Equine Welfare Under Environmental Challenges

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Abstract | Equine welfare is significantly influenced by environmental factors, particularly in the context of climate change and the increasing frequency of extreme weather events. The aim of this review is to systematise scientific evidence on the impact of major environmental stressors on the physiological and behavioural status of horses, as well as to analyse modern monitoring methods and adaptive mechanisms. Particular attention is given to the effects of heat stress, high humidity, air quality, housing conditions, transportation and seasonal temperature fluctuations. We explore the physiological and behavioural responses of horses to stress loads, including alterations in cardiovascular, endocrine, immune and reproductive systems. Contemporary welfare assessment tools are presented, ranging from infrared thermography and electromyography to microsensors and heart rate variability analysis. Adaptive mechanisms such as heat acclimatisation, genetic resilience, and the influence of age and physical condition are discussed. Risks associated with chronic stress and opportunities for implementing personalised welfare support strategies under climate-related threats are also summarised. This work emphasises the need for a systemic approach to the assessment and management of equine welfare, taking into account individual variability, ecological context and interdisciplinary solutions.

Keywords | Animal welfare, Horses, Environmental factors, Physiological responses, Behavioural indicators, Heat stress, Monitoring and adaptive strategies

INTRODUCTION

In the current context of global climate change and the increasing frequency of extreme weather events, the assessment and maintenance of equine welfare has become particularly relevant. Horses are highly sensitive to microclimatic changes, particularly the combination of elevated temperature and humidity, which imposes significant strain on their thermoregulatory system. Recent racetrack assessments indicate that even in temperate conditions, the combination of heat and exertion can lead to dehydration, electrolyte imbalance and collapse, underscoring the importance of systematic climate monitoring and thermal adaptation protocols (Knight, 2019). A critical threshold of physiological overload is reached when body temperature exceeds 41 °C, potentially leading to encephalopathy and reduced muscular performance. These findings emphasise the necessity of progressive heat acclimatisation as a key adaptive response to unfavourable environments.

At the same time, interdisciplinary studies confirm that

increased thermal load, environmental pollution and unstable anthropogenic factors significantly affect the physiological stability of animals. Rising temperatures, exposure to toxicants, environmental overloading and the degradation of aquatic and terrestrial ecosystems create the need for multilevel environmental monitoring (Mylostyvyi et al., 2023; Marenkov et al., 2021; Khromykh et al., 2023). In response to these challenges, digital tools are gaining prominence, including non-invasive animal welfare assessment methods, sensor-based technologies and algorithms for predicting the risk of heat stress (Hoffmann et al., 2021; Mylostyvyi et al., 2024). The use of such technologies improves the accuracy of welfare assessments, enables timely responses to environmental shifts and helps to minimise physiological overload.

In scientific literature, equine welfare is increasingly conceptualised as a dynamic system encompassing not only physiological and behavioural parameters but also environmental context, social interactions and management practices. This approach allows for the inclusion of both objective indicators (such as body temperature and respiratory rate) and subjective aspects (such as emotional reactivity and the ability to express natural behaviours) of animal well-being. However, despite growing recognition of this integrative view in scientific discourse, recent surveys reveal that horse owners may lack formal knowledge of these principles, underscoring the need for broader dissemination and training (Rioja-Lang et al., 2020; Watney et al., 2024). According to Delphi study results, the main threats to welfare include pain, stress, impaired thermoregulation and restricted behavioural needs. These factors often interact, resulting in cumulative strain on the animal's physiological and emotional resilience.

As highlighted in the systematic review by Hall and Kay (2024), welfare should not be treated as a universal "best practice standard" but rather as an adaptive model that accounts for the specific characteristics of the facility, available resources and staff knowledge. In this context, nutrition, environmental management, access to shelter and the use of innovations (such as pheromonal technologies) act as integral components for maintaining the health and psycho-emotional state of horses. In the systematic review by Lesimple (2020), welfare indicators were grouped into three categories: State (e.g., body temperature, heart rate), response (e.g., behavioural signs, stress patterns) and outcome (e.g., disease frequency, reproductive metrics). None of these indicators alone is sufficient; only their combination provides a reliable understanding of the welfare status of an animal within a specific environment.

Thus, modern interpretations of equine welfare are based on a multifactorial model that integrates physiological, behavioural, environmental and management-related factors. This forms the basis for a comprehensive evaluation of the animal's adaptive capacity and allows for the early identification of potential welfare threats before the onset of clinical signs. The aim of this article is to systematise data on the impact of environmental challenges on equine welfare and to outline current approaches to monitoring, diagnosis and the adaptation of management systems in response to a changing climate.

KEY ENVIRONMENTAL FACTORS INFLUENCING EQUINE WELFARE

Equine welfare is largely determined by environmental factors, among which temperature, humidity, air quality, ventilation, noise levels, access to shade and general housing conditions play a leading role. An increase in ambient temperature combined with high humidity creates particularly hazardous conditions in which the horse's thermoregulatory mechanisms may become overloaded, leading to hyperthermia, dehydration and the onset of heat stress (Kang et al., 2023). During physical exertion, rectal temperature may exceed 39 °C (Verdegaal et al., 2021), and after 30 minutes of work under a THI greater than 81, it may rise above 40 °C (Lisboa et al., 2023). Notably, surface skin temperature may increase to 30 °C up to 70 minutes before core overheating occurs, but it is not considered a reliable predictor of generalised hyperthermia (Verdegaal et al., 2022).

Transportation induces significant physiological and behavioural stress in horses, particularly during hot weather. Friend (2000) reported that horses do not always drink water in trailers even when it is available, leading to dehydration. This finding was further confirmed by Friend (2001), who observed elevated heart rates, balance disturbances and reduced immune reactivity. Purswell et al. (2006) demonstrated that airflow levels inside trailers depend on trailer design, travel speed and weather conditions. In cases of inadequate ventilation, there is a build-up of heat, ammonia and dust, contributing to thermal stress and respiratory complications.

Housing conditions also play a critical role. In the study by Poochipakorn et al. (2024), horses housed in well-ventilated stables exhibited lower salivary cortisol levels (p < 0.01), reduced heart rates and fewer stress-related behaviours compared to those in enclosed facilities. Holcomb (2017) found that at ambient temperatures above 25 °C and high humidity, horses actively seek shade. In southern regions of the United States, temperatures in open areas exceeded 40 °C, while shaded zones were 10–15 °C cooler (Sharpe and Kenny, 2025).

In colder climates, horses also display sensitive behavioural adaptations. Mejdell et al. (2020) noted that under windy and humid conditions, even temperatures below +10 °C

necessitate shelter provision. Declining temperatures increase energy demands for thermoregulation, especially when horses are clipped or lack wind protection.

Air quality in stables has a substantial impact on respiratory health. In the study by Grzyb et al. (2021), concentrations of respirable dust and bacterial aerosol increased three to fourfold during feeding and cleaning. Up to 75% of airborne particles were smaller than 4.7 µm, posing a risk for the development of obstructive airway diseases. Theelen et al. (2021) showed that housing type (stable versus pasture) accounted for up to 5% of variation in gut microbiota composition (R^2 = 0.05, p < 0.01), while seasonality explained a further 11% (R^2 = 0.11, p < 0.001), confirming the ecological influence on gastrointestinal welfare.

In field settings with limited resources for heat stress monitoring, non-invasive methods remain effective. According to Pritchard et al. (2010), behavioural indicators such as sweating, head tilting and frequent shifting of weight correlate significantly with dehydration status, and a skin tent test result greater than two seconds indicates marked fluid loss.

The welfare of free-roaming horses is closely linked to resource availability and habitat structure. According to Beck et al. (2024), excessive stocking densities of feral horses can negatively affect ecosystem integrity, contributing to overgrazing, water shortages and soil degradation. Their presence at levels exceeding ecological carrying capacity also alters vegetation dynamics and impacts other wildlife. GPS-based research by Boyce and McLoughlin (2025) demonstrated that habitat selection in feral horses is primarily influenced by proximity to water sources, vegetation type and elevation, mirroring patterns observed in other large herbivores. Additionally, Mutillod et al. (2024) found that free-ranging horses, when managed with minimal intervention, promote higher grassland biodiversity and more natural vegetation dynamics compared to intensively managed domestic herbivore systems. These findings underscore the role of environmental conditions in shaping both the ecological function and welfare status of unmanaged equine populations.

The impact of insects as an environmental stressor was analysed in the study by Rubenstein and Feinstein (2021), where fly densities above 200–300 per m² elicited protective behaviours lasting up to 20 minutes per hour, without reducing grazing time. This suggests horses possess adaptive mechanisms that compensate for irritation without compromising feed intake. These findings reinforce the complexity of behavioural adaptation in outdoor environments, where ecological interactions shape welfare in subtle but significant ways.

Finally, within the One Health framework, horses are recognised not only as companion animals but also as ecosystem indicators. Lönker et al. (2020) noted that equine health affects biodiversity, soil quality, epidemiological risks (notably Hendra virus) and social interactions in the context of climate change. Horses should therefore be integrated into interdisciplinary welfare monitoring systems encompassing humans, animals and the environment.

PHYSIOLOGICAL AND BEHAVIOURAL RESPONSES OF HORSES TO ENVIRONMENTAL STRESSORS

Heat stress exerts multifaceted effects on the equine organism, involving neuroendocrine regulation, thermoregulatory responses, cardiovascular and reproductive functions, as well as behavioural reactions. Increases in ambient temperature disrupt the balance between heat production and dissipation, resulting in hyperthermia, appetite suppression, reduced physical activity and hormonal alterations. In stallions, reduced sperm concentration and motility are observed, while mares exhibit disturbances in the oestrous cycle, including prolonged or anovulatory phases, especially during critical periods of ovulation and implantation (Abo El-Maaty, 2011).

The hypothalamic-pituitary-adrenal axis is activated under heat exposure, accompanied by elevated cortisol, adrenaline and noradrenaline levels, mobilisation of energy substrates, activation of sweating and increased respiratory rate. At the same time, secretion of gonadotropin-releasing hormone (GnRH), follicle-stimulating hormone (FSH) and luteinising hormone (LH) is suppressed, directly impairing reproductive function (Aggarwal and Upadhyay, 2012). As a result, the formation of a functional corpus luteum is disrupted, progesterone levels decrease and embryonic resorption rates increase.

The physiological response of horses to heat stress includes vasodilation, accelerated breathing and sweat production of up to 10–15 litres per hour during work. When body temperature exceeds 41 °C, the risk of heat stroke rises, which may lead to ataxia, collapse and death (Kang et al., 2023). Due to their large muscle mass and relatively limited skin surface area, horses are less efficient at heat dissipation compared to humans or ruminants.

Intense physical activity in hot climates is accompanied by elevated heart rate, increased pulmonary ventilation, electrolyte loss and activation of thermoregulatory mechanisms. High humidity impairs sweat evaporation, which compromises cooling capacity and leads to hyperthermia, dehydration and disruption of acid-base

balance (Art and Lekeux, 2005; Bartolomé and Cockram, 2016).

In studies on racehorses, post-race body temperatures exceeded 41 °C, with delayed recovery of heart rate variability and, in severe cases, collapse, ataxia and convulsions. This highlights the need for rapid post-exercise cooling using water or ice (Brownlow *et al.*, 2016). Horses transported in hot conditions, even for short distances (up to two hours), showed marked increases in cortisol levels, altered haematological profiles and expression of serotonin receptor genes, indicating neuroimmune activation (Ma *et al.*, 2023; Bruschetta *et al.*, 2024).

Cold stress is also a powerful trigger, especially during transitions in housing conditions. In Przewalski's horses reintroduced into the wild during winter, significant increases in cortisol and altered leukocyte profiles were recorded, indicating challenging adaptation even in cold-tolerant animals (Cao *et al.*, 2010).

Under stressful conditions such as competitions, training and transportation, horses exhibit circadian rhythm disturbances, elevated oxidative stress levels, reduced activity of superoxide dismutase and glutathione peroxidase, and alterations in protein metabolism (Eryzhenskaya, 2022). Antioxidant support, amino acids, adaptogens and anti-stress interventions promote the restoration of homeostasis.

Physiological changes such as heart rates reaching 180 bpm and core temperatures of up to 40.5 °C at ambient temperatures of 19.4 °C have been observed even in trained horses (Geor *et al.*, 1995, 2000; Verdegaal *et al.*, 2021). A 10 to 15-day acclimatisation period reduced increases in heart rate, rectal temperature and cortisol.

Low temperatures increase energy expenditure by up to 50 percent compared to the thermoneutral zone, particularly when combined with wind and rain (Cymbaluk, 1994; Mejdell *et al.*, 2020). Effective seasonal management includes providing shelter, coarse forage and monitoring of coat changes.

Tactile interactions, such as rubbing and brushing, have been shown to reduce cortisol and increase oxytocin levels in both horses and humans, thereby promoting positive affective states and welfare (Lansade *et al.*, 2018; Jung, 2023; Jung and Yoon, 2025). However, in therapeutic riding sessions, the mounting and dismounting phases elicit the highest frequency of stress-related behavioural reactions, even though the sessions themselves are generally well tolerated by the horses (McDuffee *et al.*, 2022). These findings underline the importance of accounting for subtle interaction phases during therapy, as stress peaks may occur before or after formal sessions rather than during the exercises themselves.

The study by Scopa *et al.* (2018) demonstrated that snore and vacuum chewing behaviours correlate with post-stress recovery of heart rate variability, supporting the hypothesis that these calming signals are associated with parasympathetic activation and emotional resilience. Surface electromyography has been shown to sensitively detect acute muscular tension in response to stressors such as isolation or loud sounds, serving as a physiological marker of acute stress (Rankins *et al.*, 2022). Additionally, experimental exposure to predator vocalisations revealed that horses exhibit variable behavioural and physiological responses depending on breed and degree of Thoroughbred ancestry, highlighting the role of genetic and experiential factors in stress reactivity (Janczarek *et al.*, 2020).

Physiological responses to stimuli such as heart rate and heart rate variability are considered more reliable indicators of stress in horses than behavioural outbursts, which tend to be less stable and more context-dependent. Heart rate typically increases during stress, while variability metrics including RMSSD and SDNN decrease, reflecting shifts in autonomic regulation. In groundwork exercises, wearable monitors successfully captured changes in heart rate variability during mild stress, confirming the method's validity for evaluating sympathetic-parasympathetic balance (Kapteijn *et al.*, 2022). These physiological indicators are especially useful in horses undergoing equine-assisted services, where overall HR and cortisol levels often remain within the normal range, but subtle variations in HRV accumulate over time, suggesting a cumulative stress load (Baxley *et al.*, 2024; Huangsaksri *et al.*, 2024).

In conclusion, the physiological and behavioural responses of horses to environmental stressors are complex and multilayered, involving adaptive mechanisms related to thermoregulation, endocrine control, cardiovascular and reproductive function, and neuro-emotional and behavioural reactions. Heat stress poses a particularly high threat due to the limited efficiency of heat dissipation in horses, which is exacerbated by high humidity, physical exertion or transportation. Stress responses are highly individualised and influenced by breed, age, training status, housing conditions and social context. Both acute reactions (such as hyperthermia, increased heart rate and cortisol, behavioural excitability) and chronic changes (including reproductive disorders, stereotypies, oxidative stress) are relevant. The combination of physiological monitoring (temperature, heart rate, cortisol, HSP70) with behavioural indicators (snore, chewing, muscle tension) allows for more accurate assessment of welfare status and the development of effective strategies for adaptation and prevention of heat overload.

Methods for monitoring and assessing welfare under variable environmental conditions

Under real-world working conditions in urban tourism, the physiological status and welfare of horses can be effectively assessed through a combination of thermoregulatory indicators, stress markers and behavioural observations. In a study conducted in Sicily involving 30 horses working during summer heat, statistically significant increases in body temperature, heart rate and salivary cortisol levels were recorded after completing a 90-minute route. Moreover, heart rate variability (HRV) metrics indicated activation of the sympathetic nervous system, reflected by decreases in root mean square of successive differences (RMSSD) and standard deviation of normal-to-normal intervals (SDNN). This integrated approach, including non-invasive saliva analysis, enabled an objective assessment of heat load impact on animal welfare (Arfuso *et al.*, 2024).

One of the most sensitive indicators of thermal load is body temperature. Accurate monitoring of core temperature is essential for assessing the severity of heat stress and guiding cooling interventions. Implanted sensors, whether placed subcutaneously or in the gastrointestinal tract, have demonstrated superior accuracy and response time compared to rectal thermometers or infrared surface readers (Green *et al.*, 2005). In a comprehensive review, Kang *et al.* (2023) highlighted the advantages of implantable and ingestible biosensors in continuously tracking internal temperature fluctuations under thermal stress. These technologies enable differentiation between physiological responses to environmental conditions and physical exertion, supporting early detection of hyperthermia. Moreover, their integration with wireless telemetry enhances real-time monitoring and allows for more effective individualised heat mitigation strategies.

Infrared thermography (IRT) enables contactless detection of localised overheating, particularly around the eyes, chest, back or limbs. An increase of 2.3 °C in eye globe temperature following physical exertion or elevated chest surface temperature in combination with creatine phosphokinase (CK) levels may signal muscular stress (Martins and Silva, 2022; Silva *et al.*, 2023). IRT has also been successfully applied in veterinary medicine for the early diagnosis of reproductive and inflammatory pathologies in animals, demonstrating its broader utility beyond musculoskeletal assessment (Skliarov *et al.*, 2023).

Cardiac indicators remain central in many welfare protocols. However, heart rate (HR) alone is not always reliable: in 30 percent of animals, acute stress response was absent (Manolachescu *et al.*, 2024). The combination of HR with HRV, cortisol and behavioural signs (blinking, reduced appetite, avoidance of contact) significantly improves assessment sensitivity.

During training or field competitions, continuous telemetry using gastrointestinal capsules and heart rate monitors with GPS tracking represents a promising method for assessing thermal load in horses. In the study by Verdegaal *et al.* (2021), temperature was recorded every 15 seconds during exercise, allowing the construction of individual thermal response profiles. These profiles revealed substantial variation in the timing and magnitude of peak body temperature, even among horses of similar type and training level, underscoring the need for personalised monitoring protocols. Building on this, a follow-up study by the same group (Verdegaal *et al.*, 2022) examined whether surface skin temperature, continuously measured during exercise, could serve as a reliable proxy for core thermoregulation. Although surface readings provided useful trends, the authors concluded that they could not consistently predict internal overheating, reinforcing the value of core temperature telemetry for accurate thermal assessment under real-world conditions.

Surface electromyography (sEMG) is used to assess muscle tone and activation patterns during physical exertion in horses. This method enables the detection of overload in specific muscle groups, including asymmetrical loading of the limbs during locomotion. As demonstrated by St. George *et al.* (2019), applying appropriate signal filtering and amplitude normalisation significantly improves the sensitivity of sEMG-based gait analysis. In particular, filtering out low-frequency noise and standardising the signal relative to maximal voluntary contraction allowed for more precise identification of differences between the leading and trailing limbs in cantering horses. These methodological refinements enhance the reliability of sEMG as a tool for detecting biomechanical imbalances and early signs of musculoskeletal stress in equine athletes.

Assessment of morphological changes through three-dimensional photonic scanning enables early detection of body volume loss and muscular atrophy in horses, even before clinical signs emerge. In the study by Valberg *et al.* (2020), 3D photonic scans were shown to reliably measure total body and thigh volumes in standing horses, with strong correlations to actual body weight (R = 0.90) and muscle mass (R = 0.82, p < 0.001). This method allows the identification of reductions greater than 5% in back or thigh volume over a 2 to 4-weeks period, which may indicate inadequate nutritional intake or excessive training. The procedure is rapid, non-invasive and highly repeatable, providing a practical tool for monitoring physical condition in performance and rehabilitation settings.

Among practical methods for alleviating heat stress in horses, the most widely applied strategies include

the use of cooling blankets, water spraying, and active ventilation. According to Noordhuizen (2025), the most effective technique involves the combined application of cool water (at 10–15 °C) and mechanical ventilation, which results in a core body temperature reduction of approximately 1.3 to 1.8 °C within 10–15 minutes post-exercise. This approach enhances evaporative cooling and is especially valuable after intense physical exertion or during prolonged exposure to high ambient temperatures. Complementary to this, Ojima et al. (2022) demonstrated that cooling blankets specifically designed for equine use not only lowered body surface temperature but also led to a statistically significant 22% reduction in salivary cortisol levels, indicating a measurable decrease in physiological stress. These findings underscore the importance of selecting targeted cooling interventions that support both thermal comfort and neuroendocrine stability in hot and humid environments.

Innovative electrochemical sensors offer a valuable tool for early welfare monitoring by measuring sodium and chloride concentrations in equine sweat in real time, achieving an accuracy of up to 5 percent. This enables timely detection of dehydration before clinical symptoms appear, thus improving intervention strategies (Pan et al., 2024). In parallel, olfactory stimulation using lavender essential oil has been shown to attenuate stress responses in horses, likely through modulation of the hypothalamic–pituitary–adrenal axis and associated behavioural calming effects. Inhalation of lavender significantly reduced heart rate and cortisol levels during potentially stressful procedures, supporting its role as a non-invasive method to enhance adaptive flexibility (Poutaraud et al., 2017).

Finally, an essential component of a comprehensive approach is considering choice and autonomy. Horses with access to shelter or the ability to regulate their level of activity demonstrated better welfare indicators than those kept in stables, even with optimal microclimatic conditions (Mejdell et al., 2020).

Thus, the most effective assessment and support of equine welfare is achieved through the integration of high-precision sensor technologies, non-invasive monitoring of temperature, heart rate and behaviour, adaptive cooling interventions and the interpretation of complex physiological and behavioural responses with attention to individual variability. This approach enables timely and accurate responses to environmental challenges and helps prevent disruptions to physiological stability in horses.

These interconnected components are summarised in Figure 1, which illustrates the pathway from environmental challenges through physiological and behavioural responses, assessment tools and adaptation strategies.
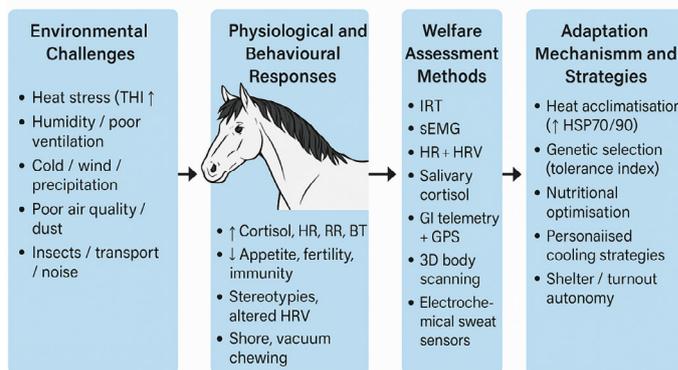

Figure 1: Conceptual framework of equine welfare under environmental stressors: from external challenges to physiological responses, monitoring methods and adaptive strategies.

ADAPTIVE MECHANISMS AND RISK FACTORS

Adaptation of horses to environmental challenges, particularly heat stress, is a multifactorial process involving physiological regulation, behavioural adjustments, molecular responses, and appropriate management. Prolonged exposure to elevated temperatures, humidity, limited access to water, and cumulative workload can exceed the organism's adaptive capacity, leading to welfare deterioration. Therefore, identifying adaptive mechanisms and risk factors is essential for optimising equine management under climate stress.

Heat stress triggers a cascade of physiological responses, including hypothalamic-pituitary-adrenal (HPA) axis activation, increased cortisol secretion, and upregulation of heat shock proteins (HSPs), which protect cellular proteins from denaturation. In a recent study, acute physical exertion significantly elevated serum concentrations of both HSP70 and cortisol in trained horses, confirming the sensitivity of these markers to combined thermal and physical load (Lee et al., 2024). These responses reflect a protective adaptation, yet prolonged elevation may indicate a transition from adaptive to pathological stress. Complementary results from Ebisuda et al. (2024) showed increased expression of HSP70 and HSP90 in skeletal muscle after 15 days of heat exposure, supporting the role of these cytoprotective proteins in enhancing resilience during prolonged environmental challenge.

Genetic and breed-related differences play a crucial role in thermoregulatory capacity. Santos et al. (2022) demonstrated that Pantaneiro horses, adapted to tropical conditions, exhibited superior heat tolerance indices under different exercise regimes compared to non-native breeds. Traits such as coat characteristics, sweat gland distribution, and cardiovascular recovery capacity contributed to thermal resilience. This highlights the importance of considering

local adaptability in breed selection and training protocols for hot environments.

Thermal adaptation is further supported by behavioural and autonomic markers. In vector-protected arenas, horses exposed to moderate physical activity under controlled thermal load showed stabilised heart rates, cortisol levels, and improved behavioural profiles (Poochipakorn et al., 2023). These findings underscore the synergistic value of combining environmental control with training acclimatisation for welfare optimisation.

Stress biomarkers are essential for early detection of maladaptation. In addition to classical indicators like cortisol and heart rate variability, substance P has emerged as a sensitive parameter reflecting both physiological and emotional stress in equine models. Under controlled experimental stressors, substance P levels increased in a dose-dependent manner, correlating with behavioural agitation and cardiovascular strain (Scholler et al., 2023). This expands the scope of welfare diagnostics and reinforces the need for multimodal assessment.

At the management level, the prioritisation of risk factors is critical. According to a Delphi study conducted by Rioja-Lang et al. (2020), the most urgent threats to equine welfare included pain, impaired thermoregulation, and inability to express natural behaviours. These factors often interact synergistically under environmental stress, intensifying the physiological burden. Adaptive strategies must therefore include environmental modification, behavioural monitoring, and training optimisation to build resilience and maintain homeostasis.

Finally, at the systemic level, heat stress induces broad molecular and metabolic changes. A cross-species analysis by Prates (2025) highlighted conserved mechanisms in monogastric animals, including altered redox balance, mitochondrial dysfunction, and downregulation of immune responses. While much of this evidence comes from pigs and poultry, parallels with equine physiology suggest that antioxidant support and hydration strategies are crucial for maintaining adaptive potential under heat load.

Melatonin has been proposed as a promising intervention to modulate thermoregulatory stress responses in equines. In a controlled experiment, Fox et al. (2025) found that oral administration of melatonin over a 14-days period significantly reduced respiratory rate, heart rate and rectal temperature in horses undergoing physical exertion under heat load. The authors attribute these effects to melatonin's antioxidant and anti-inflammatory properties, which stabilise hypothalamic control and improve peripheral

circulation. Such results open new avenues for non-invasive stress mitigation strategies in performance horses.

Adaptation is also reflected in metabolic and biochemical parameters. Padilha et al. (2017) demonstrated that Brazilian sport horses undergoing regular training in tropical climates maintain stable biochemical profiles, including electrolytes and muscle enzymes, provided workload is balanced. This supports the use of controlled exercise regimes for promoting acclimatisation without compromising homeostasis.

Thermal tolerance is partially age-dependent. As shown in studies by McKeever et al. (2010), ageing is associated with reduced sweat output, delayed post-exercise cooling and lower cardiac output. These changes increase the risk of heat-related disorders, especially in older performance or therapy horses. Therefore, individualised training and environmental adjustment are necessary to maintain welfare in ageing equine populations.

Repeated transport in hot environments represents another critical risk factor. In a recent study, Lertratanachai et al. (2024) observed that horses exposed to suboptimal truck ventilation exhibited elevated cortisol, altered heart rate variability and signs of autonomic imbalance. These responses accumulated over successive journeys, reinforcing the cumulative impact of chronic stressors. Furthermore, behavioural observations during transportation, such as agitation and loss of balance, have been shown to predict the severity of stress responses and contamination of the lower airways (Padalino et al., 2018). These findings highlight the need for transport management systems that integrate physiological, behavioural and environmental control strategies.

Even brief competition cycles can impose stress. However, Filho et al. (2024) demonstrated that short recovery intervals (e.g. in barrel racing) do not necessarily compromise welfare, provided hydration and thermal regulation are maintained. This finding highlights the adaptive capacity of trained animals under high-frequency events, provided support systems are robust.

The assessment of physiological stress responses must also account for limitations of individual indicators. Although heart rate is commonly used, it is not always a reliable marker of acute stress. Manolachescu et al. (2024) reported that in 30% of tested horses, heart rate failed to reflect stress despite behavioural or hormonal changes. This underscores the need for composite indices combining HR, HRV, cortisol and behavioural cues for accurate welfare evaluation.

Lastly, welfare resilience depends on the intersection of environmental support and behavioural autonomy. Horses that are allowed access to shelter, companionship and choice in activity tend to exhibit lower basal stress markers, better thermal regulation and faster recovery from acute stress episodes. Integrating behavioural enrichment and proactive climate adaptation is thus a cornerstone of sustainable welfare strategy in changing climates.

In summary the adaptation of horses to environmental stressors, particularly thermal load, is a dynamic and multifaceted process involving coordinated physiological, molecular, behavioural and managerial responses. Effective adaptation is supported by genetic predisposition, controlled acclimatisation protocols, environmental modifications and careful monitoring of stress biomarkers. However, individual variability, age, transport conditions and workload intensity remain critical risk factors that can compromise welfare. The integration of real-time physiological data, behavioural assessments and strategic interventions such as antioxidant support or melatonin administration offers a comprehensive pathway for mitigating heat-related risks. Strengthening adaptive capacity through proactive evidence-based welfare strategies is essential to ensure the health and performance of equine populations in the face of escalating climate challenges.

CONCLUSIONS

Current understanding of equine welfare under environmental challenges is based on the integration of physiological, behavioural, environmental and management-related factors, which interact within a complex adaptive system. Heat stress, as the leading environmental threat, exerts systemic effects on the equine body, disrupting thermoregulation, cardiovascular homeostasis, reproductive function and immune reactivity. Behavioural and physiological indicators (such as body temperature, respiratory rate, heart rate variability and cortisol levels), when combined with modern monitoring technologies (including infrared thermography, surface electromyography and microsensors), provide accurate assessments of animal condition and enable timely detection of stress loads. Adaptive mechanisms, including heat acclimatisation, selection based on resilience traits and nutritional optimisation, play a key role in reducing horses' vulnerability to adverse conditions. However, the effectiveness of these strategies depends on individual variability, age, breed and housing conditions. Sustaining equine welfare requires a systemic approach that integrates precise monitoring, personalised interventions and interdisciplinary perspectives within the context of global environmental change.

NOVELTY STATEMENT

This review is the first to provide a comprehensive synthesis of environmental stressors affecting equine welfare with a specific focus on physiological, behavioural, and technological dimensions under climate change conditions. By integrating recent findings on heat stress, housing, transport, and monitoring innovations such as biosensors, infrared thermography, and heart rate variability analysis, the article highlights the complexity of equine adaptation mechanisms. The review offers a novel, systems-based perspective on equine welfare assessment, emphasising the importance of personalised strategies and interdisciplinary solutions in the face of escalating environmental challenges.

AUTHOR'S CONTRIBUTION

All authors contributed equally to the work. All authors have read and agreed to the published version of the manuscript.

GENERATIVE AI OR AI-ASSISTED TECHNOLOGY STATEMENT

The authors declare that no Genrative AI was used in the creation of this manuscript.

CONFLICTS OF INTEREST

The authors have declared no conflict of interest.

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