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MULTIDIMENSIONAL ADAPTIVE STRATEGIES OF FARM ANIMALS FACING CLIMATE CHALLENGES

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Abstract: Modern livestock farming operates within increasingly challenging climatic boundaries, making adaptation the cornerstone of sustainable development. In confronting climate change, the innate adaptive abilities of domestic animals must not be underestimated or neglected, as they provide the essential biological foundation for survival and productivity in an ever more demanding environment. Alongside human interventions, understanding and enhancing animal adaptations lay the groundwork for developing resilient and sustainable livestock systems.The strategies through which animals respond to climate challenges encompass physiological, biochemical, immunological, morphological, and behavioral mechanisms-from panting and sweating, changes in blood composition and endocrine function, to modifications in body size, coat characteristics, and behaviors such as seeking shade or reducing feed intake. Interspecies and interbreed differences further underscore the critical importance of genetic diversity in fostering resilience. These insights offer a basis for designing strategies that support not only productivity but also animal welfare under global warming conditions. While human interventions may alleviate the immediate impacts of climatic stressors, it is the integration of animal adaptations that provides the long-term foundation for the stability and future of livestock farming.

Key words: climate change, livestock, adaptation, heat stress, biological mechanisms, animal resilience

Introduction

Climate change today poses one of the most significant challenges to agricultural sustainability, particularly for livestock production, which is directly influenced by climatic factors (Gaughan et al., 2019). Adaptation to these changes entails a dual strategy: spontaneous animal-based mechanisms and human-initiated practices and technologies. While the literature often highlights the importance of human interventions, the study of animal adaptations is equally, if not more, important, as the biological resilience of farm animals forms the basis of their survival and productivity under ever more challenging climate conditions.

The impacts of climate change on livestock are multifaceted, with heat stress standing out as one of the greatest challenges for farm animals (Henry et al., 2018). It is important to note that animals rarely encounter a single stressor; heat stress is frequently accompanied by combined influences such as inadequate nutrition, limited water access, or poor diet quality, where the synergy of multiple stressors can have a stronger effect than each acting alone (Cheng et al., 2022).

Animals possess innate capacities to cope with climatic challenges through the process of adaptation. Their response to stress includes an initial reaction to changing conditions, as well as deeper adaptive mechanisms, including activation of the endocrine system. In cases of prolonged stress, beneficial adaptations may become permanently established through genetic fixation (Collier et al., 2008).

This paper aims to present the significance and diversity of adaptive mechanisms in domestic animals, as well as key strategies for overcoming adverse environmental conditions. In the era of climate change, the resilience and adaptability of animals reflect the dynamic relationship between evolution and survival. To maintain homeostasis, animals activate a range of mechanisms—behavioral, physiological, biochemical, immunological, anatomical—or their combinations (Figure 1), with the effectiveness of these responses determined by previous exposure, duration and intensity of stress, physiological status, and environmental conditions (Ratnakaran et al., 2017; Sejian et al., 2018).

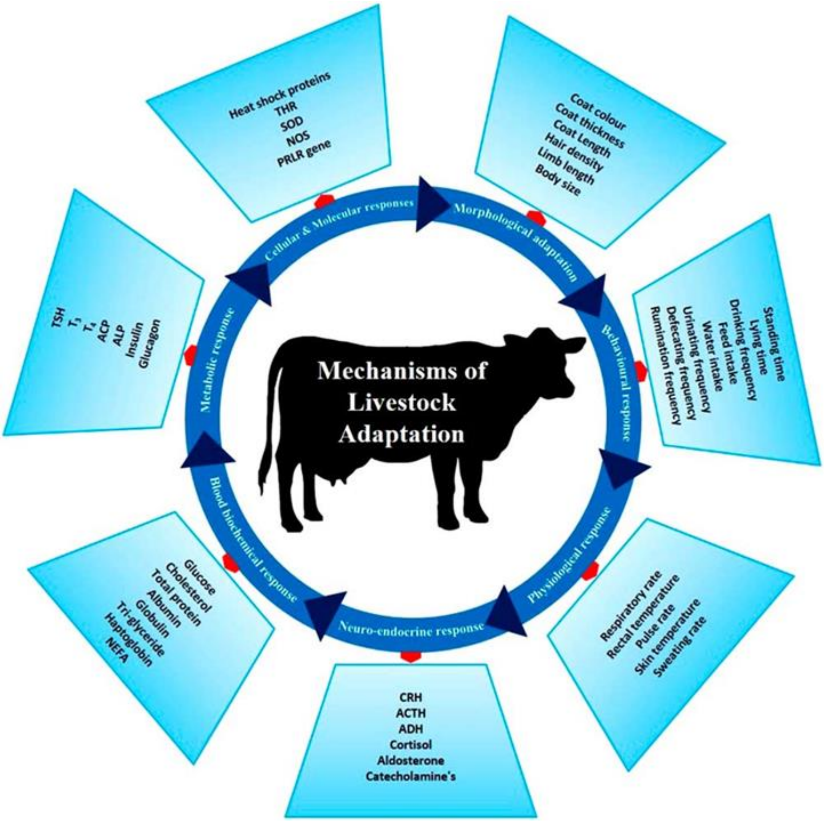

Figure 1. Adaptive strategies of farm animals coping with climate change (adapted from McManus et al., 2008)
THR=thyroid hormone receptor; SOD=super oxide dismutase; NOS=nitrous oxide synthase; PRLR=prolactin receptor; CRH=corticotropin-releasing hormone; ACTH=adrenocoticotropic hormone; ADH=antidiuretic hormone; NEFA=non-esterified fatty acids; TSH=thyroid-stimulating hormone; T_3=triiodothyronine; T_4=thyroxine; ACP=acid phosphatase; ALP=alkaline phosphatase.

Physiological strategies

Physiological strategies represent adaptive mechanisms by which domestic animals maintain homeostasis and mitigate the impact of climate stressors, regulating bodily, metabolic, and endocrine functions (Zhang et al., 2017). Mechanisms such as panting and sweating play a crucial role in thermoregulation, enabling efficient dissipation of excess heat (Bernabucci, 2019). Accelerated breathing increases moisture evaporation (Renaudeau et al., 2012), while an elevated heart rate improves circulation and directs blood flow to the body surface, facilitating heat loss (Maibam et al., 2017). Increased rectal temperature (El-Tarabany et al., 2017) and adapted renal function help maintain fluid balance within the organism.

Pigs, due to the lack of sweat glands and relatively small lungs, struggle more with high temperatures and rely heavily on heat release through the skin. Goats, on the other hand, exhibit an exceptional ability to reduce metabolic rate and enter a state of torpor to conserve energy during extreme thermal conditions (Berihulay et al., 2019).

Among endocrine organs, the adrenal and thyroid glands play a central role in organismal adaptation to high temperatures (Romanello et al., 2018). Activation of the HPA and SAM axes leads to the release of several hormones essential for maintaining thermal homeostasis, including glucocorticoids, catecholamines, ADH, thyroid hormones, mineralocorticoids, growth hormone, and prolactin (Sheba et al., 2012). Increased cortisol concentrations support adaptive processes by stimulating hepatic gluconeogenesis, thus providing additional energy to animals under stress (Chen et al., 2015). In lactating cows and heifers exposed to heat stress (Zhang et al., 2014), reductions in TSH, T3, and T4 levels have been documented, representing a mechanism for reducing metabolic heat production.

Biochemical Strategies

Domestic animals employ biochemical adaptation mechanisms to climate change through alterations in blood composition and cellular adaptation. These mechanisms fall into two main groups: hematological responses and cellular-molecular responses.

Hematological Responses

Exposure to high temperatures leads to reduced erythrocyte counts and lower hemoglobin levels (Marai and Habeeb, 2010), as well as decreased packed cell volume (PCV) due to hemodilution, which enables more efficient heat dissipation (Garkal et al., 2016). Under heat stress, plasma albumin concentration increases, likely owing to its antioxidative role (Rasooli et al., 2004). Blood glucose level typically decreases as a result of diminished gluconeogenesis (Alberghina et al., 2013), while lower NEFA concentrations indicate increased utilization as an energy source (Skibiel et al., 2018). According to Baumgard and Rhoads (2013), the use of glucose to reduce metabolic heat production represents an important adaptive mechanism.

Cellular-Molecular Response

At the cellular level, one of the most important defense mechanisms is the increased production of heat shock proteins (HSP), which stabilize and protect cells from damage (Basirico et al., 2011). Heat stress conditions result in decreased DNA synthesis, transcription, and translation (Saxena and Krishnaswamy, 2012), as well as reduced fatty acid metabolism, increased glucose oxidation, and activation of the immune and endocrine systems (Collier et al., 2008). Genes involved in HSP synthesis and heat tolerance hold potential for use in selection and breeding of livestock lines resistant to climatic stressors (Kumar et al., 2017).

Immunological Strategies

Climate change significantly affects the health and welfare of domestic animals, promoting the spread of vector-borne diseases and weakening the immune system, which results in increased susceptibility to infections (Bernabucci, 2019). Heat stress disrupts immune cell balance, reduces antibody production, and impairs organs such as the thymus and spleen, thereby raising disease risk (Caroprese et al., 2021).

Different species and breeds display varying levels of immunological resistance, largely determined by genetics and environmental conditions. Cattle, especially dairy cows, are notably sensitive to the negative impacts of heat stress (Dahl et al., 2020). In contrast, dromedary camels exhibit heightened immune cell activity and superior antimicrobial responses (Hussen, 2021), while Bos indicus (zebu) are characterized by pronounced thermotolerance and a robust capacity to maintain immune function under elevated temperatures (Hansen, 2004).

Increased expression of immune genes, such as TLR2/4 and IL2/6, in Tharparkar cattle confirms their resilience (Bharati et al., 2017), and higher TLR gene expression in Osmanabadi goats under heat and nutritional stress indicates their adaptive capacity (Sophia et al., 2016).

For sheep, heat stress may weaken immune responses and raise infection risk; however, African Damaras maintain stable immune function and resistance (Almeida, 2011). Hungarian Cikta sheep exhibit superior thermotolerance compared to other breeds (Astuti et al., 2023), and goats have a higher lymphocyte-to-neutrophil ratio, indicating a well-developed immune system (Daramola and Adeloye, 2009).

Anatomical-Morphological Strategies

Anatomical changes are among the key ways in which domestic animals adapt to heat stress, revealing their remarkable plasticity and capacity for adaptation (Hall, 2004). These changes encompass variations in body size and specific body parts, hair color, type and density, as well as modifications in the respiratory system (McManus et al., 2008). Additionally, certain species develop unique morphological traits such as enlarged salivary glands, expanded absorptive mucosal surfaces, and an increased foregut volume when consuming fiber-rich diets (Renaudeau et al., 2012).

The physical structure of hair plays a crucial role in protecting the body from overheating. Attributes such as color, length, and density directly affect heat exchange with the environment, shielding against solar radiation and facilitating heat loss via convection and evaporation (McManus et al., 2008). In tropical regions, animals with light-colored coats can reflect a greater portion of solar radiation, while dark coats increase heat absorption. Thus, shades like white or light brown are advantageous in hot climates. Cattle in such environments also possess smooth, short, thin hair and fewer follicles per unit area, which significantly enhance heat dissipation (Henry et al., 2018; Bernabucci, 2019).

In sheep, thick wool acts as insulation during cold periods, but in high temperatures, long and dense fleece may lead to overheating (Renaudeau et al., 2012). Conversely, lower fiber thickness and density, combined with short and compact wool, enable more efficient heat loss and maintenance of homeostasis. Indigenous sheep breeds in arid and semi-arid regions often have a “carpet-type” fleece, which not only provides protection from solar radiation but also allows for more effective heat dissipation (Renaudeau et al., 2012). Furthermore, in some breeds, a fat tail represents a unique morphological adaptation that further facilitates thermoregulation (Berihulay et al., 2019).

Body Size

Body size directly affects the energy requirements of animals for maintenance, growth, and production, and changes in size have important implications for thermal biology. In warmer climates, reduced body mass may serve as a crucial adaptive mechanism, as a higher surface-area-to-volume ratio enables more efficient heat dissipation (Elayadeth-Meethal et al., 2021).

Research by Elayadeth-Meethal et al. (2021) has demonstrated that dwarf cattle breeds (DCB, Bos taurus indicus) possess superior thermotolerance compared to standard breeds (SCB, Bos taurus indicus × Bos taurus taurus crossbreds). While SCB can acclimatize to elevated temperatures in the short term, DCB are much better adapted to living in hotter climates over the long term. Their higher hemoglobin concentration and smaller cell size further enhance their capacity to cope with heat stress.

Body Parts – Extremities

The size and shape of body parts such as the tail, beak, and legs play a significant role in regulating body temperature through heat exchange. Animals inhabiting warmer climates often develop larger extremities relative to their body size, consistent with Allen's rule, which remains underappreciated in the context of climate adaptation studies (Allen, 1877). Such extremities contribute to more efficient thermoregulation under high temperatures, whereas their impact is considerably less in cold environments.

In birds, the beak and legs serve as important "natural radiators"—well vascularized and not covered by feathers, they facilitate substantial heat loss. Mammals exhibit similar adaptations with ears and tails, as exemplified by Brahman cattle and Nubian goats, where these body parts play a crucial role in maintaining thermal equilibrium, fully supporting the predictions of Allen's rule.

Respiratory System

The respiratory system of domestic animals exhibits a degree of plasticity in response to climate change. Modifications such as increased lung capacity or altered breathing patterns (e.g., enhanced panting) enable animals to regulate body temperature more efficiently, thereby attenuating the negative effects of heat stress (Bernabucci, 2019).

Morphological Adaptations in Different Species

Goats stand out as the most adaptable species, capable of dissipating heat through their horns and surviving even with minimal vegetation. Burs and Nubian goats are particularly noteworthy, with long ears and wrinkled skin serving as efficient adaptations to arid conditions. In contrast, sheep show lower heat tolerance; while wool can provide protection, sheep with hair instead of wool, such as Red Maasai and Sahel sheep, as well as breeds like Dorper and Karakul, exhibit greater resilience. These breeds utilize unique survival mechanisms, such as fat storage in the tail, enabling them to withstand extended droughts and limited water availability.

Continental high-yield dairy cattle are more sensitive to heat stress compared to tropical types such as Zebu, Brahman, and Gir. It is therefore

recommended to improve their resilience by introducing genes characteristic of tropical populations, such as shorter hair or elongated body shape.
In poultry, morphological traits like naked necks (as seen in "naked-neck" chickens) or markedly larger combs and wattles in chicks significantly contribute to enhanced thermotolerance.

Pigs, on the other hand, are the most sensitive species to heat stress due to a lack of sweat glands, small lungs, and limited thermoregulatory capacity. While breeds such as Duroc show moderate resistance, certain Chinese breeds—Luchuan, Dianan, Bamaxiang, and Wuzhishan—possess genetic adaptations making them more robust and offering potential directions for genetic improvement of heat resistance in pigs.

Figure 2. Morphological characteristics of climate-resilient farm animal species

Behavioral Strategies

In addition to physiological, biochemical, and anatomical mechanisms, farm animals display a range of behavioral strategies to cope with climate challenges (Bernabucci, 2019). These adaptations, aimed at mitigating the effects of heat stress and maintaining thermal balance, include changes in movement, habits, and feeding behaviors (Renaudeau et al., 2012).

Figure 3. Behavioral patterns leading to cooling in different species of domestic animals

One of the most common forms of adaptation is seeking shade and cooler areas, bathing, or spraying water to cool the body (Zhang et al., 2017; Bernabucci, 2019). Cattle, for example, demonstrate a marked preference for natural tree shade, as dense foliage provides more effective evaporative cooling compared to artificial shelters (Ratnakaran et al., 2017). Poultry dissipate heat by spreading their wings and increasing heat loss through exposed body parts, while pigs—being particularly sensitive—find relief by wallowing in mud or lying on cool surfaces.

In cattle, increased heat load leads to reduced time spent resting and more time standing, which maximizes the body surface exposed to air and facilitates evaporative cooling, reducing the impact of radiant and convective heat from the ground (Sejian et al., 2018). Technological solutions such as sprinklers and fans have also proven effective in lowering heat stress, thereby increasing rest time and improving animal welfare (Henry et al., 2018).

Heat stress affects feeding habits as well. Animals often reduce food intake to lower metabolic heat production, and grazing cattle shift activity towards nighttime during the hottest days (Cheng et al., 2022). High temperatures also reduce the frequency of urination and defecation, depending on water availability, food supply, and environmental conditions (Sejian et al., 2018).

The need for water rises dramatically under such conditions; animals typically prefer moderate or cooler water, as it directly contributes to sustaining thermal stability.

All these behavioral adaptations reflect the innate ability of animals to recognize environmental cues and adapt their behavior accordingly. This interaction between ambient conditions and behavior serves as a crucial mechanism for survival amid climate change.

Conclusion

Climate change represents one of the greatest challenges for modern livestock production, directly affecting the health, productivity, and welfare of domestic animals. Although human interventions, such as technological and management solutions, can significantly mitigate the effects of climatic stressors, the long-term foundation of sustainability is primarily the biological adaptability of the animals themselves. Therefore, understanding and integrating animal adaptations is key to creating livestock systems that are resilient to climate change.

Analysis of physiological, biochemical, immunological, morphological, and behavioral mechanisms demonstrates that animals possess remarkable plasticity and the ability to maintain homeostasis under extreme conditions. These adaptations should not be seen merely as stress responses, but as a valuable biological basis for the selection and improvement of future populations. Their application in modern practice creates opportunities for the development of innovative strategies—from genetic programs aimed at increasing thermoresilience, to optimizing the management of nutrition, housing, and animal welfare.

While human adaptations are essential for immediate mitigation of climate-related impacts, only deeper understanding and utilization of animal adaptations can provide the foundation for the long-term stability and productivity of livestock production. In this way, the combination of the evolutionary strengths of animals and modern management practices may become the most effective response to the challenges of climate change—not only today, but also in the future.

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Conflict of interest

The authors declare that they have no conflict of interest.

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