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Review Article

Managing heat stress in goats for sustainable climate-resilient production

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ABSTRACT: Heat stress has been identified as a significant factor affecting goat production, particularly in tropical and subtropical regions where elevated temperatures are prevalent. Numerous studies have documented the physiological and behavioural responses of goats to heat stress, such as reduced feed intake, lower growth rates, impaired reproductive performance and increased susceptibility to diseases. These effects lead(s) to decreased productivity and economic losses, which are exacerbated by climate change. This review highlights the impacts of heat stress on goats, focusing on key physiological responses such as altered reproduction, immune suppression, rumen dysfunction, acid-base imbalances, and oxidative stress. Heat stress also significantly impacts productivity by reducing feed intake, growth rates, and milk yields. High temperatures inhibit hypothalamic appetite regulation, leading to negative energy balance and reduced nutrient availability for milk synthesis. Meat quality is similarly affected, with changes in pH, tenderness, and colour. The review examines management strategies employed to mitigate these effects, including improvements in housing design for better shade and ventilation, optimised feeding regimes and water management systems. Additionally, digital technologies such as temperature sensors and automated cooling systems are discussed as innovative approaches to monitor and reduce heat stress. Genetic selection for heat tolerance is also explored as a potential long-term solution. This review aims to provide a comprehensive understanding of heat stress in goats and offers insights into effective management practices. These findings can guide future research and practical applications to enhance goat welfare and productivity in heat-stressed environments.

Keywords: Climate change, goat management, heat stress, sustainable production, thermoregulation.

INTRODUCTION

Goat farming in the tropics

Goat farming is vital to the livelihoods of millions of people and provides numerous advantages to individuals, communities and ecosystems (Koluman, 2023; Bisawas *et al.,* 2024). They are a source of food, important nutrients and high-quality protein, which help communities with limited resources meet their nutritional demands and provide food security (Peacock, 2015). Goat products, such as meat, milk, fibre and skins, are easily sold in local markets and enable smallholder farmers, especially women who typically play a major role in goat rearing, to make a living (Sumberg *et al.,* 2018). This income facilitates financial investments in healthcare, education and other aspects of life. In many tropical communities, goats are deeply religious and culturally significant, frequently being included in rituals and ceremonies (Sumberg *et al.,* 2018). Goat ownership can improve social standing and cohesiveness among the community. Raising goats contributes to ecological understanding and cultural heritage by utilising and conserving important traditional knowledge and practices about animal husbandry, breeding, and veterinary care (Hosono *et al.,* 2019). According to Peacock (2015), their browsing habit helps manage land by reducing soil erosion, encouraging biodiversity, and suppressing weeds and brush.

Heat stress in goats

Thermal stress represents a critical challenge in the context of rapidly changing climates, posing significant threats to livestock productivity and health (Kaliber *et al.,* 2016). This issue is particularly acute in tropical, subtropical, arid, and semi-arid regions globally (Lian *et al.,* 2020; Sejian *et al.,* 2022; Ren *et al.,* 2020). Heat stress is defined as the physiological strain and discomfort experienced by animals when exposed to excessively high environmental temperatures (Gupta *et al.,* 2013). Livestock generate metabolic heat during the digestion of feed, which supports essential physiological functions such as lactation, gestation, growth, and maintenance. Increased feed intake correlates with higher metabolic heat production, necessitating more efficient heat dissipation mechanisms.

Among livestock species, dairy animals are particularly susceptible to heat stress due to their substantial energy requirements for sustained milk production. Both lactating dairy goats and meat goats fed for growth are vulnerable to thermal stress. Physiological indicators such as panting and increased water intake serve as visible signs of heat stress in these animals. Economically, heat stress in dairy cattle manifests through reduced feed consumption, diminished milk yield, and lower concentrations of milk solids (Li *et al.,* 2023). Moreover, reproductive performance is adversely affected. For instance, Cui *et al.* (2019) reported a significant decline in conception rates as the average daily temperature-humidity index (THI) increased from 70 to 84, causing conception rates to drop from 55% to 10%.

Although goats exhibit better heat tolerance than cattle, attributable to their smaller body size, lower maintenance feed requirements, and higher digestive efficiency (Ortiz *et al.,* 2019), they are not immune to heat stress. Factors such as breed-specific differences in sweating rates and coat thickness significantly influence the degree of heat stress experienced by goats. The global challenge of climate change continues to threaten small ruminant productivity and health, with environmental factors like high ambient temperature, solar radiation, and humidity playing pivotal roles in animal welfare (Berihulay *et al.,* 2019; Joy *et al.,* 2020).

High ambient temperatures compromise the animal's ability to maintain energy balance, thermoregulation, water retention, hormonal stability, and mineral homeostasis (Daramola *et al.,* 2021). This study aims to evaluate the multifaceted impacts of heat stress on goats and propose effective mitigation strategies to support industry sustainability.

Factors contributing to heat stress

Animal welfare, growth, and productivity are profoundly influenced by both management practices and climatic conditions. Heat stress refers to the detrimental effects of environmental factors on livestock, as evidenced by changes in their physiological functions and productive performance (Baumgard and Rhoads, 2023). Livestock systems, particularly mixed and grazing systems involving small ruminants, are increasingly susceptible to the impacts of global warming. Key climatic changes, such as prolonged droughts, reduced rainfall, and elevated ambient temperatures, directly affect disease prevalence, the availability of feed and water, and the nutritional quality of forage (Nardone *et al.,* 2010). Among these environmental stressors, temperature fluctuations have been identified as exerting the most significant influence on livestock health and performance (Sejian *et al.,* 2019; Joy *et al.,* 2020).

The ability of animals to tolerate rising temperatures without experiencing stress varies across and within species. Small ruminants, such as goats and sheep, generally exhibit greater resilience to high temperatures compared to larger ruminants. This is demonstrated by their superior survival rates, productivity, and reproductive performance under heat stress conditions (Berihulay *et al.,* 2019). Tropical breeds, in particular, show enhanced adaptability to heat stress when compared to high-yielding temperate breeds (Sejian *et al.,* 2022). Despite this resilience, physiological and behavioural adaptations to heat stress can still negatively affect the productivity and health of small ruminants (Habeeb *et al.,* 2023). Therefore, expanding the understanding of heat stress impacts on small ruminant production is essential for developing and implementing effective mitigation strategies.

Multiple environmental factors contribute to the onset of heat stress in livestock. These include high ambient temperatures, relative humidity, direct and indirect solar radiation, wind speed, and precipitation. Among these, ambient temperature has the most significant impact on livestock wellbeing (Oguntunji *et al.,* 2019; Ayoola *et al.,* 2020; Joy *et al.,* 2020). Generally, livestock maintain normal physiological functions and productivity within a specific range of environmental conditions, known as the thermo neutral zone. When ambient temperatures exceed 80°F and relative humidity surpasses 70%, the body's natural cooling mechanisms become compromised (Sejian *et al.,* 2019).

The Temperature-Humidity Index (THI) provides a more precise measure of heat stress risk by combining ambient temperature and humidity levels into a single metric (Osei-Amponsah *et al.,* 2019). For goats, heat stress occurs at moderate THI levels (82-84°F), becomes severe between 84-86°F, and reaches extreme levels at THI ≥86°F (Danso *et al.,* 2024) (Figure 1). In addition to temperature and humidity, low wind speeds exacerbate heat stress by hindering the convective loss of excess body heat.

TEMP ° F	RELATIVE HUMIDITY															
	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
50 ° F	54	53	53	53	53	52	52	52	52	52	51	51	51	51	50	50
55 ° F	56	56	56	56	56	56	56	56	56	56	55	55	55	55	55	55
60 ° F	59	59	59	59	59	59	59	60	60	60	60	60	60	60	60	60
65 ° F	62	62	62	62	63	63	63	63	63	64	64	64	64	64	65	65
70 ° F	65	65	65	66	66	66	67	67	67	68	68	68	69	69	69	70
75 ° F	68	68	68	69	69	70	70	71	71	72	72	73	73	74	74	74
80 ° F	70	71	72	72	73	73	74	75	75	76	76	77	78	78	79	79
85 ° F	73	74	75	75	76	77	78	78	79	80	81	81	82[a]	83[a]	84[b]	84[b]
90 ° F	76	77	78	79	79	80	81	82[a]	83[a]	84[b]	85[b]	86[c]	86[c]	87[c]	88[c]	89[c]
95 ° F	79	80	81	82	83	84[b]	85[b]	86[b]	87[c]	88[c]	89[c]	90[c]	91[c]	92[c]	93[c]	94[c]
100 ° F	82[a]	83[a]	84[b]	85[b]	86[b]	87[c]	88[c]	90[c]	91[c]	92[c]	93[c]	94[c]	95[c]	97[c]	98[c]	99[c]

Figure 1. THI heat stress zones: [a]Moderate (yellow) 82 - 84 °F, [b]Severe (orange) 84 - 86 °F, [c]Extreme (red) ≥86 °F (Danso *et al*., 2024).

Furthermore, direct exposure to sunlight increases heat accumulation in animals, highlighting the critical role of providing adequate shade to mitigate heat stress effects.

PHYSIOLOGICAL RESPONSES TO HEAT STRESS

Decline in reproduction

Animals' reproductive systems are more temperature-sensitive than the rest of their bodies. At high ambient temperature, several organs of the reproductive system in both sexes of the animal are affected. In males, it reduces libido by affecting the level of testosterone, ejaculate volume, and sperm motility by increasing the proportion of morphologically abnormal sperm in the ejaculate (Afsal *et al.,* 2018). In females, it decreases the size of ovarian follicles, maturation of oocytes (Mustafi *et al.,* 2009). Additionally, it influences the rate of conception and the growth of embryos (Mustefa *et al.,* 2019).

According to Fatet *et al*. (2011) and Ribeiro *et al.* (2018), the data demonstrated that the dairy goats subjected to extreme heat stress conditions showed the lowest reproductive performances. A strong influence of environmental fluctuations on reproductive characteristics of small ruminants has been noticed in the literature (Das *et al.,* 2016; Mustefa *et al.,* 2019; Hansen, 2019). One of the primary factors affecting goats' rate of conception is the mating season. Climate can have detrimental effects on livestock's ability to reproduce (El-Tarabany and El-Bayoumi, 2015). Heat stress disrupts the hormonal secretions from the ovaries and hypothalamo-hypophyseal regions. Additionally, it is linked to a modification of the uterine environment, a change in folliculogenesis, and a decline in oocyte quality (Marai *et al.,* 2004). Reduced fertility, higher anovulatory anoestrus, delayed recovery of ovarian activity, and increased embryonic mortality are the results of these changes in reproductive function (Marai *et al.,* 2004; Sejian *et al.,* 2012).

The fertilisation of oocytes to create good, viable, and genetically promising concepts is directly related to Buck's fertility. Males in mammalian species have a special physiological mechanism called testicular thermoregulation that allows them to continue reproducing even in harsh environmental circumstances. The effectiveness of local thermoregulation in ruminants is largely dependent on the higher density of sweat glands in their scrotum. An effective sperm production process requires that the testicular temperature be 4–5°C lower than the rectal temperature (Mishra *et al.,* 2013). According to Nichi *et al.* (2006), elevated temperatures impair the oxidative metabolism of glucose in spermatic cells due to mitochondrial dysfunctions, reactive oxygen species buildup, and increased lipid peroxidation, all of which contribute to sperm deformity. Male heat stress affects spermatogenesis, endocrine secretions, testicular function, sexual activity, and the physical and chemical properties of semen, among other biological events. Low sperm quality can result from environmental temperature extremes. High temperature can also affect semen production and quality during epididymal maturation or spermatogenesis, not only at the moment of semen collection but up to 70 days before collection (Krishnan *et al.,* 2017).

Weakened immune system

The immune system is the body's primary line of defence. Key indicators of immune function, like white blood cells (WBCs), red blood cells (RBCs), haemoglobin, packed cell volume, glucose, and protein levels, are affected by thermal stress (Ayoola *et al.,* 2023). WBC counts rise by 21-26%, while RBC counts fall by 12-20% in thermally stressed cattle, likely due to RBC destruction or thyroid and lymphatic tissue dysfunction. Sejian *et al.* (2012) observed significant variations in haemoglobin, packed cell volume, plasma glucose, total protein, and albumin levels in Malpura ewes exposed to different temperatures. This PCV increase is an adaptive response to provide more water to the bloodstream, which is essential for evaporative cooling (Al-Haidary, 2004). In contrast to these findings, Atasoglu *et al.* (2008) reported a reduction in haemoglobin and Packed cell volume levels caused by either RBC membrane damage from free radicals or insufficient nutrients for Hb synthesis due to reduced feed intake.

Cortisol is released into the bloodstream of animals experiencing heat stress, causing a reduction in L-selectin expression on the surface of neutrophils (Bagath *et al.,* 2019). These WBCs become less effective at adhering to blood vessel walls and moving towards sites of infection or tissue damage to combat pathogens, resulting in increased disease susceptibility. Increased circulating cortisol also increases the levels of heat shock proteins (HSPs) in the cell. HSPs alert the immune system of potential danger, prompting the destruction of harmful bacteria by increasing the activity of immune cells like neutrophils and macrophages (Choudhury and Mandrekar, 2019). Regular blood testing is crucial in evaluating the health of animals in hot and humid environments.

Elevated physiological variables

Goats, as homeothermic animals, possess physiological mechanisms to regulate body temperature under thermal stress. Increased muscle activity during elevated respiratory rates and reduced peripheral vascular resistance enhances blood circulation to dissipate heat through the skin, often accompanied by a rise in heart rate. This elevated pulse facilitates blood flow from the body's core to its periphery, promoting heat dissipation through conduction, convection, radiation, and water loss via skin diffusion. In goats, the average heart rate is approximately 90 beats per minute, ranging from 70 to 120 beats per minute under normal conditions (Swenson & Reece, 2006; Akinmoladun *et al.,* 2023).

Heat exchange in mammals, including goats, largely occurs through the skin, where blood flow adjusts to regulate rectal temperature. Vasodilation and the redistribution of blood flow to the skin's surface enhance heat dissipation, dependent on the temperature gradient between the body and the environment. Insensible heat loss, such as evaporation, becomes critical when superficial temperature rises due to increased peripheral blood flow (Ribeiro *et al.,* 2018). Under thermally neutral conditions, skin surface temperature remains approximately 5–6°C lower than the body's core temperature. However, extreme environmental temperatures can minimise this gradient, as surface temperature approaches core temperature (Silpa *et al.,* 2021).

Peripheral vasodilation occurs in response to heat stress, promoting heat loss, while cold stimuli trigger vasoconstriction to conserve heat. The extent of heat dissipation varies with climatic factors, such as season and time of day, and physiological conditions like vascularisation and sweating. Goats, with their smaller body size and greater surface area relative to mass, are more efficient at dissipating heat than larger ungulates (Soriani *et al.,* 2013). Elevated ambient temperatures enhance heat loss through the skin and respiratory tract, balancing the body's thermal state.

When heat dissipation is insufficient, rectal temperature rises, and goats activate compensatory morphological, haematological, and biochemical mechanisms to maintain thermal equilibrium. These adaptive responses underscore the species' resilience to thermal stress and its reliance on integrated physiological pathways for temperature regulation.

Altered rumen physiology

Rumen physiology is negatively impacted under heat stress, making ruminants more prone to metabolic disorders and other health problems (Nardone *et al.,* 2010; Soriani *et al.,* 2013). The microbial population and pH of the rumen are altered, and roughage consumption is reduced (Nardone *et al.,* 2010; Soriani *et al.,* 2013). This causes a reduction in rumen motility, effectively disrupting the digestion process in ruminants. Rumen motility is crucial for efficient digestion in ruminants. It facilitates the thorough mixing of ingested feed with saliva and rumen microbes, which helps break down fibrous materials and enhances nutrient release. It also supports rumination, where the animal re-chews food to further aid digestion and stimulate saliva production, which buffers acids in the rumen. Additionally, it plays a key role in removing gases produced during digestion, preventing discomfort and conditions like bloat. Reduced rumen motility will result in less efficient digestion, ultimately affecting the animal's health and nutrient intake (Nardone *et al.,* 2010; Soriani *et al.,* 2013). Heat stress also results in hypofunction of the thyroid gland, causing the animal to reduce metabolic heat production (Afsal *et al.,* 2018).

Acid-base imbalance

Animals under heat stress exhibit increased respiratory rate and sweating, causing loss of body fluids. This increases the body's requirements for maintaining blood homeostasis and hydration. As the respiratory rate increases, the lungs expel more carbon dioxide (CO_2), lowering the concentration of carbonic acid in the blood. This gives rise to respiratory alkalosis, a condition where the blood becomes too alkaline. This imbalance can disrupt various bodily functions and may result in symptoms such as dizziness, tingling in the extremities, and muscle cramps. To maintain the equilibrium of carbonic acid and bicarbonate in the blood, animals excrete excess bicarbonate through their urine when blood pH becomes too high (Archana *et al.,* 2018). Prolonged hyperthermia can result in severe loss of appetite, thereby increasing carbonic acid buildup in the rumen. Rumen pH consequently drops, resulting in subclinical or acute rumen acidosis (Mlynek *et al.,* 2022).

Oxidative stress

Heat stressed animals have increased reactive oxygen species (ROS) in different cells and tissues ~~of~~ due to oxidative stress, and these can disrupt normal physiological functions and body metabolism. Antioxidants that help counteract these effects include superoxide dismutase (SOD), glutathione (GSH) peroxidase, and catalase; non-enzymatic antioxidants like albumin, L-cysteine, homocysteine, melatonin, and protein sulfhydryl groups; and non-enzymatic low molecular weight antioxidants such as ascorbic acid, GSH, uric acid, α-tocopherol, β-carotene, pyruvate, and retinol. In response to stressors, the body may also increase the production of these antioxidants to provide additional protection (Okoruwa *et al.,* 2014).

Other ways in which heat stress impacts body physiology include an increase in rectal temperature, which is a key measure as even a 1°C change can be significant (Karkori, 2024) and heart and pulse rate. Goats typically maintain a heart rate of 90 to 95 beats per minute under normal conditions. However, when subjected to heat stress, this rate increases to a range of 74 to 91 beats per minute, highlighting the significant strain placed on their cardiovascular system (Leite *et al.,* 2017).

HEAT STRESS EFFECTS ON PRODUCTIVITY

Effect on feed/water intake and body weight gain

Heat stress significantly impacts the performance and physiological well-being of animals, leading to reduced feed intake and body weight. In goats, thermal stress diminishes dry matter intake, as highlighted by Cruz *et al*. (2011) and Chauhan *et al*. (2016). This reduction results in decreased daily weight gain and body weight (Ribeiro *et al.,* 2018), attributed to the increased energy requirement for heat dissipation through respiratory evaporation, which limits the availability of water for metabolic storage (Habeeb *et al.,* 2023). Notably, dairy goats experience a 30% decline in dry matter intake during heat stress (Cruz *et al.,* 2011). To mitigate these effects, researchers recommend dietary modifications, including increasing nutrient density, maintaining feed intake, and incorporating strategies to minimise thermal stress (Baumgard and Rhoads, 2023).

Water is an essential nutrient for goats, playing a pivotal role in maintaining physiological functions, including thermoregulation, reproduction, digestion, waste elimination, and nutrient transport (Akinmoladun *et al.,* 2023). The demand for water increases under heat stress due to losses from evaporation, urine, faeces, and milk production. Environmental factors such as high temperatures, solar radiation, and water scarcity exacerbate these challenges, particularly in arid and remote grazing areas (Marai *et al.,* 2008). While water is critical for sustaining livestock performance, it is often overlooked compared to feed ingredients. Goats exhibit remarkable adaptability to drought and heat stress, surpassing sheep in water conservation due to their browsing diet (Danso *et al.,* 2024). When exposed to heat stress, goats demonstrate a substantial increase in water intake to enhance heat dissipation through sweating and panting (Rahardja *et al.,* 2011). Heat-stressed goats evaporate up to three times more water than non-stressed controls, utilising this mechanism to maintain thermal equilibrium.

High environmental temperatures directly influence the hypothalamic appetite centre, reducing feed intake in livestock (Habeeb *et al.,* 2023). For instance, lactating cows exhibit a decline in feed intake at 25–26°C, with a sharp reduction above 30°C, reaching up to 40% at 40°C. Similar patterns occur in buffalo heifers and dairy goats, with feed intake decreasing by 8–10% and 22–35%, respectively (Hooda & Singh, 2010). Additionally, animals under heat stress face increased maintenance energy demands for thermoregulation, leading to a negative energy balance (NEB), weight loss, and reduced body condition scores (Baumgard and Rhoads, 2023). Although goats and sheep are more resilient to heat stress than other livestock species, prolonged exposure may overwhelm their thermoregulatory mechanisms, compromising their ability to maintain body thermal balance (Danso *et al*., 2024).

Lower milk yields

Milk is one of the primary products derived from female goats, and its production is influenced by various environmental factors, including genetics, lactation stage, physiology, climate, and nutrition. These factors significantly affect milk productivity, particularly in genetically improved animals, as they are more sensitive to environmental challenges (Islam *et al.,* 2021).

Heat stress is a critical environmental factor that negatively impacts milk production in goats. Under heat stress conditions, a substantial amount of energy is diverted from milk synthesis to maintaining thermoregulation. Reduced feed intake further exacerbates this issue, as goats consume fewer nutrients required for optimal milk production. Additionally, dehydration and metabolic disturbances caused by elevated temperatures strain the animal, leading to reduced milk yields. High-producing animals, due to their greater metabolic heat generation, are particularly vulnerable to heat stress. This heightened sensitivity lowers the threshold temperature at which milk production declines (Nardone *et al.,* 2010; Lian *et al.,* 2020).

Successful dairy goat farming requires a production system that incorporates specialised animals, proper nutritional and reproductive management, and, most importantly, adequate thermal comfort. Thermal stress leads to a reduction in feed intake, an increase in water consumption, and decreased milk production (Nair *et al.,* 2021). Moreover, heat stress adversely affects milk composition, reducing fat content and total solids due to inadequate diets and high ambient temperatures (Nguembou *et al.,* 2014).

The association between heat stress and reduced milk, fat, and protein yields is well-documented (Dalcin *et al.,* 2016; Galik *et al.,* 2021). Early lactating goats experiencing heat stress show a 9% reduction in milk production, with significant declines in milk fat and protein percentages and elevated somatic cell counts (Rong *et al.,* 2019). The temperature-humidity index (THI) is a key measure used to assess the environmental heat load on animals. Goats generally maintain normal milk production up to a THI level of 80, with moderate decreases observed between THI 80 and 85. However, milk yield is severely impacted when the THI exceeds 85, with reductions attributed to decreased feed intake and metabolic adaptations (Miztal, 2017; Camargo *et al.,* 2022).

Heat stress also alters metabolic pathways in the mammary glands of lactating goats. It disrupts glycolysis, lactose synthesis, ketogenesis, the tricarboxylic acid (TCA) cycle, and amino acid and nucleotide metabolism, thereby impairing the supply of essential precursors for milk production. These metabolic modifications significantly impact both milk synthesis and composition (Miztal, 2017; Carabano *et al.,* 2019).

Reduction in meat quality

Heat stress significantly alters the physiology and metabolism of animals, impacting redox balance, apoptosis, and various biological processes that influence meat quality. Reduced feed intake and hyperthermia associated with heat stress lower glycogen concentrations, predisposing muscle to a higher ultimate pH, which aligns with the definition of dark firm dry (DFD) meat (pH ≥ 5.8 or 6.0). When glycogen concentrations remain above the threshold for postmortem glycolysis, acute heat stress before slaughter can cause a rapid decline in muscle pH, leading to pale soft exudate (PSE) meat (Gonzalez-Rivas *et al.,* 2021).

Physiological mechanisms and behavioural adaptations that confer heat tolerance can mitigate the adverse effects of heat stress on meat quality. These adaptations reduce muscle fatigue, potentially enhancing meat tenderness. Additionally, metabolic changes under heat stress may decrease fat breakdown, improving the flavour and aroma of the meat. However, severe or prolonged heat stress can overwhelm even climate-adapted animals, negatively impacting meat quality when coping mechanisms fail.

Heat stress also influences carcass quality, as evidenced by alterations in subcutaneous and intramuscular fat (IMF) levels (Park *et al.,* 2018). Meat colour, which depends on myoglobin concentration and its chemical state, is affected by changes in pH and oxidation under thermal stress. Research indicates that heat stress often increases meat redness and reduces lightness, with enhanced colour stability attributed to a higher ultimate pH and altered oxidation state, causing the meat to appear darker than normal (Zhang *et al.,* 2020). One of the most consistent negative outcomes of heat stress in ruminants is the increased prevalence of DFD meat, characterised by higher ultimate pH (Misztal, 2017). Heat-stressed ruminants also produce meat with reduced water-holding capacity (WHC) (Kadim *et al.,* 2008; Archana *et al.,* 2018). This reduced WHC is often associated with lower ultimate pH, potentially resulting from oxidative protein modifications caused by heat-induced oxidative stress. Beyond WHC, heat stress also impacts meat tenderness (Kadim *et al.,* 2008; Zhang *et al.,* 2020).

BEHAVIORAL RESPONSES TO HEAT STRESS

Seeking shade

Extreme thermal stress in goats can lead to observable signs such as lack of coordination, palpitations, and recumbency. Animals adapted to desert environments often exhibit nocturnal activity patterns, becoming more active during the night to avoid the adverse effects of high daytime temperatures. Shade-seeking behaviour represents a prominent adaptive strategy, wherein goats seek shelter under trees, bushes, or artificial structures to reduce heat exposure. In the absence of shade, they may adopt a vertical posture relative to the sun to minimise the body surface area exposed to solar radiation (Sejian *et al.,* 2022). Additionally, goats may adjust their posture—standing or spreading out—to enhance heat dissipation and often decrease their activity levels during periods of thermal stress.

Animal housing plays a critical role in ensuring the welfare and productivity of goats. Properly designed sheds with adequate space, ventilation, and hygiene provide optimal comfort and reduce heat stress (Cui *et al.,* 2019). Goats exhibit preferences for solid, dry flooring and often rest against walls rather than lying in the centre of pens, possibly as an anti-predator strategy (Danso *et al.,* 2024). Housing environments that are clean, dry, and well-ventilated are essential to maintaining goat health and comfort, protecting them from disease risks, and promoting behavioural adjustments that indicate optimal welfare (Berihulay *et al.,* 2019).

Effective housing design incorporates three key principles: comfort around resting, thermal comfort, and ease of movement. These principles ensure that goats can express their natural behaviours and cope with environmental challenges. During peak sunlight hours, for instance, goats instinctively seek shaded areas to mitigate heat stress. By reducing exposure to solar radiation and remaining inactive in shaded locations during the hottest parts of the day, typically mid-afternoon, goats effectively manage their heat load and maintain physiological stability (Sejian *et al.,* 2022).

Changes in grazing patterns

Under elevated ambient temperatures, grazing ruminants exhibit a marked reduction in grazing activity, opting instead to minimise movement by resting and seeking shelter in shaded areas (Renaudeau *et al.,* 2012; Danso *et al.,* 2024). These behavioural adaptations, including standing and resting, are crucial for mitigating heat absorption from the ground and enhancing heat dissipation efficiency.

The interplay between thermal strain and nutritional intake often results in nutritional deficiencies, primarily due to a significant reduction in feed consumption under heat stress conditions. Heat stress directly influences the hypothalamic feeding centre, triggering hormonal responses that may suppress metabolic rate (Berihulay *et al.,* 2019; Danso *et al.,* 2024). To mitigate the production of metabolic heat—an inevitable byproduct of digestion, heat-stressed animals deliberately decrease their food intake (Okoruwa, 2014).

Moreover, heat stress has been shown to elevate maintenance energy requirements by approximately 30% (Al-Dawood, 2017). Although the resultant bioenergetic state is akin to the negative energy balance observed during early lactation, it does not reach the same extent. This negative energy balance induces a spectrum of metabolic and hormonal changes.

Goats, in particular, adjust their grazing behaviors in response to thermal stress. They tend to be more active during cooler periods, such as early mornings and late evenings, while significantly reducing or entirely avoiding grazing during midday, when temperatures peak (Sejian *et al.,* 2022). This temporal shift in grazing activity minimizes additional heat production associated with digestion and physical exertion, thereby conserving energy and mitigating the risk of hyperthermia.

Increased social distancing

Goats may spread out to avoid crowding, which can increase body heat exchange. During high-temperature conditions, goats are more likely to distance themselves from other members of the herd to prevent further heat accumulation through close physical proximity (Okoruwa, 2014). Crowding can hinder effective heat dissipation, so goats maintain personal space as a way to regulate body temperature. Heat stress can also reduce the frequency of aggressive or competitive behaviours among goats, such as butting or fighting for dominance (Sejian *et al.,* 2022).

This is likely a way to conserve energy and avoid generating excess body heat from physical exertion. Physical activity generates heat, which can exacerbate the effects of heat stress. To counteract this, goats reduce their overall activity levels during periods of intense heat. They may spend more time resting or lying down, minimising movement and energy expenditure (Baumgard and Rhoads, 2023). Reduced activity helps lower their internal body temperature and decreases the heat burden they experience.

ADAPTATION AND RESILIENCE STRATEGIES

Genetic selection

Recent advancements in phenomics, genomics, and transcriptomics have significantly enhanced the ability to accurately select heat-tolerant animals without compromising productivity traits, such as milk yield (Carabaño, 2019). The integration of sequence data and gene expression studies facilitates the persistence of genomic breeding values across breeds and generations. Furthermore, genome-wide association studies (GWAS) have proven instrumental in identifying specific genomic regions linked to economically important traits in ruminant livestock (Pryce *et al.,* 2016).

Signatures of selection in small ruminants, such as sheep and goats indigenous to hot, arid environments, have been elucidated through genome-wide SNP scans, leading to the identification of several candidate regions associated with environmental adaptation (Sejian *et al.,* 2019). These findings offer a foundation for exploring ruminant evolution and functional genomics in species inhabiting similar climates. Notably, candidate genes associated with small ruminant adaptation include those coding for growth hormone (GH), growth hormone receptor (GHR), insulin-like growth factor (IGF-1), leptin receptor (LEPR), and thyroid hormone receptor (THR)

(Hayes *et al.,* 2013). Genes related to heat stress resilience, such as heat shock factor 1 (HSF1), heat shock protein 60 (HSP60), HSP70, HSP90, and ubiquitin, are also prominent. Among these, HSP70 is widely recognised as a genetic marker for thermotolerance in small ruminants. The identification of such cellular and molecular markers is pivotal for the development of climate-resilient breeds (Hayes *et al.,* 2013; Sejian *et al.,* 2019).

Phenotypic variations among Santa Ines sheep illustrate differences in heat tolerance, with white-coated sheep exhibiting greater resilience compared to those with longer, thicker, and darker coats, which are more susceptible to heat stress. Similarly, wool-bearing sheep display reduced adaptability to tropical climates (Hicey *et al.,* 2024). Breed-specific responses to heat stress (HS) have been documented, with breeds possessing less thermal insulation demonstrating more efficient physiological mechanisms for heat dissipation (Aleena *et al.,* 2018). While environmental modifications and nutritional strategies can mitigate the impact of thermal stress, long-term adaptation strategies, including selective breeding for heat tolerance, are essential. Identifying and breeding goats with superior heat tolerance can incrementally improve herd resilience to hot climates. Although the genetic mechanisms underlying heat adaptation are not fully elucidated, mitochondrial genes have been implicated due to their role in energy metabolism. Mitochondrial DNA exhibits rapid evolutionary rates, maternal inheritance, and conserved gene content, which may influence heat tolerance (Zhao *et al*., 2023; Hicey *et al.,* 2024).

Heat shock proteins (HSPs) are critical in thermotolerance and serve as markers in assisted selection and genome-wide selection programs aimed at developing heat-tolerant breeding bulls. Major HSP families include HSP100, HSP90, HSP70, HSP60, HSP40, and small HSPs (<30 kDa), all of which play essential roles in cellular recovery from stress and protection against damage (Ghosh et al., 2018). Under heat stress, HSP gene expression is modulated through the activation of heat shock transcription factor 1 (HSF1), upregulation of HSP genes, downregulation of other proteins, increased glucose and amino acid oxidation, decreased fatty acid metabolism, activation of the endocrine stress response, and immune system modulation via extracellular HSP secretion.

A complex genetic network underlies the adaptation of animals to hot or arid environments (Li et al., 2024). Genomic studies have facilitated the identification of thermotolerant genes regulating body temperature in small ruminants (Aleena *et al.,* 2018). Garner *et al.* (2016) demonstrated that incorporating DNA markers distributed across the genome enhances the prediction of heat stress tolerance and other traits. In desert-adapted sheep, Kim *et al.* (2016) identified chromosome 10 (OAR10) as harbouring multiple stress-related genes, including those involved in tumour suppression, angiogenesis, and wound healing. In goats, stress-related genes were located within a selection sweep region on chromosome 6 (26–46 Mb). Mwacharo *et al*. (2017) identified 11 potential selection sweep regions across 12 chromosomes in Egyptian sheep subjected to heat stress.

Hair sheep breeds generally exhibit superior heat stress adaptation due to lower thyroid hormone concentrations, reduced metabolic heat production, and slower respiration rates compared to wool breeds. Zulfiqar *et al.* (2021) reported that skin and coat characteristics in these breeds facilitate heat stress adaptation. Dorper × Pelibuey ewes, for instance, display high adaptive capacity to summer heat stress by maintaining normal rectal temperatures and efficiently dissipating body heat through increased respiratory rates and skin temperatures (Aleena *et al.,* 2018). Additionally, reduced kidney function during summer may indicate activation of dehydration-prevention mechanisms, contributing to the maintenance of homeothermy (Zhao *et al.,* 2023; Hicey *et al.,* 2024).

MANAGEMENT PRACTICES FOR HEAT STRESS MITIGATION

Successful adaptation strategies for heat stress in goats often involve a combination of management practices, genetic selection, and environmental modifications (Bagath *et al.,* 2019). Proactive health management also involves monitoring livestock for signs and symptoms like panting, fast breathing, and decreased feed intake allows for early management and implementing timely interventions to prevent heat-related illnesses (Sejian *et al.,* 2018). Let us take a deeper dive into some of these management practices below:

Adaptive nutrition and feeding

Alteration of nutrition requirements due to heat stress necessitate reformulation of diets. Since energy is generally the most limiting factor, the forage component of rations should be reduced in favor of concentrates which are more energy dense (Aggarwal and Upadhyay, 2013). It is also important to consider how diet impacts heat production in the body of the animal. Low forage to concentrate ratio diets reduce acetate metabolism which is closely linked to heat production (Atrian and Shahryar, 2012). Adjusting the fat content in the diet of heat-stressed dairy goats can positively impact their physiological response and milk production (Chumak *et al.,* 2021).

Increasing the protein content of the diet can help offset a reduction in feed intake, but it may also result in excessive nitrogen consumption (Zhang *et al.,* 2020). Crude proteins produce more heat when metabolized compared to starch or fat, contributing to increased endogenous heat production. Beyond the amount of protein provided, the quality of the protein source should be considered as well. Dietary essential amino acids may contribute to the prevention of heat stress. Methionine is a primary amino acid that is often lacking in ruminant diets. When supplemented, it can improve milk yield, milk composition, and antioxidant capacity in dairy cows (Han *et al.,* 2009 and Han *et al.,* 2018). Rumen-protected methionine supplementation reduces lymphocyte apoptosis and modulates the expression of apoptosis-related genes, increasing Bcl-2 and decreasing Bax mRNA abundance (Han et al., 2009). It also enhances the immune response by increasing the phagocytic capacity of neutrophils and monocytes, and improving antioxidant status through glutathione production (Lopes *et al.,* 2019).

Incorporating additives like vitamins C, E and live yeast into feed can offset the impact of heat stress (Alabi *et al.,* 2021; David, 2023). Combining vitamin C with electrolyte supplementation was shown to alleviate oxidative stress and enhance cell-mediated immunity in buffaloes (Ocheja *et al.,* 2020). The antioxidant nature of vitamin C and E regulates the animal's health condition and shields the body's defence system from an excessive amount of free radical formation (Leite *et al.,* 2017). Adenkola and Okoro (2014) also found that supplementing with vitamin E and C reduced the temperature and respiration rate of the rectal area of rams. Supplementation of electrolytes, particularly sodium and potassium, during heat stress helps improve the regulation of blood acid-base balance, thus maintaining normal body status (Al-Haidary, 2004). Live yeast enhances the digestibility of nutrients by increasing the production of volatile fatty acids in the rumen (Li *et al.,* 2023), decreasing the production of ruminal ammonia and increasing the ruminal microorganism population (Zhang *et al.,* 2020).

Nevertheless, further evaluations of the efficiency of dietary protein utilisation are required. To minimise the combined impact of metabolic heat production and environmental heat stress, it is advisable to feed animals during the cooler parts of the day, such as before sunrise, during dawn, and at night encourages them to maintain their regular feed intake (Dwyer, 2022). Furthermore, feeding animals more frequently reduces the amount of variation in ruminal metabolism throughout the day and improves feed utilisation efficiency in the rumen (Ghosh *et al.,* 2018).

Water provision and hydration management

Water is vital for the proper functioning of all bodily systems and life itself. It is a basic molecule in the body of vertebrates, and plays a major role in the elasticity of tissue (by electrolyte balance and osmotic regulation), lubrication and thermoregulation, nutrient transport and excretion. Water shortages can adversely affect the health of goats, leading to decreased food consumption, higher body temperature and breathing rate, hypoglycemia, and increased blood urea nitrogen (Kaliber *et al.*, 2016). Providing access to plenty of fresh, cool drinking water is extremely important during hot weather (Kim *et al.,* 2016; Atrian and Shahryar, 2012). On average, sheep and goats should consume approximately 1-2 gallons of water daily, with lactating individuals requiring higher quantities. This can be achieved by stocking enough watering equipment (making sure pressure is adequate to refill) and giving more water sources in the pasture (Atrian and Shahryar, 2012).

Physical modifications of environment

Adjusting the microenvironment to facilitate heat dissipation is a key consideration in hot environments. Offering shade is among the most straightforward and broadly applicable strategies (Bailey et al., 2018). According to Berihulay *et al.* (2019), providing shade for goats enhances weight gain, milk production, and reproductive performance and lowers rectal temperature. 30% to 50% less heat load can be achieved with a well-designed shade structure (Karkori, 2024).

A relatively small percentage of goats are kept in permanent housing, although the bulk are housed only at night and when grazing is unsuitable (Kandemir *et al.,* 2013). Goats graze outdoors mostly during the day, making it impossible to employ fans or evaporative cooling in semi-intensive systems. Alternative tactics, such as portable shades, are hence required. Trees offer a cost-effective way to provide shade and also cool their surroundings through the evaporation of moisture from their leaves (Onyewotu *et al.,* 2003). In the absence of natural shade, artificial shade structures can be used to provide protection from the harmful effects of solar radiation. Evaporative cooling systems, which use water in the form of fog, mist, or sprinkles with natural or forced air movement, and cooling ponds, can also be implemented (Atrian and Shahryar, 2012).

Overcrowding can exacerbate heat stress in goats by increasing competition for resources and limiting airflow. Improving ventilation, maintaining appropriate stocking densities and separating goats into smaller groups can reduce heat stress and improve overall herd welfare. For effective heat stress management, housing design and location should prioritise low radiation, cooler air temperatures, lower humidity, and high air velocity (Sejian *et al.,* 2012). Thoughtful consideration of space requirements, management of excrement buildup, and meticulous monitoring of temperature, relative humidity, and air quality are also imperative (Kandemir *et al.,* 2013). Furthermore, because of the lower natural air velocity in hot areas, totally enclosed shelters are not advised.

Proper transport and handling

Goats should be physically strong and in good health for transportation, and should have received recommended vaccinations and parasite control procedures (FAO, 2012). Prolonged travel causes weariness and possible health hazards. In order to prevent hunger and dehydration, pre-transport fasting periods should be kept to a minimum. Overloading can cause heat stress, injuries, and reduce access to food and drink (Nguembou *et al.,* 2014). Heat stress can be further exacerbated by high outside temperatures and inadequate ventilation, especially in humid tropical climates (Grewal *et al.,* 2018). Guidelines specify precise space allowances to guarantee the comfort and well-being of goats of various breeds and ages (OIE, 2018). It is also recommended that transport vehicles have secure flooring, good ventilation, and enough room to reduce slippage and injury (FAO, 2012). In order to prevent needless tension and injury, unloading should be done gently and effectively, after which water and shade should be made available to the animals (FAO, 2012). Enough time must be provided to recover from their transport voyage and relax before undergoing stressful operations or additional handling (Grewal *et al.,* 2018). Moreover, as little as possible should be done when handling animals. For example, milking can be done in the early morning or late evening; midday activities should be avoided while the body temperature is already up. Delaying afternoon milking for one to two hours is a useful strategy for preventing heat stress (Atrian and Shahryar, 2012).

APPLICATION OF SMART TECHNOLOGY FOR HEAT STRESS MONITORING AND MANAGEMENT

Advancements in smart technologies are revolutionising small ruminant production by facilitating the automated collection of critical health and behavioural data. The utilisation of accelerometers has highlighted the potential of wearable sensors to differentiate between grazing, standing, and walking behaviours in sheep, aiding in the detection of lameness (Lewis *et al.,* 2023) and investigating the effects of social isolation (Salvin *et al.,* 2020). Additionally, accelerometers combined with machine learning algorithms have been successfully employed to classify sheep behaviours based on posture and activity levels (Price *et al.,* 2022).

Multi-sensor tags, incorporating accelerometers, magnetometers, temperature sensors, and GPS, have been used in conjunction with geographic information systems (GIS) to assess feeding patterns, energy expenditure, and environmental factors influencing Merino sheep production (Di Virgilio *et al.,* 2018). Similar methodologies have been applied to examine the effects of climatic conditions on the grazing behaviour of Mongolian sheep (Horie *et al.,* 2023). Motion sensors embedded in collars have achieved classification accuracy rates ranging from 67–78% (Evans *et al.,* 2022) to 78–92% (Vazquez-Diosdado *et al.,* 2019) for behaviours such as eating, ruminating, standing, and lying, through machine learning algorithms. Accelerometer data have also been utilised to estimate urination volumes based on ewe squatting time, resulting in an average of 2.15 ± 0.04 L per day (Marsden *et al.,* 2021). Various tracking systems have been explored to determine animal positioning (Walker *et al*., 2024), with technologies such as UWB, infrared cameras, and 3D computer vision demonstrating high accuracy in monitoring the location and behaviour of small ruminants (Ren *et al.,* 2020).

GPS collars, often combined with machine learning algorithms (Liu *et al.,* 2023) or additional sensors like accelerometers and weather stations (Fogarty *et al.,* 2021), have been employed to detect lambing events with up to 91% accuracy (Evans *et al.,* 2022; Parnell *et al.,* 2023). Heat stress management in small ruminants has underscored the importance of real-time body temperature data collection, utilising methods such as surgical implantation, rumen boluses, and non-invasive techniques (Marsden *et al.,* 2021; Lewis Baida *et al.,* 2021). While surgical implants provide accurate temperature readings (38.3–39.9°C), their applicability in agricultural settings remains limited. Remote-controlled systems have been developed to assess pain responses in sheep, while wearable technologies monitor physiological parameters like heart rate and skin temperature to evaluate behaviour and stress, including during transportation (Cui *et al.,* 2019; Zhang *et al.,* 2020). Despite challenges related to energy autonomy and core temperature measurement accuracy (Kearton et al., 2020), these technologies offer significant potential for enhancing animal health monitoring. Validation of sensor data accuracy through ground-truth data and visual observation remains a critical area for further research (Liu *et al.,* 2023).

Sensor-equipped systems enable remote monitoring of environmental conditions and animal behaviour, providing valuable data on temperature, humidity, air quality, and activity levels to facilitate timely interventions for heat stress prevention (Price *et al.,* 2022). Parameters such as body temperature, pulse rate, respiratory rate, and activity levels are tracked in real-time, offering early warnings of heat stress. Remote monitoring tools, including rumen-reticular boluses, vaginal and rectal probes, ear canal sensors, and thermal imaging, have proven effective in this regard (Ren *et al.,* 2020). However, limitations exist as these systems often detect temperature deviations only after animals have exceeded homeothermic thresholds, potentially leading to productivity declines (Reis *et al.,* 2023). Telemetric measurements, while effective, are costly and constrained by range, tracking capacity, and monitoring duration, with radio frequency interferences potentially compromising data accuracy (Gaughan *et al.,* 2010).

GPS-based technologies are increasingly employed for outdoor animal tracking (Bailey *et al.,* 2018). Real-time location systems (RTLS), using fixed receivers to wirelessly gather location data from ID tags, are primarily utilised indoors or in confined areas where GPS signals may be unreliable (Boulos and Berry, 2017). Integration of GPS data with GIS facilitates the assessment of animal behaviour and pasture utilisation. RTLS data support the development of behavioural metrics and algorithms to monitor activities like eating and drinking, particularly in environments with poor satellite coverage or signal interference (Meunier *et al.,* 2017). Smart barns, equipped with sensors, actuators, and automated control systems, optimise environmental conditions by regulating ventilation, cooling, and humidity based on real-time data, thus creating comfortable environments for goats during heat stress periods. Machine learning and predictive analytics algorithms analyse historical and environmental data to forecast heat stress risks, enabling proactive management strategies (Nair *et al.,* 2021).

Thermal imaging cameras provide non-invasive detection of body temperature changes and heat distribu-tion in goats, identifying individuals or barn areas affected by heat stress for targeted interventions (Lopes *et al.,* 2019). Mobile applications designed for heat stress mana-gement offer real-time alerts, recommendations, and guidance based on weather conditions and goat physiology, aiding informed decision-making (Islam *et al.,* 2021).

Climate-smart livestock extension services leverage information communication technologies (ICT), including artificial intelligence (AI) and machine learning (ML), to address challenges within and beyond livestock extension systems. Despite ongoing deployment, ICT applications face hurdles such as language diversity, content localisation, and infrastructure limitations, including internet connectivity and smartphone access. Integrating conventional service delivery systems with communication tools can enhance information dissemination within farming communities.

Acquiring localised data on farming practices and resources is essential for developing tailored content. Subsequently, generating advisory information and forecasts for farmers and sharing this information with those with limited ICT access are critical steps. The Internet of Things (IoT), AI, and ML facilitate these processes. IoT devices enable non-invasive quantification of animals' physiological conditions and climatic stress, linking environmental factors with animal health (Sejian *et al.,* 2022). Periodic data capture allows for data ingestion, preprocessing, and AI model development. ML algorithms can estimate indices such as thermal stress (ITSC) and shade time (ITS), generating weather-specific advisories. These AI models, evaluated and deployed alongside conventional extension systems, enhance information sharing, providing near real-time advisory services to farming clusters through local and government farm collaborations.

The integration of IoT-enabled advisory systems with livestock extension services fosters real-time, data-based guidance for farming communities, addressing barriers related to ICT infrastructure, mobile access, and digital literacy.

SOCIO-ECONOMIC IMPLICATIONS

Goat meat commands a premium due to its unique flavour and perceived health benefits, which some consumers find more appealing than beef or lamb. Goat milk also offers notable nutritional value, particularly its high vitamin B1 content and relatively low cholesterol compared to cow milk. Although the medicinal properties of goat meat are not universally recognised, its perceived health benefits contribute to its higher price (Nair, 2021).

When considered collectively, it is evident that heat stress adversely affects both goat meat and milk quality (Kaliber *et al.,* 2016). Heat-stressed goats exhibit poor growth, reduced muscular mass, and lower-quality meat, which may decrease their market value and breeding demand. Preferred meat attributes such as shear force, cooking loss, water-holding capacity, pH, tenderness and colour are also decreased (Archana *et al.,* 2018).

These adverse effects translate into reduced revenue from sales, while increased costs for medical care, supplements, and preventive measures further strain the farmer's budget. Moreover, the potential for higher mortality rates adds to the financial burden by necessitating the replacement of lost animals and affecting herd stability. The financial stability of marginalised and impoverished farmers whose primary source of income is goat farming is endangered as a result. Goat farmers may need to make investments in cooling equipment such as fans, misters, shade structures, and enough ventilation in barns and shelters to hedge against the effects of heat stress. The total cost of manufacturing could go up as a result of these increased operational and infrastructure expenses.

FUTURE RESEARCH DIRECTIONS

Heat stress management

Developing effective strategies to mitigate heat stress in tropical climates is crucial for maintaining goat welfare and productivity. Research could explore novel cooling methods, such as alternative cooling materials or structures, to provide goats with relief from high temperatures.

Nutritional strategies

Investigating dietary interventions to improve heat tolerance and overall health in tropical goats is essential. Research could focus on formulating diets with ingredients that support heat stress resilience and optimise nutrient utilisation under hot and humid conditions.

Disease prevention and control

Tropical environments often harbour a variety of pathogens and parasites that can impact goat health and welfare. Research could explore innovative approaches to disease prevention and control, such as developing vaccines, improving diagnostic tools, and implementing integrated parasite management programs.

Breeding for resilience

Selective breeding for heat tolerance, disease resistance, and other desirable traits is essential for enhancing the resilience of tropical goat populations. Research could focus on identifying genetic markers associated with heat stress resilience and incorporating this information into breeding programs.

Behavioral adaptations

Understanding how goats behaviorally cope with heat stress in tropical environments can inform management practices that promote welfare. Research could investigate natural behaviours exhibited by goats during heat stress periods and develop strategies to encourage these behaviours in husbandry practices.

Housing and shelter design

Designing housing and shelter systems that are well-suited to tropical climates is critical for protecting goats from adverse weather conditions. Research could explore innovative architectural designs, materials, and ventilation systems to optimise thermal comfort and air quality in goat housing facilities.

Water management

Access to clean and sufficient water is essential for goat welfare, particularly in tropical climates where water availability may be variable. Research could focus on developing water management strategies, such as rainwater harvesting, water conservation techniques, and efficient watering systems, to ensure goats have access to adequate hydration.

Social and economic factors

Considering the social and economic context of goat farming in tropical regions is essential for implementing welfare improvements effectively. Research could explore the socio-economic factors influencing goat welfare practices and identify barriers and opportunities for enhancing welfare within local communities.

CONCLUSION

Effective heat stress management in tropical goat farming requires a comprehensive approach integrating proven adaptation strategies, emerging technologies, and continuous research efforts. Key adaptation measures include adequate shelter, optimised nutrition, and efficient cooling systems, which collectively enhance goat welfare and productivity. Technological advancements, such as heat stress monitoring devices, enable early detection and mitigation of thermal stress, improving management efficiency.

Further research is essential to develop nutritional strategies that enhance heat tolerance and nutrient absorption, explore innovative disease prevention methods, and advance selective breeding for resilience. Additionally, understanding behavioural adaptations to heat stress can refine management practices, while optimised housing design improves thermal comfort and air quality. Sustainable water management and the integration of social and economic factors are crucial for practical implementation. A multidisciplinary approach combining these strategies will ensure the long-term sustainability of goat farming in tropical climates, benefiting both animals and farmers..

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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