2014).

A study carried out in heat stressed sheep, reported the positive effects of probiotics, *Saccharomyces cerevisiae*, along with raisin flour which was reflected as increased pH (7.15±0.02) in heat stressed lambs when compared to control (no dietary raisin supplementation; rumen pH: 6.95±0.01) (Mahdi et al., 2020). The potential of *Saccharomyces cerevisiae* to reduce stress and function as an antioxidant could additionally play a pivotal role in decreasing the lactate in heat stressed rumen, thereby improving feed efficiency (Schingoethe et al., 2004). In line with this study, Mao et al. (2023) reported the potential use of probiotic supplementation in alleviating the oxidative stress of growth retarded lambs by increasing the SOD and GSH-Px activities whilst decreasing the MDA levels.

Prebiotics are mostly fructo- and galacto-oligosaccharides produced from indigestible carbohydrates from cell wall of yeast (Estrada-Angulo et al., 2021). The majority of studies that are currently available on heat stressed animals showed that feeding probiotics, prebiotics, or synbiotics altered the gut microbiota and improved gut barrier function. These improvements were accompanied by an increase in productivity, health, and/or welfare (Ringseis and Eder, 2022). These results suggest that nutritional treatments intended to protect animals from the harmful effects of heat stress conditions should prioritize the restoration of gut homeostasis and function. A study reported that finishing lambs supplemented with probiotics and/or prebiotics in subtropical climate scenarios suggested that these supplements contribute to mitigate the deleterious effects of high ambient heat load on dietary energy utilization (Estrada-Angulo et al., 2021).

The results of an experiment in Barki lambs report that prebiotics and probiotics have positive impact on rumen parameters, growth, digestibility and economic efficiency (Soliman et al., 2016). It has been studied in heat stressed broilers that prebiotics supplemented at varied levels result in an insignificant change in concentration of blood metabolites and minerals. However, use of prebiotic and probiotic potentially improves blood parameters, antioxidant and immune system of heat stressed birds (Ghorbani et al., 2017). Other studies in chicken report the role of prebiotics in benefiting intestinal microbiome, gut morphology, oxidative status, physiological response and growth performance of heat stressed birds (Awad et al., 2021). However, further research is needed in identifying the role of prebiotics in heat stress abatement in sheep.

Herbal products

Phytogenics, or herbal plant bioactive substances have been employed in human and animal nutrition to improve performance and to prevent diseases under stress-related situations (Rochfort et al., 2008). Herbs and botanicals have the ability to stimulate the immune system, increase feed intake, and produce digestive juice. They also have antibacterial qualities. For instance, a recent study reports that betaine protects heat stressed bovine mammary epithelial cells (BMECs) from oxidative damage (Saleh et al., 2023). There are many evidences proving the importance of different herbal supplements in heat stress mitigation in sheep.

A study evaluated the use of phytogenic-rich herbal mixture in enhancing growth performance, feed intake, serum and antioxidant status of heat stressed lambs (Hashemzadeh et al., 2022). In addition, herbal supplements like chestnut tannins improved the meat quality, stress parameters and the antioxidant system of the heat stressed lambs (Liu et al., 2016). The incorporation of amla and giloy stem powder has been suggested to be used as an effective heat alleviation strategy in lambs raised under heat stress conditions (Joshi et al., 2023).

A study established that under heat stress circumstances, the growth performance, immunological response, and antioxidant status of fattening lambs were enhanced by the addition of dietary curcumin nano-micelles (Bokharaeian et al., 2023). Furthermore, evidence suggests the role of herbal supplements like rocket oil (watercress oil) improved body weight gain, growth performance at puberty, reproductive ability and feed efficiency of lambs under hot climatic conditions (El-Badawy et al., 2018). Moreover, a study reported that use of flaxseed in the diet improved Na and Cl concentrations in sheep under heat stress, which aids in improving rumen metabolism (Caroprese et al., 2012).

A study demonstrated that cornus supplementation in conjunction with oregano and thyme has the ability to significantly improve feed utilization and the productivity of high-yielding dairy ewes under heat stress (Kalaitsidis et al., 2021). Supplementing diets with chamomile flowers as a herbal feed addition promoted sheep reproductive performance, with the highest amount of supplementation showing the greatest increase (Saleh and Abozed, 2018). Furthermore, the supplementation increased the examined physiological responses to heat stress while having no detrimental impacts on blood metabolites. *Moringa oleifera* has been demonstrated to modulate the thermo-tolerance response parameters, metabolites, liver and kidney functions, thereby alleviating the adverse impacts of heat stress in ewes reared in sub-tropical regions (Al Mufarji et al., 2022). Moreover, supplementation of curcumin in the diet of Hu sheep has been reported to improve the lipid metabolism, antioxidant capacity, immune function in addition to the testicular development, thereby showing protective effects against the negative heat stress effects (Jiang et al., 2019).

Heat stress has been established to increase the maintenance needs of the animals due to physiological adaptive mechanism like increased respiration, panting, etc. In this regard, offering methyl donors such as betaine (trimethyl glycine), a naturally occurring amino acid derivative, is a significant dietary intervention for mitigating the deleterious effects of heat stress. Betaine has a significant part in osmoregulatory action, which can minimize the energy required for ion exchange (Dunshea et al., 2022). The positive role of dietary betaine has been validated in a study that reported the effect of dietary betaine in improving the growth performance and physiological responses to heat stress in a dose dependent manner in sheep (Dunshea et al., 2017). The study conducted in heat stressed Merino ewes revealed improvement in physiological responses upon betaine supplementation (DiGiacomo et al., 2016).

A study reported that the use of herbal mixture composed of cinnamon, turmeric, rosemary, and clove can improve the glucose utilization and enhance the expression pattern of genes related to insulin in the muscle of heat stressed feedlot lambs (Hashemzadeh et al., 2023).

Thus, these evidences suggest that herbal remedies can be an effective feed supplement to alleviate heat stress in sheep. Despite their long record of application, the majority of the herbal supplements have not been scientifically evaluated and many of the standardized herbal products used in animal feed are yet to be completely standardized according to the species.

Conclusion

Heat stress affects the productivity and welfare of sheep by acting as an important stressor leading to multiple stresses like nutritional stress, oxidative stress and so on, making animals more vulnerable to diseases. The rising demand for animal products paralleled by the alarming climate breakdown scenario has imposed a significant pressure on the livestock sector. In this regard, many targeted approaches for heat stress abatement have been framed and they include genetic strategies, management and nutritional. Management and nutritional measures have been aimed towards physiological and metabolic adaptations in animals and are considered to be simple and short-term solutions. The nutritional interventions to alleviate heat stress in sheep have been practiced and feed supplements have been extensively employed in recent years. The feed supplements tailored to mitigate heat stress mainly improve the immune responses and the antioxidant defences of the animals, thus leading to improved performance under high ambient temperature conditions. The feed supplements alleviate heat stress in animals by mainly modulating the physiological responses and blood metabolites. However, knowledge gaps in understanding about the pathways through which feed supplements act in heat stress mitigation process still persist. Given the negative impacts of heat stress on sheep performance, the beneficial effects of feed supplements can never be overlooked as they play a significant role in heat stress moderation in sheep. Therefore, provision of feed supplements for heat stressed sheep could be a way forward nutritional manipulation strategy that effectively mitigates heat stress ensuring optimal production.

Future perspectives

The nutritional interventions including feed supplements in animal diet have been a green flag for sheep producers facing the heat stress challenge. However, future work should target on understanding the role of feed supplements in heat stress mitigation pathways to improve the efficiency. Further, the standardization of feed supplements according to the species and breed is crucial. Future work should target on gaining knowledge about the synergistic and inhibitory effects of various combinations of feed supplements. The use of feed supplements in the diet of heat stressed animals can be a simple and farmer-friendly approach. Thus, efforts on creating awareness among sheep producers are crucial in effective transfer of the improved nutritional measures that can ensure precision nutrition in the coming years. In addition, considering the substantial detrimental effects of heat stress in sheep performance, it is vital to further experiment different combinations of nutritional remedies and other heat stress amelioration strategies to assist in revolutionizing the sheep production systems in this climate change scenario, assuring sustainability.

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