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Heat stress in domestic dogs: morphological and environmental risk factors for dog welfare in a warming world

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Global temperature rise increasingly exposes domestic dogs (*Canis lupus familiaris*) to thermal challenges, especially in tropical and urban regions where climate change, artificial structures, and inadequate care converge. Despite the species' adaptive capacity, morphological traits such as dense coats, brachycephalic conformation, and obesity reduce thermoregulatory efficiency, heightening the risk of heat stress. This review synthesizes evidence on physiological heat exchange mechanisms, discusses subclinical indicators of thermal overload, and presents preventive management strategies tailored to breed profiles and environmental contexts. Emerging technologies, such as wearable thermal sensors, and educational actions targeting caregivers and professionals are explored as tools to promote adaptive care. By adopting a One Welfare perspective, the article connects animal welfare, public health, and sustainability, contributing to professional, policy, and educational practices aimed at protecting dogs from thermal stress in a warming world.

KEYWORDS

anatomy, brachycephalic dogs, canine thermoregulation, heatstroke, heat -related injury, urban microclimate, welfare-oriented interventions

Introduction

The thermal environment plays a critical role in animal health and productivity and is widely recognized as a major challenge for animal welfare. Climate change, coupled with regional environmental characteristics, directly affects animals' ability to maintain homeostasis. This interaction can lead to reduced welfare and physiological challenges -

factors that negatively impact quality of life and performance. Over time, animals have developed a range of physiological and behavioral thermoregulatory mechanisms to cope with environmental challenges (Ames, 1980).

Although animals possess physiological plasticity that enables adaptation to thermal variation, the adverse effects of excessive heat and intense solar radiation - common in many regions of Brazil and globally - have been extensively investigated in livestock species (Takahashi, 2012; Dash et al., 2016; Passini et al., 2020). In contrast, research on domestic dogs (*Canis lupus familiaris*) has largely focused on pathological conditions associated with hyperthermia, while broader implications for their physical, behavioral, and emotional welfare have received limited attention (Bruchim et al., 2009; 2017; Hall et al., 2020).

Severe clinical outcomes highlight the urgency of this issue. Bruchim et al. (2006) reported that, over a five-year period, 54 dogs were treated at a university veterinary hospital in Israel for heatstroke between March and October, with most cases occurring during the warmer months of the year. The overall mortality rate was approximately 50%, despite appropriate treatment. Similar outcomes were observed by Teichmann et al. (2014) in southern Germany, highlighting the severity of heat-related episodes in dogs across different geographic contexts. Nevertheless, the physiological and behavioral responses of dogs to thermal stress remain poorly understood (Seebacher et al., 2015).

However, some recent research has attempted to expand the understanding of heat stress in dogs, going beyond clinical heatstroke to encompass behavioral, perceptual, and occupational factors. For example, Etue et al. (2025) studied how dog owners perceive extreme heat and its effects on their pets' behavior. Slotta-Bachmayr et al. (2024) focused on working detection dogs and found that these dogs showed reduced work efficiency in hot weather. Similarly, Packer et al. (2019) found that owners of brachycephalic dog breeds often normalize clinical signs of heat-related illnesses, perceiving them as typical or inherent to the breed, rather than pathological indicators. This normalization can delay veterinary care and reduce the likelihood of implementing preventive strategies, illustrating how human perception can directly influence canine welfare. Together, these studies illustrate that heat stress is a complex welfare issue that encompasses more than just clinical symptoms, underscoring the importance of integrated preventive strategies.

Even with this recent research, the knowledge gap remains, and it becomes even more concerning given the growing dog population in urban areas, the increasing frequency of extreme heat events, and persistent inequalities in access to thermally safe environments - especially for abandoned, neglected, or socially vulnerable animals (Protopopova et al., 2021; Koohsari et al., 2022). In this context, understanding the physiological limits of domestic dogs exposed to environmental heat is crucial to developing effective and practical welfare strategies.

To this end, it is necessary to examine the anatomical and physiological adaptations that have occurred throughout canine evolution, especially those influencing thermoregulation. Understanding how domestic dogs cope with thermal challenges is essential for the development of evidence-based strategies aimed at minimizing heat stress and safeguarding animal welfare.

Accordingly, we aimed through this review to gather and critically analyze the main factors affecting thermoregulation in domestic dogs, with a focus on physiological capacity, evolutionary background, and contemporary environmental challenges. We identified methodological gaps and proposed future research with direct implications for animal management, public policy, and caregiver education.

This effort is aligned with global sustainability goals, particularly the United Nations Sustainable Development Goals (SDGs) (United Nations, 2015): Good Health and Well-being (SDG 3), Sustainable Cities and Communities (SDG 11), and Climate Action (SDG 13). These complex interactions between environmental variables and intrinsic characteristics result in highly variable thermal responses in dogs. Figure 1 provides an integrative overview of the main determinants of canine heat stress, linking environmental factors and contextual conditions to the anatomical, physical, and physiological characteristics of these animals, and how behavioral and physiological adjustments interact to influence thermoregulation and clinical outcomes.

Phenotypic diversity and evolutionary pathways shaping thermal tolerance in domestic dogs

Understanding these predispositions requires exploring the evolutionary and selective forces that have shaped the domestic dog (*Canis lupus familiaris*), one of the most phenotypically diverse mammalian species, both morphologically and behaviorally. This diversity is the result of a long and multifaceted domestication process, during which dogs evolved alongside humans, adapting to various environments and roles through a combination of natural and human-driven artificial selection (Cook et al., 2014; Georgevsky et al., 2014).

Although the Eurasian gray wolf (*Canis lupus*) is widely recognized as the primary ancestor of modern dogs, some evolutionary models also consider *Canis lepophagus*, a species from the early Pliocene in North America, as a relevant precursor (Cherin et al., 2014; Germonpré et al., 2009). Regardless of the specific origin, there is consensus that selective pressures - initially environmental and later anthropogenic - have shaped the physiology, behavior, and morphology of domestic dogs in diverse and sometimes conflicting directions.

Today's diversity reflects multiple phases of selective pressure. Early dog breeds, for instance, emerged under strong natural selection in harsh climates, which favored morphological traits that enhanced survival. Darker skin pigmentation and curled coats, seen in certain African lineages, may have evolved as protective adaptations against ultraviolet radiation and thermal overload in tropical environments (Liu et al., 2017).

In contrast, modern artificial selection has prioritized aesthetic or behavioral traits that do not necessarily favor thermoregulatory efficiency. Traits such as shortened muzzles, dense coats, and

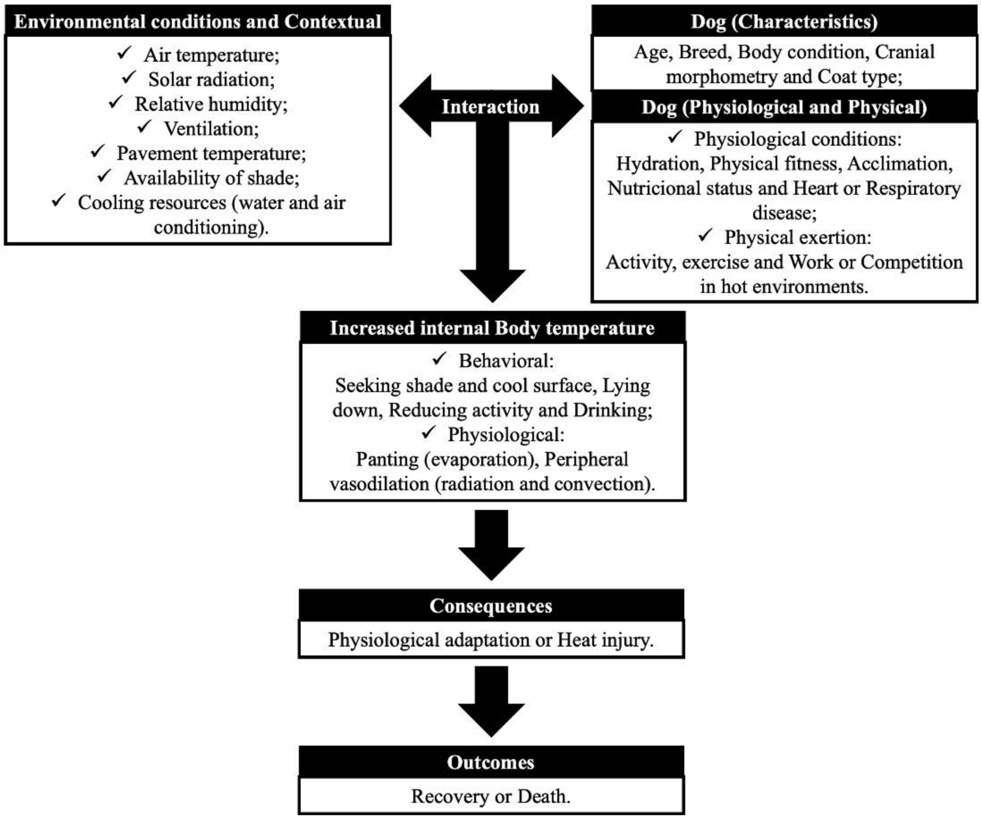

FIGURE 1
Multifactorial determinants of heat stress in domestic dogs.

extreme body conformations have been widely selected despite impairing heat dissipation (Akey et al., 2010; Hall et al., 2021; Beard et al., 2024). In some cases - such as the brachycephalic skull of the Saint Bernard - these features not only fail to confer thermophysiological advantage but may also increase susceptibility to heat stress (Drake and Klingenberg, 2008).

Artificial selection has also shaped behavioral profiles, promoting traits such as docility, reactivity, and aggression to fulfill specific social or working functions (Careau et al., 2010). These traits may influence how dogs respond behaviorally to thermal discomfort or environmental stressors.

From an anatomical standpoint, a critical factor affecting thermoregulation in dogs is the absence of functional sweat glands over most of the body, with the exception of the paw pads. Comparative studies with wild canids - such as wolves and coyotes - have shown that dogs, particularly those from colder regions, exhibit a higher density of eccrine glands and greater sweating capacity in the paw pads, possibly as an adaptation to prevent frostbite (Sands et al., 1977; Affolter and Moore, 1994).

These findings indicate that while some adaptations enhance thermoregulation in specific contexts, others - driven by human aesthetic or functional preferences - may significantly impair dogs' ability to cope with environmental heat. Understanding the evolutionary and artificial selection factors that shape these traits is essential for identifying breed-specific vulnerabilities to heat stress and for developing evidence-based management and welfare strategies in increasingly hot climates.

Such knowledge lays the foundation for understanding how these vulnerabilities manifest in dogs' everyday interactions with their environment - particularly under conditions of chronic thermal exposure.

Dog-environment interactions and thermal welfare: from daily exposure to chronic risk

Building on this understanding, it is crucial to examine how domestic dogs - especially those with compromised thermoregulatory traits - interact with their environments on a daily basis. In contrast to livestock species, where the effects of the thermal environment are detected or routinely monitored through changes in productivity and reproductive efficiency, domestic dogs are seldom evaluated in terms of how climatic conditions influence their daily welfare. However, dogs - particularly those living in warm and urbanized environments - are increasingly vulnerable to thermal stress, a factor that often goes unnoticed until it manifests as clinical symptoms, limiting early intervention and effective prevention strategies (Moon et al., 2021).

Thermoregulatory capacity in dogs varies with age and developmental stage. Classical studies by Jensen and Ederstrom (1955) and McIntyre and Ederstrom (1958) demonstrated that puppies only develop functional thermoregulation after the third or fourth week of life. Until then, they rely heavily on passive thermal support and are particularly susceptible to environmental fluctuations.

In adult dogs, both acute and chronic thermal exposure significantly affect hydration, behavior, and physiological stability. O'Connor (1977) observed that radiant heat exposure markedly increased water loss in mixed-breed dogs, with effects comparable to intense physical exercise. Notably, Otto et al. (2017), studying hydration in working detection dogs, found that certain electrolyte supplements may paradoxically increase the risk of dehydration under extreme heat, clearly illustrating the complexity and context-specific nature of physiological responses to thermal load.

Breed and environmental history also play key roles in thermal adaptation. Research involving dogs living in cold climates shows that seasonal acclimation results in measurable physiological changes, including increased metabolic rate and enhanced insulation. For example, Siberian Huskies increase food intake and develop thicker, more insulating coats when exposed to decreasing temperatures (Durrer and Hannon, 1962). Similarly, Sugano (1981) found that dogs kept outdoors during the Japanese winter exhibited increased resting heat production and greater thermal insulation.

In contrast, evidence suggests that some dogs have adapted to hot environments, although these adaptations likely evolved under persistently warm rather than seasonally hot conditions. For instance, non-indigenous dog breeds in Nigeria appeared to experience mild heat stress compared to native breeds, indicating local thermal adaptation (Zakari and Omontese, 2023). Moreover, African hunting dogs display specialized thermoregulatory mechanisms that allow prolonged running in high temperatures (Taylor et al., 1971). Nonetheless, whether domestic dogs exhibit seasonal physiological adjustments to heat, analogous to those observed in cold acclimation, remains uncertain.

Importantly, recent evidence indicates that owners of cold-adapted breeds, such as the Siberian Husky living in Brazil, recognize thermoregulatory challenges in their dogs and adjust certain aspects of care, such as walk timing, in response to perceived heat sensitivity. In a large-scale survey of 624 Husky owners, most reported heat-avoidant behaviors in their dogs and showed preference for walking during thermally comfortable periods - though time constraints still led some to expose their dogs to high solar load (Veríssimo et al., 2023). These findings highlight the role of caregiver perception in mitigating or exacerbating thermal stress, reinforcing the need for public education and breed-specific management recommendations.

Despite these contributions, research on heat stress in dogs continues to focus narrowly on severe clinical conditions such as heatstroke. A welfare-centered approach, however, must consider subclinical signs, cumulative thermal loads, and breed-specific vulnerabilities - factors often overlooked in conventional veterinary assessments (Flournoy and Wohl, 2003).

As urbanization accelerates and global temperatures rise, it becomes increasingly urgent to understand how domestic dogs cope with daily thermal challenges. This includes not only analyzing extreme events but also monitoring chronic exposure to elevated temperatures - particularly in breeds with morphological traits that compromise heat dissipation. Breed-specific strategies - such as adjusting walking schedules, improving shelter conditions, and educating caretakers about their dog's coping limits, are essential to prevent avoidable suffering. Furthermore, incorporating thermal welfare considerations into breeding standards and public health policies offers a concrete opportunity to address these challenges in a more integrated and systematic manner, with direct impacts on animal health and responsible dog ownership.

In addition to its clinical implications, exposing dogs to heat raises important public health concerns. These include increased risks of zoonotic diseases, behavioral changes that may compromise safety, and emotional distress among caregivers living in urban areas vulnerable to high temperatures (American Animal Hospital Association (AAHA), 2019). Companion dogs experience similar climatic and structural challenges as humans, especially in urban heat islands, where poor ventilation, limited vegetation, and reflective surfaces increase heat exposure (Moon et al., 2021). Episodes of heat distress in dogs frequently align with peaks in human health issues during heatwaves, highlighting a shared vulnerability to extreme environmental conditions (Beard et al., 2024).

From a One Welfare perspective, reducing heat stress in dogs not only benefits animal welfare but also promotes public health, caregiver well-being, and sustainable urban living. This integrated approach recognizes that animal welfare, human health, and environmental resilience are interconnected. It emphasizes the need for cross-sector policies and public education to protect all members of our shared ecosystems (Pinillos et al., 2016; Pinillos, 2018).

Anatomical and physiological features influencing canine thermoregulation

To effectively address these challenges, it is necessary to examine the anatomical and physiological traits that underlie dogs' varied responses to heat. Domestic dogs (*Canis lupus familiaris*) exhibit one of the widest anatomical variations among mammals - a legacy of both natural evolution and intense artificial selection. This variation encompasses not only visible traits such as coat type and skull shape but also physiological factors like respiratory efficiency and metabolic rate, all of which influence thermoregulatory capacity and welfare under heat stress.

With over 360 recognized breeds worldwide, and substantial variability even within breeds, dogs present a broad spectrum of thermal susceptibilities (Suzanski, 2013). While this diversity is fascinating from a genetic standpoint, it poses significant challenges for understanding and managing heat-related risks - especially since many phenotypes have been selected without regard for environmental compatibility.

One of the factors that is commonly cited as influencing thermal balance is coat color. Darker coats absorb more solar radiation, converting light energy into heat - a phenomenon well established in physics and widely applied to animal science (McNicholl et al., 2016). However, empirical findings remain inconsistent. For instance, Neander et al. (2019) found no significant differences in body temperature or respiratory rate between black and yellow Labrador Retrievers under controlled conditions, suggesting that coat color alone is insufficient to predict heat sensitivity.

Coat structure and hair density are additional critical modifiers of heat exchange, as dogs with different coat types have been observed to have different surface temperatures during exercise (Jimenez et al., 2022). This is because, as demonstrated by Walsberg (1988) in other mammals, the optical properties and structure of the coat can have a greater impact on solar radiation absorption than just a single characteristic such as surface pigmentation. Kwon and Brundage (2019) demonstrated that dogs with short, smooth coats exhibited significantly higher surface temperatures than those with long or curly fur, likely due to reduced insulation and altered heat flux. Unfortunately, the absence of coat color data in their study limited conclusions regarding the combined effects of color and structure.

Beyond external features, body conformation plays a pivotal role. Dogs with high body mass or compact physiques tend to have a lower surface area-to-volume ratio, reducing their ability to dissipate excess heat. Brachycephalic breeds — such as Bulldogs and Pugs — present unique thermoregulatory limitations due to shortened nasal passages and compromised upper airway anatomy, reducing the efficiency of evaporative cooling via panting (Davis et al., 2017). The nasal turbinates and upper respiratory tract play a crucial role in evaporative cooling by providing an extensive mucosal surface for heat exchange during panting (Shapiro et al., 1973). In these breeds, even mild physical activity in warm environments can rapidly lead to overheating and respiratory distress.

Additionally, obesity significantly increases heat stress risk, not only due to the insulating effect of adipose tissue but also because of increased cardiovascular and respiratory strain. Unlike humans, dogs lack functional sweat glands over most of their bodies. Under moderate ambient conditions, more than 70% of body heat is dissipated through radiation and convection from body surfaces (Bruchim et al., 2017; Lewis and Foster, 1976). As environmental or body temperature rises, panting becomes the predominant cooling mechanism, relying on evaporative heat loss through the respiratory tract — particularly the nasal turbinates, sinuses, and tongue (Hemmelgarn and Gannon, 2013). Minor contributions to heat dissipation also occur through non-haired skin regions, such as paw pads and the inguinal and axillary areas, primarily via conduction and limited evaporation (Lewis and Foster, 1976). Any anatomical or physiological impairment of these mechanisms exponentially increases susceptibility to heat stress.

Among the mechanisms that contribute to peripheral heat loss in dogs are radiation, evaporation, and conduction, which occur mainly in regions such as the tongue, axillae, inguinal region, and paw pads. These pathways operate in conjunction with other physiological responses, such as panting and systemic vasodilation, which also contribute to thermoregulation. Figure 2 illustrates all forms of heat transfer involved in thermal exchange, providing an overview of how heat moves between the canine body and the external environment under heat stress conditions.

It's important to note that these characteristics are often overlooked in routine veterinary evaluations or in public communications about heat-related risks. Breed standards rarely take thermoregulatory efficiency into account, and some aesthetic characteristics persist despite well-documented health concerns, such as in breeds with brachycephaly, such as the French Bulldog (Ladlow et al., 2018; O'Neill et al., 2021). In this context, anatomical and physiological profiling should be integrated into breed management strategies, caretaker education, and welfare policy.

Recognizing the thermophysiological implications of breed-specific traits is essential not only for preventing acute heat-related events but also for reducing the chronic thermal burden that many companion dogs face in increasingly hot urban environments. Epidemiological studies have shown that brachycephalic breeds, such as Bulldogs and Pugs, as well as retrievers and large-bodied dogs, are the most commonly affected by heatstroke (Hall et al., 2020; Drobatz and Macintire, 1996). These insights form the foundation for targeted interventions, which will be addressed in the following sections.

Thermoregulation in domestic dogs: interactions between anatomy and environmental stressors

Building upon the anatomical and physiological traits discussed earlier, this section explores how these internal features interact with environmental conditions to shape real-world thermoregulatory outcomes in domestic dogs.

As homeothermic mammals, domestic dogs rely on a delicate balance between metabolic heat production and heat dissipation to maintain internal thermal stability. Under thermoneutral conditions, sensible heat loss mechanisms - namely conduction, convection, and radiation - are highly effective, accounting for more than 70% of total heat dissipation (Shapiro et al., 1973).

Peripheral vasodilation plays a critical role in canine thermoregulation, facilitating heat loss through radiation and convection as cutaneous blood flow increases. Experimental work in the 1970s demonstrated that thermal exposure triggers reflex vasodilation mediated by hypothalamic thermoreceptors, resulting in increased skin temperature and peripheral perfusion (Hales and Dampney, 1975). These mechanisms remain central to our understanding of thermoregulatory physiology in domestic dogs.

As illustrated in Figure 3, which qualitatively demonstrates the decreasing efficiency of sensitive heat dissipation mechanisms, making them less effective in hot and dry environments (Rocha and Moraes, 2017). This occurs as the ambient air temperature approaches the dog's skin temperature (Mount, 1979), which

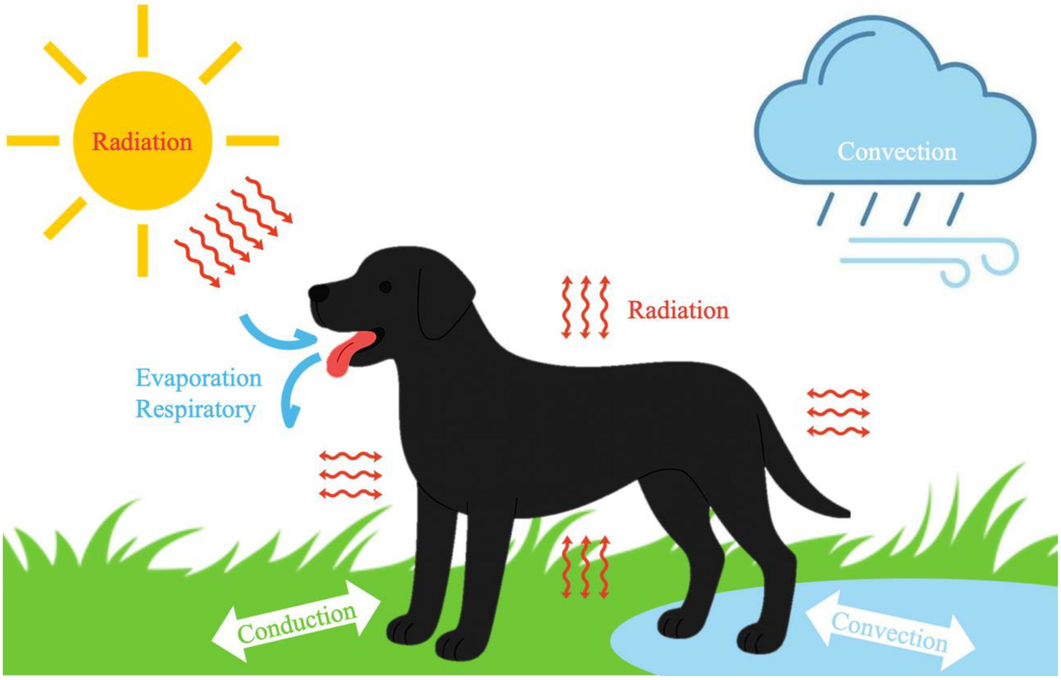

FIGURE 2
All forms of heat transfer in domestic dogs.

typically ranges from 30°C to 35°C (Souza et al., 2014). Under such conditions, evaporative cooling becomes the primary thermoregulatory pathway, primarily through panting. Unlike humans, dogs have very few functional sweat glands, located primarily on the paw pads, and their contribution to heat loss is minimal (Affolter and Moore, 1994). Panting can also be potentiated by hypersalivation, which consists of increased oral humidification. However, hypersalivation has been proposed as a potential factor contributing to dehydration during prolonged heat exposure, particularly in dogs with limited evaporative efficiency. Although this relationship has been discussed by Bruchim et al. (2017), it has not been empirically confirmed in controlled studies and therefore remains speculative.

Although companion dogs often spend a portion of the day indoors (to the different of street or feral dogs), they are frequently exposed to outdoor conditions during walks or physical activity - often at times of peak solar radiation, especially in tropical and subtropical regions. Unfortunately, many thermal models

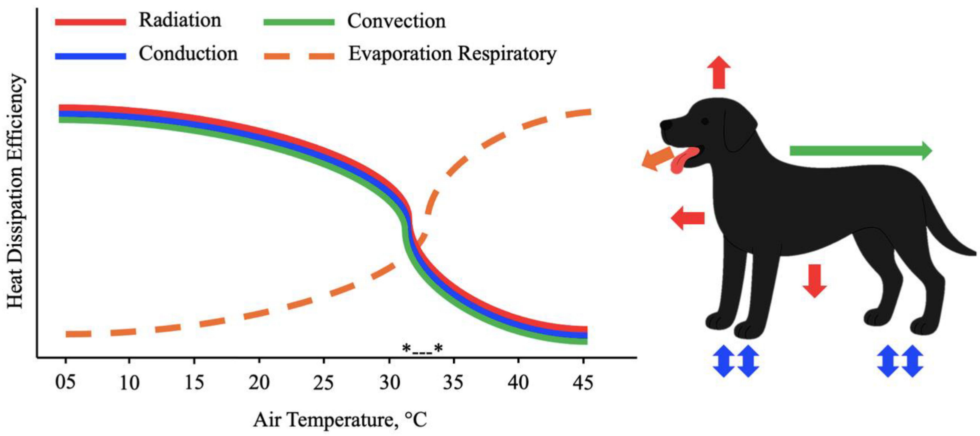

FIGURE 3
Efficiency of sensible heat dissipation mechanisms as ambient air temperature approaches canine skin temperature. The figure presents a trend line - without numerical values - indicating the progressive decline in the efficiency of conduction, convection, and radiation under warm, low-humidity conditions. *—* indicates the typical skin temperature range in dogs (Adapted from Veríssimo, 2022).

underestimate actual heat stress risk by focusing solely on ambient air temperature while ignoring solar radiation load. As noted by Mitchell et al. (2018), solar radiation, surface temperature, and reflective urban materials can drastically increase a dog's body heat load, particularly in the absence of shade and ventilation.

To better predict these risks, Potter et al. (2020) proposed the Canine Thermal Model (CTM), which integrates metabolic heat production (M), physical effort or work (W), radiative heat exchange (R), convective transfer (C), and evaporative loss (E), according to the equation:

$$\mathbf{S = M \pm W \pm R \pm C - E},$$

where S represents the net heat stored in the body. Similar formulations for thermal balance and heat exchange in dogs have also been discussed in previous studies (e.g., McNicholl et al., 2016; O'Brien et al., 2020), providing additional support for the theoretical basis of the CTM.

Although innovative, these models generally omit conductive heat transfer, which is increasingly relevant in urban environments where dogs walk or rest on sun-heated surfaces such as asphalt, ceramic tile, or sand (Jim, 2016; Vanos et al., 2016). This limitation highlights the challenge of applying standardized models to real-world scenarios, in which variables such as body posture, coat thickness, and behavioral choices directly affect thermal load dynamics (Kwon and Brundage, 2019; Silva et al., 2022).

These environmental challenges are even more acute for working dogs - those employed in military, police, or search and rescue - who endure intense physical exertion in thermally demanding conditions. They are also for assistance dogs - such as guide dogs, dogs for the deaf, or medical alert dogs - since these animals accompany their human companions almost everywhere and at any time of day. In such cases, even mild impairments in evaporative cooling efficiency can result in rapid heat accumulation and physiological collapse (Robertshaw, 2006). Similarly, companion dogs walked during the hottest hours - often on surfaces exceeding 50°C - may struggle to self-regulate due to fatigue, anatomical limitations, or inadequate hydration (Hales and Webster, 1995; Potter et al., 2018).

Thermoregulation is also impaired by urban microclimates, where heat island effects and low airflow exacerbate environmental heat stress (Gunawardena et al., 2017). Dogs with dense coats, brachycephalic skull conformation, or excess body fat are particularly vulnerable in these settings (Hall et al., 2020). Furthermore, repeated exposure to suboptimal conditions may lead to chronic thermal burden, with long-term impacts on health, behavior, and welfare (Leon and Helwig, 2010).

Addressing these risks requires context-sensitive assessment tools and a paradigm shift - from static, fixed-threshold models to dynamic, individualized welfare frameworks. Breed-specific guidelines, the development of wearable thermal sensors, and public education campaigns may be essential strategies to reduce heat-related suffering in domestic dogs as global temperatures continue to rise.

Heat stress as a welfare threat in domestic dogs

Given the previously discussed anatomical and environmental constraints, it becomes essential to understand how heat stress manifests and progresses as a concrete threat to the welfare of domestic dogs.

The widespread distribution of dog breeds across regions with climatic conditions that often contrast sharply with their evolutionary or selective origins has led to frequent mismatches between thermophysiological traits and the environments in which dogs live. These mismatches are especially evident in areas experiencing frequent heat waves, high tropical humidity, and rapid urbanization, where dogs' thermal adaptation capacity is frequently exceeded (Freedman et al., 2016). Moreover, dogs living in temperate regions face additional risks during short but intense heat events. Because these regions typically have limited periods of heat exposure, both animals and their owners may be less physiologically and behaviorally adapted to high temperatures. As a result, sudden heatwaves in such climates can lead to disproportionate rates of heat-related illness and mortality, exacerbated by low public awareness of canine heat-health risks (Lewis and Foster, 1976; Bruchim et al., 2017).

Unlike livestock species, for which thermal comfort zones and heat stress thresholds are well defined, determining thermoneutral ranges and critical temperature limits for domestic dogs remains challenging. This difficulty arises from the remarkable phenotypic variability within the species: breeds differ substantially in body mass, coat thickness, skull conformation, and respiratory anatomy (National Research Council, 2006). As a result, generalized recommendations fail to adequately reflect the true vulnerability of specific subgroups - particularly brachycephalic, long-haired, obese, elderly, and working dogs - making it difficult to establish effective clinical protocols and preventive guidelines.

Among the earliest physiological signs of heat stress are increases in respiratory rate (RR) and rectal temperature (RT). Although panting is a key evaporative heat loss mechanism, it comes at a high physiological cost. Sustained elevated RR can lead to respiratory alkalosis, muscle fatigue, hypoglycemia, and reduced cardiac output (Kanter, 1959; Higgins and Iampietro, 1967).

The progressive rise in rectal temperature (RT) is an important physiological indicator during heat exposure. However, recent studies show that body temperature alone is not a reliable predictor of the severity of heat injury. While earlier literature suggested that neurological damage may occur when RT exceeds 41°C (Lewis and Foster, 1976). More recent experimental and field research has demonstrated that well-conditioned and acclimated dogs can tolerate core temperatures of up to 42°C without experiencing adverse effects (Robbins et al., 2017; Carter and Hall, 2018). This variability underscores the significant impact of physical fitness, hydration status, and environmental conditions on thermal tolerance. Evidence indicates that physical conditioning enhances cardiovascular and evaporative efficiency, significantly improving dogs' heat tolerance (Davis et al., 2017; Hall et al., 2020). Therefore, RT should be evaluated alongside other complementary indicators - such as heart rate, respiratory effort, mental status, and hydration level - to enhance diagnostic accuracy and clinical prognosis in cases of heat-related stress.

This physiological cascade may culminate in heatstroke, a critical event triggered either by extreme environmental exposure (classic heatstroke) or by intense physical exertion (exertional heatstroke). In both cases, thermoregulatory mechanisms become overwhelmed, resulting in systemic collapse. In a retrospective study conducted in Israel, Bruchim et al. (2006) reported a 50% mortality rate among 54 dogs diagnosed with heatstroke - most cases occurring during the hottest months of the year. Belgian Malinois, often employed in high-intensity tasks, were particularly susceptible to exertional heatstroke. Brachycephalic breeds and overweight dogs were also disproportionately represented among the fatalities.

Similar findings were reported by Teichmann et al. (2014) in Germany. In contrast, Hall et al. (2020), using a broader surveillance approach in the United Kingdom, reported an overall mortality rate of 14.18% for heat-related illness (HRI) in dogs. However, this study included all grades of HRI - from mild heat stress to severe heatstroke - which partly explains the lower overall fatality. When cases were stratified by severity in Hall et al.'s follow-up study, a fatality rate of 56.76% was reported for dogs with severe HRI (Hall et al., 2021), consistent with the findings of Bruchim et al. (2017) and Teichmann et al. (2014). Interestingly, Tripovich et al. (2023) observed markedly lower incidence and fatality rates of HRI in dogs from New South Wales, Australia - a region characterized by high ambient temperatures. These results may reflect both improved public awareness of heat risk and the mitigating effects of long-term heat acclimation in local canine populations.

Despite this growing body of evidence, public understanding of canine heat stress remains alarmingly limited. Many dog owners associate heat risk exclusively with extreme events, overlooking more subtle yet cumulatively harmful exposures, such as midday walks on hot pavement or extended confinement in poorly ventilated areas (Etue et al., 2025). Breed-specific vulnerabilities are often unknown or underestimated, particularly among owners of brachycephalic or thick-coated dogs, some of whom perceive respiratory distress or heat intolerance as "normal for the breed" rather than as clinical warning signs (Packer et al., 2019).

This knowledge gap is particularly concerning in large, climatically diverse countries such as Brazil, where regional temperature variation and urban heat islands intensify thermal burdens on dogs. Furthermore, socioeconomic inequalities exacerbate these risks: homeless or vulnerably housed individuals often live with pets under conditions of poor ventilation and high ambient temperature, while urban housing associated with low-income or aging populations is frequently located in areas of elevated heat exposure (Macintyre et al., 2018). Yet, there remains a critical lack of breed-, region-, and context-specific data to inform veterinary care, guide public education, and shape effective policy. Without such information, both professionals and caregivers are left without meaningful reference points for prevention or intervention.

Recognizing heat stress as a welfare issue - not merely a clinical emergency - requires a paradigm shift. It must be integrated into routine veterinary evaluations, urban planning, caregiver education, and even breed standards. In a warming world, protecting companion animals from preventable thermal suffering must become a proactive, evidence-based priority across sectors.

Final considerations and recommendations

Having examined the multifactorial determinants of heat stress in domestic dogs - including evolutionary background, physiological traits, and environmental exposures - it becomes possible to synthesize practical and evidence-based actions to mitigate these risks.

Exposure to high ambient temperatures, coupled with elevated humidity and intense solar radiation, poses a serious and escalating threat to the health and welfare of domestic dogs - particularly in tropical and urbanized regions. Urban heat islands disproportionately impact low-income and densely populated areas, where limited access to green spaces, ventilation, and cooling infrastructure increases health risks during heatwaves. Macintyre et al. (2018) found that thermal exposure in these environments is closely linked to social inequality, highlighting the interdependence of environmental and socioeconomic vulnerabilities. These conditions also increase the thermal stress endured by companion animals living in these areas, demonstrating a shared risk scenario for both humans and animals within urban ecosystems. Public education campaigns should therefore prioritize clear, actionable guidance on early recognition and response to heat distress, such as immediate cessation of activity, relocation to a shaded or cooler environment, offering water, and initiating active cooling. These steps are consistent with established emergency care guidelines for dogs (Hanel et al., 2016).

Although not specifically investigated in the study, the findings of Tripovich et al. (2023) indicate that dogs engaged in outdoor physical activity are particularly prone to heat-related illness, especially during high-temperature periods. This observation implies that working and assistance dogs - such as guide, hearing, or medical alert dogs - may represent an under-recognized risk group due to their unavoidable exposure during human outdoor activities. These animals often accompany their handlers in urban environments characterized by limited shade, reflective surfaces, and restricted airflow, all of which intensify environmental heat load. Such conditions create a shared vulnerability for both humans and their companion or service animals, emphasizing the need for preventive strategies that consider the welfare of both species. From a One Welfare perspective, promoting thermal safety for working and assistance dogs not only protects animal health but also safeguards human independence, emotional well-being, and social inclusion, reinforcing the interconnection between animal welfare,

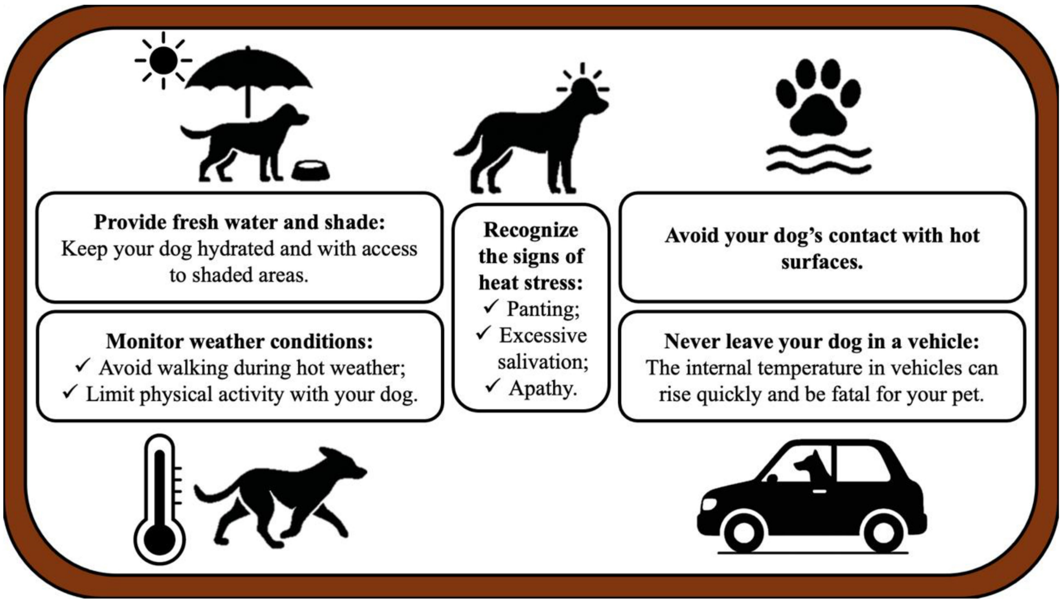

FIGURE 4
Best practices for managing canine heat stress in daily care routines.

human health, and environmental resilience (Pinillos et al., 2016; Pinillos, 2018).

Additionally, dogs in temperate regions may face acute risks during short, intense heatwaves, as limited seasonal acclimation reduces their physiological resilience to sudden temperature increases. Although physiological resilience and physical conditioning may buffer some effects in certain individuals, environmental conditions can surpass even the most heat-tolerant dogs' adaptive capacities.

Because most dogs live in environments where microclimate modifications are not always feasible - especially during walks or outdoor activities - the focus must shift toward preventive strategies and increased caregiver awareness. These include:

- Adjusting the timing and duration of outdoor activities to avoid peak heat periods;
- Ensuring access to shade and fresh water during all outdoor exposures;
- Avoiding hot surfaces such as asphalt or concrete during warm hours;
- Recognizing early signs of thermal discomfort, such as excessive panting, reluctance to move, or behavioral changes;
- Promoting controlled exercise and fitness maintenance.

When implemented consistently, these measures can substantially reduce the risk of preventable heat-related suffering. However, the success of such interventions depends on owner behavior and awareness. Given the ongoing challenges in achieving behavior change and the generally low level of heat-stress awareness among dog owners, broad-based educational campaigns may be more effective than breed-specific guidance alone. Breed-focused materials should still play a complementary role by addressing unique physiological vulnerabilities in brachycephalic, long-haired, obese, or chronically ill dogs, particularly during hotter months.

Emerging research highlights the importance of understanding the psychological dimension of owner responses to pet heat stress. Teigen and Zottarelli (2025) discuss how emotional engagement and perceived climate anxiety can influence preventive behaviors, suggesting that effective communication strategies should not only inform but also motivate caregivers to act. Figure 4 summarizes best practices for managing canine heat exposure through a practical, evidence-based checklist designed to support daily decision-making by caregivers and professionals.

At a broader level, thermal welfare must be integrated into breeding standards, urban planning, and public education campaigns. The development of accessible technologies - such as wearable temperature sensors, infrared thermography tools, or smartphone apps that combine meteorological data with breed-specific profiles - can support real-time, informed decisions by caregivers.

From a research perspective, further studies are urgently needed to:

- Establish comfortable zones and critical temperature limits in different breeds and morphotypes;
- Quantify the cumulative effects of chronic heat exposure on behavior, physiology, and long-term welfare consequences;
- Assess the efficacy of interventions (e.g., cooling vests, surface protection, hydration strategies) across various climates and canine profiles.

To this end, academic institutions, postgraduate programs, and funding agencies must be encouraged and supported to prioritize applied research on canine thermal welfare, fostering evidence-based policies and professional training.

In a warming world, ensuring thermal welfare for domestic dogs is no longer optional - it is a moral, scientific, and societal imperative. As sentient companions sharing human spaces, dogs are particularly vulnerable to anthropogenic environmental change, yet often lack systemic protections from heat-related distress.

This review offers a comprehensive synthesis of the anatomical, physiological, behavioral, and environmental determinants of heat stress in domestic dogs, translating complex scientific evidence into practical, breed-sensitive strategies. In doing so, it contributes directly to a One Welfare perspective, aligning animal welfare with sustainable development and public accountability.

Promoting thermally adaptive canine care is not merely about avoiding acute suffering - it reflects our ethical responsibility in the Anthropocene, where climate, species, and society converge. Advancing this agenda supports global commitments to SDG 3 (Good Health and Well-being), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action), reminding us that a humane future must also be thermally just.

Author contributions

PN: Conceptualization, Formal Analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. TV: Investigation, Methodology, Visualization, Writing – review & editing. WS: Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – review & editing. MM: Investigation, Methodology, Writing – review & editing. LC: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Writing – review & editing. ES: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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