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Thermoregulation in Sheep and Goats: A Review

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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Review Article

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ABSTRACT

Thermoregulation is the capability of an animal to maintain its core internal temperature by homeostasis. Small ruminants like sheep and goats acclimate to different environmental changes and often perform better during heat stress than other ruminants. Adapting small ruminants to exceptional weather events occurs through behavioral, genetic, physiological, and morphological mechanisms. Small ruminants can mitigate the consequences of thermal stress using behavioral strategies such as consuming more water, looking for shade, consuming less feed, standing instead of lying down behavior, and other morphological mechanisms such as size, shape, coat color, coat depth, pigmentation, and fat storage. Small ruminants also respond to thermal changes through physiological mechanisms such as variations in respiration, heart rate, core temperature, sweating rate, metabolic rate, and endocrine functions. From the genetic point of view, animals could inherit traits that favor their survival in specific climatic conditions. The adaptation of small ruminants to different thermal environments is determined by an elaborate network of genes with specific genome-wide DNA markers improving toleration to excessive heat. Therefore, genetic identification and analysis of thermotolerance genes should be applied as markers in breeding programs.

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1. INTRODUCTION

Small ruminants like sheep and goats have been primarily kept in various environments and grazing systems, requiring multiple adaptations, especially concerning temperature changes through thermoregulation [1]. From a biological perspective, thermoregulation can be defined as how animals maintain their core internal temperature through the physiological process of homeostasis [2]. The effect of the heat surroundings on animals is mainly achieved via energy exchange which involves convection, conduction, radiation, and evaporation [3]. Many factors (e.g., breed, genetics, health state, body condition, and skin color) affect metabolism, thermal exchange rate, and insulation, all of which contribute to animal thermal comfort [4]. The optimal internal temperature ranges for different animals and is determined by several factors, including the temperature of the ambient environment and energy requirements [5]. Throughout the world, small ruminants are affected by heat stress regularly [6,7]. As a limiting factor, excessive heat stress can lead to impaired production, reproduction, compromised natural immunity, and increased susceptibility to diseases, in general, the well-being of the animals [1,4]. Heat stress affects ruminants s through various environmental factors like extreme temperatures, high solar radiation, relative humidity, wind, rainfall, and nutrition [8]. However, sheep and goats adapt to different environmental changes and often perform better during heat stress than other ruminants [1]. This review explains the process of thermoregulation in sheep and goats. It describes various physiological features of ruminants that enhance their ability to perform better during stress.

Small ruminants adapt to severe weather conditions through behavioral, genetic, physiological, and morphological mechanisms that are divided into those that modulate heat production rates and the rate at which heat flows in and out of the organisms. From a morphological perspective, the coat color of the sheep or goat plays a critical function in the absorption of heat, with the light-colored coated animal absorbing less heat than those with darker coats. Genetically, scientific evidence has shown that different genetic factors enable sheep and goats to thrive well in heat-stressed environments [9]. Other genes associated with adaptability to temperature changes have been found in sheep and goats, including HSP70, which is a set of heat shock protein genes that defend the animals from overheating, and the ENOX2 gene, which has been found in goats susceptible to heat stress [10,11]. Other polymorphic genes, including MCIR, ASIP, and TYRP1, have been observed in different sheep species and are related to wool color, which controls the rate of heat absorption [12]. Accordingly, ruminants' capability to endure, develop, and produce in harsh climates is responsible for their adaptation to different climates. The current review provides an integrative discussion of the various adaptative responses of small ruminants in hot climates.

2. ADAPTATION OF ANIMALS TO ENVIRONMENTAL STRESS

Different environmental states affect the productivity of livestock while also having an impact on various physiological parameters [13]. An animal's body undergoes a chain of physiological, anatomical, and behavioral changes when the temperature rises above the thermoneutral zone, including reduced feed intake, reduced performance (growth, reproduction, and milk production), a drop in activity, an acceleration of breathing rate and core temperature, as well as changes in peripheral blood flow, sweating, and endocrine function [3,14,15]. There is evidence that thermal stress affects dynamic digestion and neuroendocrine factors linked to metabolism [1]. Reducing feed intake is a significant cause of declined milk production in livestock species [14]. Several research studies have investigated the relationship between ecological changes and animal response [1,7,16]. According to a research study by Leite [17], livestock tends to show reduced productivity levels under high environmental radiation due to changes in their physiological processes. As expected, animals often develop adaptive features to cope with environmental changes to guarantee survival. In their study, Leite [17] highlighted hair characteristics as one of the features directly associated with heat exchanges with the environment. Hair structure serves two primary functions: protection from direct solar radiation and promoting heat loss through convection and evaporation. The efficiency of the performance of these roles is entirely dependent on the hair coat's physical structure (coat color, depth, length, and pigmentation) [18]. Animals with dark coats are more likely to be affected by heat than those with lighter coats. Helal [19] mentioned that an increase in thermal insulation occurs with an increase in coating depth.

Air space between hair fibers increases, which can be attributed to this phenomenon. An animal's long hair is an insulator, protecting its body and surroundings [18]. Therefore, the form of the hair coat is considered a prominent physical thermoregulatory feature of livestock, especially in sheep and goats. Other physiological changes involved the reduction of the basal metabolic rate, modifications in the acid-base balance, and hormonal balance changes [14,15]. Heat stress significantly induces the synthesis of hormones connected to metabolic processes (thyroid hormones, somatotropins, and glucocorticoids) and fluid balance (aldosterone and antidiuretic hormone). When heat stress occurs, thyroid hormone secretion is reduced. As heat stress persists, growth hormone secretion rates reduce [14]. In response to stress, animals release adrenal corticoids, primarily cortisol, from their adrenal glands [15, 20, 21]. Therefore, thermoregulation is part of a homeostatic mechanism to maintain the animal at an ideal temperature despite extreme temperatures outside [22]. From the viewpoint of genetics, animals can inherit traits that favor their survival in specific environmental conditions [9]. Berihulay [9] reported that small ruminants are rural animals that can quickly adapt to diverse climates and are less sensitive to high temperatures than other ruminants. Therefore, it is essential to consider genotype-environment interactions and high productivity when selecting animals adapted to thermal stress and utilize these genes as identifiers in the selection process.

3. MORPHOLOGICAL THERMOREGULATION IN SHEEP AND GOATS

Morphological thermoregulation in sheep and goats occurs through physical changes that enhance their fitness in their operational environment. According to Berihulay [9], the central morphological adaptations of sheep and goats to differences in thermal conditions include body shape and size, skin and coat color, coat texture, and fat accumulation. To be specific, Leite [17] reported different breeds of sheep and goats that use these adaptations to survive in thermally stressed conditions. According to Leite [17], the Sudanese Saleh and Egyptian Zaraiby goats have long legs and ears as a thermoregulatory morphological adaptation, while West African goats have short legs. The authors report that the Awassi sheep have loose coarse wool and adipose tissue reserves as a thermoregulatory morphological adaptation to heat changes in their environment, in contrast, the Damar sheep have fat tails.

On the other hand, Massese, Xalda, and Soay sheep use coat color as the thermoregulatory morphological adaptive feature, during Barki sheep and goats use skin pigmentation. The size and shape of an animal's body are dominant morphological characteristics influencing its thermoregulatory means during scorching weather [1,23]. Biologically, larger animals are expected to have a reduced metabolic rate and gain heat more slowly than smaller ones [24]. As such, small ruminants in scorching environments are expected to have a larger body size to reduce the rate of metabolism and heat absorption. Also, as reported by Joy [23], taller animals are expected to release more heat compared to short and squat-bodied animals, which explains why the Sudanese Saleh and Egyptian Zaraiby goats have long legs and ears as thermoregulatory morphological adaptive features for evaporative heat loss. In terms of fat storage, Moradi [25] reports that one-quarter of the global sheep population are fat-tailed breeds and extensively thrive in tropical environmental conditions and can accumulate and mobilize body fat from their internal fat depots. It is important to note that sheep and goats use fat tails and fat rumps as a thermoregulatory morphological feature based on their operational environmental condition. Therefore, body size, shape, and fat storage are important thermoregulatory morphological features and mechanisms for sheep and goats. It is thought that the development of thermal insulation between the subcutaneous fatty tissue and the supercutaneous hair affects heat flow to and from the organism along the gradient of heat flow to and from the environment [26,27]. This implies that sheep fleece morphology affects heat dissipation from their skin surface through thermoregulatory mechanisms [7]. The morphology of the external coat of sheep changed significantly during domestication. It is believed that there are primitive sheep breeds that still possess a double coat of thick external hairs and thinner internal hairs, like Soay sheep [28]. Rather than having two follicles, modern wooled sheep (e.g., Merino) have a single coat containing both primary and secondary follicles [29]. However, there is a wide variation in skin and coat morphology across different body regions. Skin thickness decreases from the dorsal side to the ventral on the trunk and from proximally to distally on the limbs [30]. There is a positive correlation between skin thickness, mean fiber diameter, and staple length [31]. Among sheep, the pinnae, axillary, inguinal, and perianal regions have the thinnest skin, with an average thickness of 2.6 mm in adults [32]. These areas with thinner skin and shorter hair act as "thermal windows" for heat dissipation [7,33]. Al-Ramamneh [7] found that unshorn sheep suffered heat stress even at moderate temperatures. It has been reported that panting accounts for 65% of the total heat loss in unshorn sheep and 59% in shorn sheep due to increased respiratory rate. The thermoregulatory mechanisms of wool sheep changed immediately following shearing, from evaporative cooling (via panting) to heat radiation through the skin in moderate temperatures [7]. In this context, Infrared electromagnetic waves can measure the flow of thermal energy between the skin and the environment [7,34,35], providing real-time information and an accurate description of animal temperature patterns. Infrared thermography (IR) non-invasive techniques offer high precision, do not require direct contact with the animals, and will not disturb animal behavior, which can be suitable for evaluating animals' thermal states [16,35]. Usually, surface temperature controls the amount of infrared radiation emitted by bare-skinned animals. According to Peng [36], environmental factors significantly impact body surface temperatures more than rectal ones.

Small ruminants have entirely different coats and skins in tropical and desert climates than in temperate climates [23]. The ability of the hair coat to absorb radiant heat depends on its surface area, pigmentation, structure, length, and condition [37]. Several studies have shown that black-pigmented hair in bright sunshine has a greater surface temperature than hair with other colors, whether in sheep or goats [23,38,39]. Animals' coat colors influence the amount of heat they absorb and the amount of heat they reflect and absorb [40,41]. It is easier for those with light coats to absorb heat than those with dark coats [40,41]. Heat stress can be more readily caused by sheep with dark pigmentation than those with lighter pigmentation [17]. Sensible heat is generated whenever the surface does not reflect or transmit the radiation [34]. A darker coat color absorbs solar radiation more efficiently, providing more heat and emitting more energy [42]. Consequently, animals adapted to hot climates have been observed to change their hair coat colors to alter their solar absorption [3]. Therefore, selecting animals with a light color is essential for the welfare and production efficiency of the sheep. According to Fadare [43], the effects of coat coloring related to climatic-stress-tolerance traits in the west African dwarf sheep include the rate of respiration, the rectal temperature, the heart rate packed cell volume, plasma sodium, and potassium. Therefore, skin and coat pigments are essential thermoregulatory morphological features used by sheep and goats to survive in different thermal environments.

4. BEHAVIORAL AND PHYSIOLOGICAL MECHANISMS OF THERMOREGULATION

The behavioral adaptation of small ruminants to different environments is based on their instinctive reaction to changes in their external environment by performing various activities to control their body temperature [6, 16]. According to Berihulay [9], the behavioral adaptation of small ruminants is meant to protect themselves from extreme environmental factors through the control of feed, water intake, and hair growth. Also, it is essential to note that small ruminants are nocturnal and active during the daytime to control the amount of heat and energy requirements based on their operation environment [16, 44]. When excessively high temperatures, ruminant animals reduce feed intake to reduce heat production [7]. According to Joy [23], a goat's eating behavior in hot environments enables it to adapt better to heat stress than other ruminants. For example, Heat-stressed Saanen goats have larger meals but fewer meals than German-improved Fawn goats [45]. Stressed goats consume less feed, gain less weight, and grow slower to maintain their body temperature and thermoregulatory mechanisms [1]. When the physiological mechanisms of animals cannot address the effects of various heat changes, the body temperature can fluctuate to the extent that the animal's health is compromised [7]. Body temperature measures how much heat is lost and gained by an animal due to its internal heat gain and loss processes [46]. The critical physiological adaptation mechanisms in small ruminants include changes in core temperature, heartbeat, and amount of panting [1]. In goats and sheep, rectal temperatures are a standard way to measure core temperatures, regardless of changes in the temperature of other body parts [7]. Small ruminants utilize panting to maintain a comfortable body temperature in high temperatures [7]. Another physiological thermoregulatory mechanism small ruminants use is panting, resulting from an increased panting rate [7]. It is vital to note that in sheep and goats, physiological adjustments accompany varying temperature changes.

In most cases, animals exposed to heat stress tend to have an elevated core body temperature, breathing rate, heart rate, changing endocrine function, sweating, and metabolic activity [7,16,47,48]. According to Marques [49], an increase in the goats' core temperature from 38.0 ^{0}C to 39.0 ^{0} C indicates that the animal has been kept at a hot ambient temperature for more than six hours. Another study by Al-Dawood [50] reported that an increase in rectal temperature above 44 ^{0}C indicates that the animal has been exposed to higher temperatures. A study conducted by Al-Dawood [50] showed that goats with walking stress of more than 14 kilometers increased their core body temperature and respiratory rate. An increase in the temperature of small ruminants above the thermal comfort leads to the activation of evaporative cooling mechanisms, reducing sensible heat loss [1,48]. Therefore, the rate of respiration and core temperature serve as crucial physiological measures of environmental temperature.

5. GENETIC MECHANISMS OF THERMOREGULATION

Adaptation concerning genetic aspects is associated with animal inherited characteristics or features that enhance their resilience or tolerance to their external environment [51]. In most cases, adaptive features are characterized by low heritability of the genetic variation within a population, providing the flexibility of adaptability to different environments. Studies have shown that genes that explain sheep and goats' ability to survive in a heat-stressed environment are complicated because the mitochondrial genes have a high association with adaptability to temperature changes, as it has a crucial role in energy production [52]. Most organelles in small ruminants like sheep and goats have a specific genome with one particular modified genetic code, with the mitochondrial DNA being circular and double-stranded molecule [53]. In addition to its smaller size and limited recombination ability, mitochondrial DNA has outstanding properties that contribute to thermal regulation. Multiple genes and specific genome-wide DNA markers have been associated with sheep and goats' ability to adapt to different thermal environments [9, 53].

6. ENDOCRINE AND METABOLIC THERMOREGULATORY ADAPTATION

Heat stress generally affects livestock productivity, but we know little about their cellular reactions to heat. Stress affects animals' immune responses both innately and adaptively [54]. As a result of stress, the immune system does not respond directly but instead responds via the neuroendocrine system [55]. Stress-related hormones modulate immune responses through their receptors on immune cells. Pathogens that enter the host animal are the primary target of the innate immune response [54]. As described by Roach [56], Almost every vertebrate genome contains genes for one of the six TLR families (TLR1-6 and TLR11). Transient thermal tolerance is conferred by the heat shock response, partly due to the expression of heat shock proteins (HSPs). It is believed that HSP70 is the most dominant HSP in protecting cells against heat-induced damage [57]. Several studies [57, 58] show that tissue subjected to thermal stress rapidly synthesizes heat shock proteins (HSPs). HSP aids in folding and refolding damaged proteins in living tissues and maintaining their structural integrity, preventing their aggregation, and preventing aggregation [59,60]. A gene known as HSP90 is essential for eukaryotes to be viable and to survive. In several studies, HSP90 has been shown to influence the folding of cytosolic proteins, the integrity of their structural framework, and the proper regulation of a broad range of proteins within the cytosol [61,62,63,64].

Furthermore, a report has shown that when the intracellular concentration of HSP 60 is decreased at high temperatures, the mortality of mammalian cells increases as a consequence. According to research findings, HSP 60 is a crucial candidate for protecting native macromolecule structure and function, particularly during transport time across membranes [58]. The plasma cortisol concentration in the blood determines the endocrine adaptation of sheep and goats to different thermal environments. According to Abhijith [65], the Salem Black goats in India have reduced plasma cortisol concentrations, which indicates their superiority in adaptability to stressful conditions compared to the

Osmanabadi goats, with a relatively high concentration of plasma cortisol in their blood during the summer. The plasma T3/T4 concentrations also determine the variations in the breeds of sheep and goats with their response to different heat conditions [66]. According to Joy [23], Chokla crossbred sheep exhibited higher plasma T3 levels during the summer, which indicates that their thyroid glands were not functioning well and that their thermoregulation was poor in heat-stressed environments. In addition, the author indicates that sheep breeds with low plasma thyroid hormone concentrations exhibit more excellent adaptation to heat-stressed as a result of a decrease in thermogenesis. In addition, various goat breeds have been shown to have significantly higher plasma growth hormone levels when subjected to heat stress [67]. Therefore, the endocrine system plays a crucial role in thermoregulation in small ruminants.

Regarding metabolism, the size of the sheep and goats often determines the natural selection for the genotypes of adaptability to different environments. According to Joy [23], metabolism is a crucial determinant of thermoregulation which determines the net temperature of the animal. Sheep and goats with relatively small sizes have reduced metabolic requirements and reduced heat production, which helps them to survive in heat-stressed environments [1]. The reduced size of sheep and goats often confers an advantage on the tropical breeds, ensuring their survival in such environmental conditions. In addition, volatile fatty acids in the rumen, which determine energy supply in animals, are essential determinants of heat production in ruminants. The fatty acids determine the amount of heat gained or lost, which determines the net temperature of the animal [23]. According to Pragna [68], the Salem goat breeds have a higher propionate production than the Osmanabadi and Malabari breeds, leading to reduced methane synthesis. Additionally, goats exposed to heat stress challenges have a higher proportion of volatile fatty acids in their diets, determining their digestibility and the size of their rumen microbe population [68]. A sheep or goat's metabolic activities determine the animal's temperature and how they react to different thermal environments, so they are important determinants of their temperature.

7. CONCLUSIONS

The current review explored the processes of thermoregulation in sheep and goats and described the various physiological features of the ruminants that enhance their ability to perform better during stress. Numerous studies have investigated the relationship between environmental changes and animal response. However, limited extensive research has been conducted to determine how sheep and goats respond to temperature changes through thermoregulatory processes. Heat stress can impede the growth of small ruminants and lead to impaired production, reproduction, compromised natural immunity, and increased susceptibility to diseases. The adaptation of small ruminants to different thermal conditions through behavioral, genetic, physiological, and morphological bases. Morphologically (size, shape, coat color, and pigmentation) play a crucial role in their energy exchange with the surrounding environment, which is controlled by convection, radiation, and evaporation. Sheep and goats with lighter coat colors absorb less heat than those with darker coat colors, as they have a lighter coat color. The behavioral adaptation of small ruminants to different environments is based on their instinctive reaction to changes in their external environment by performing various activities (Drinking more water, reducing feed intake, seeking shade, and standing rather than lying down) to control their body temperature. Sheep and goats use fat tails and fat rumps as a thermoregulatory morphological feature based on their operational environmental conditions. A high ambient temperature can also lead to increased breathing, heartbeat, and core temperature in livestock. Therefore, thermoregulation in small ruminants occurs through behavioral, genetic, physiological, and morphological mechanisms.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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