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REVIEW ARTICLE

Thermoregulation and Physiological Responses to Heat Stress in Poultry: A Comprehensive Review

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Abstract

Heat stress represents a major constraint in poultry production, adversely affecting bird health, productivity and welfare. This review examines the physiological and biochemical consequences of heat stress in poultry, with particular emphasis on its effects on feed intake, egg production and immune competence. It outlines the principal thermoregulatory mechanisms, including conduction, convection, radiation and evaporative heat loss, through which birds maintain thermal homeostasis. In addition, the roles of stress-associated hormones and metabolic adaptations under elevated ambient temperatures are discussed. Collectively, these physiological alterations lead to reductions in feed intake, growth rate, eggshell formation, egg quality and overall performance, while prolonged exposure may result in increased mortality. The evidence reviewed indicates that heat stress constitutes a multifactorial disturbance, involving coordinated disruptions across metabolic, endocrine, immune and behavioural systems.

INTRODUCTION

Animals are broadly classified into two groups based on their mechanisms of body temperature regulation, namely cold-blooded (heterothermic) and warm-blooded (homeothermic). Birds are homeothermic animals that maintain a relatively constant internal body temperature despite fluctuations in ambient conditions[1,2]. However, their thermoregulatory efficiency is optimal only within a defined thermoneutral range of 27.5 to 37.7 °C[3,4]. Although birds share general thermoregulatory characteristics with other endotherms, they possess specialized adaptations, including plumage, subcutaneous fat insulation and salt glands, which contribute to temperature regulation[4,5].

Heat stress represents a major constraint in poultry production, adversely affecting bird health, productivity and welfare. This review examines the physiological and biochemical consequences of heat stress in poultry, with particular emphasis on its effects on feed intake, egg production and immune competence. It outlines the principal outlines the principal thermoregulatory mechanisms, including conduction, convection, radiation, and evaporative heat loss, through which birds maintain thermal homeostasis. In addition, the roles of stress-associated hormones and metabolic adaptations under elevated ambient temperatures are discussed. Collectively, these physiological alterations lead to reductions in feed intake, growth rate, eggshell formation, egg quality and overall performance, while prolonged exposure may result in increased mortality. The evidence reviewed indicates that heat stress constitutes a multifactorial disturbance, involving coordinated disruptions across metabolic, endocrine, immune and behavioural systems.

As endotherms, birds generate heat internally through metabolic processes, including glycolysis, the Krebs cycle and the pentose phosphate pathway, as well as through muscular activity[6-8]. Heat production in poultry is influenced by multiple factors, including enzyme activity, hormonal regulation, physical activity, oxygen consumption, ambient temperature and circadian rhythms[4,9,10]. To prevent hyperthermia, birds dissipate excess metabolic heat primarily through conductive and convective mechanisms at the cellular and vascular levels[2,4].

In laying hen production systems, thermal comfort is often inferred from productivity parameters rather than direct welfare indicators. Environmental sustainability, food safety and animal welfare constitute three major challenges in modern poultry production[11]. The thermoneutral zone in birds varies with body weight and age[12]. The interaction between environmental temperature and endogenous heat production in laying hens can be interpreted through thermal comfort thresholds, which integrate physiological responses to evaluate productive performance. In laying hens, the optimal ambient temperature generally ranges from 21 to 28°C[13]. Ferreira[14] reported that productivity improves under conditions of relative humidity between 40 and 70%. However, the capacity of birds to dissipate heat declines as ambient temperature and relative humidity exceed the thermoneutral zone, resulting in an increase in body temperature and the onset of heat stress[4,15-17].

What is stress: In all livestock production systems, animals inevitably experience stress as a result of diverse environmental and management-related factors (Fig. 1). Stress is a biological response mechanism that enables the maintenance of internal equilibrium, or homeostasis[18]. Among environmental stressors in poultry production, heat stress represents a major challenge, occurring when ambient temperature and humidity exceed the birds' capacity for effective thermoregulation. Stress activates a cascade of complex physiological processes involving the endocrine, nervous and immune systems, collectively referred to as the stress response[19]. This response induces a range of behavioral and physiological adaptations that enhance an animal's capacity to cope with adverse conditions[20]. Behavioral responses to stress may include increased alertness, transient euphoria, enhanced cognitive performance and elevated pain

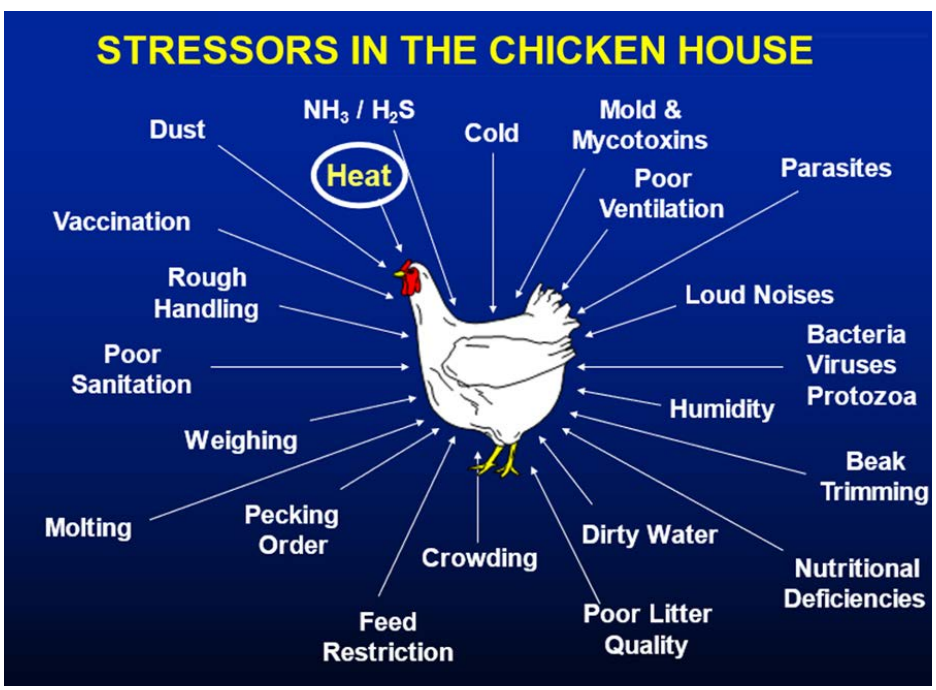

Fig. 1: Cause of stress in the poultry house

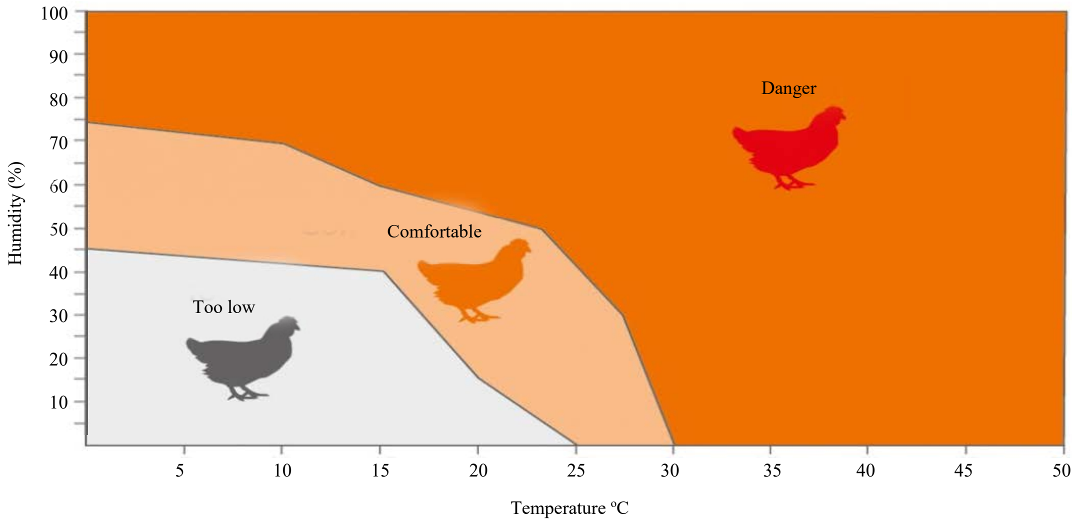

Fig. 2: The range of the thermohumid comfort zone in poultry

tolerance[21]. Physiologically, stress is associated with increased heart rate, elevated respiration, heightened metabolic activity and suppression of essential bodily functions[20,22].

Poultry possess a relatively narrow thermoregulatory range, rendering them particularly susceptible to heat stress (Fig. 2). Although, selective breeding has substantially improved growth rates and muscle accretion, it has not led to a corresponding enhancement in thermoregulatory capacity. Consequently, heat stress remains a persistent concern, especially in hot and arid climates, where it contributes to significant economic losses[18,23,24]. This condition arises when birds are unable to maintain a balance between heat production and heat dissipation. Environmental factors, including elevated ambient temperature, radiant heat, high humidity and inadequate ventilation, exacerbate this imbalance, with ambient temperature being the most critical determinant.

In response to elevated temperatures, poultry employ a range of physiological and behavioral mechanisms to preserve homeostasis[25]. The primary thermolytic strategy is evaporative heat loss through increased respiratory activity; however, this mechanism is often insufficient under severe conditions, necessitating external cooling interventions[26]. Heat stress exerts detrimental effects on poultry production by reducing feed intake, impairing growth performance, lowering meat and egg quality, suppressing immune function and increasing mortality rates[27,28,29]. In the context of climate change and rising global temperatures, the mitigation of heat stress has become a critical priority in poultry production systems. A variety of management strategies have therefore been developed to alleviate its impact and sustain poultry health and productivity[30]. Elevated summer temperatures can markedly impair poultry performance by decreasing feed consumption, reducing egg production and compromising overall health status[18,31,32]. This review focuses on effective strategies for mitigating heat stress in laying hens to optimize their productivity under high-temperature conditions.

Thermoregulation: Birds exhibit marked differences in thermoregulatory capacity immediately after hatching and are broadly classified as either precocial or altricial. Precocial (nidifugous) species hatch with a covering of down feathers and exhibit a high degree of mobility from birth[33]. These birds, including chickens, quails, ducks, geese, shorebirds, waders, tinamous and hoatzins, emerge with open eyes and well-developed plumage. They are capable of responding to environmental temperature fluctuations soon after hatching and can maintain body temperature to a limited extent, although thermoregulatory efficiency improves with age. Precocial species are generally able to forage independently, albeit often with parental guidance and typically leave the nest shortly after hatching.

In contrast, altricial birds hatch in a relatively underdeveloped state and lack effective thermoregulatory mechanisms, rendering them highly dependent on parental care for warmth and survival. In poultry production, newly hatched chicks require carefully controlled environmental conditions. Optimal brooding temperatures range between 87-92°F (30-33°C)[34], with relative humidity maintained at 40-60%[35]. Exposure to drafts must be minimized to prevent wind chill. As chicks develop, environmental temperature should be gradu ally reduced by approximately 4°F (2°C) per

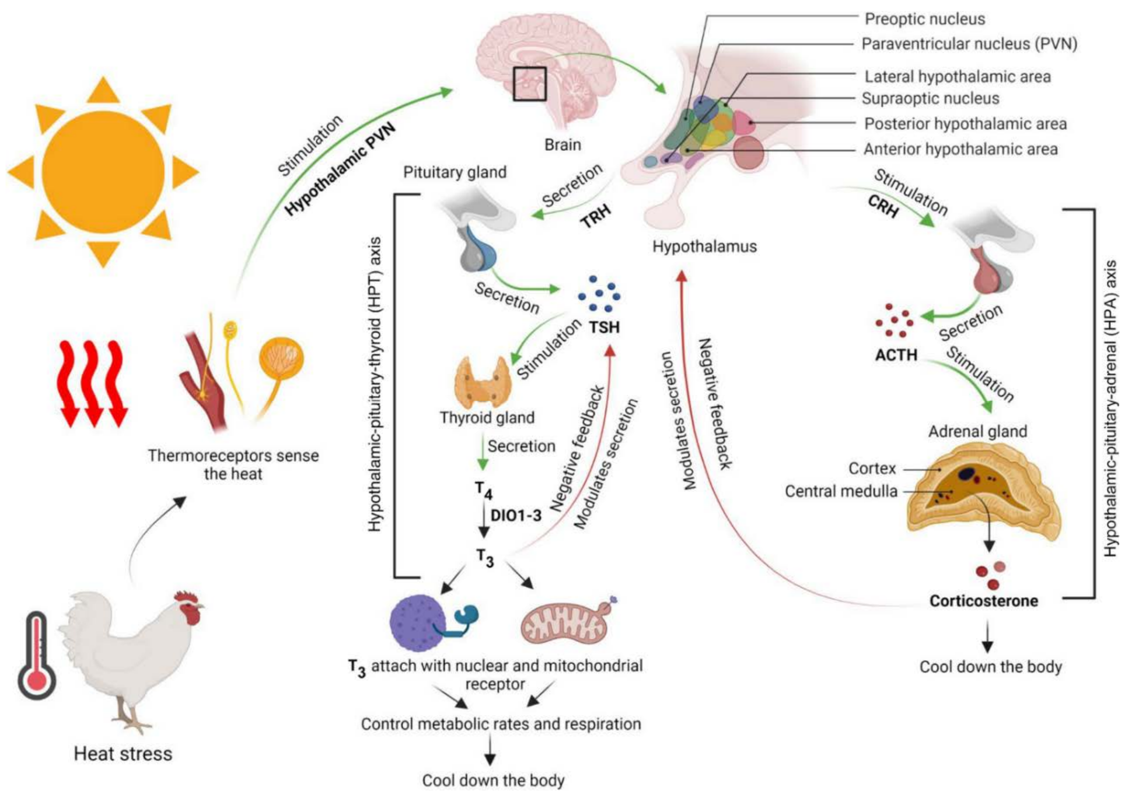

Fig. 3: Thermal manipulation: a strategy to mitigate heat stress in broiler chickens for sustainable poultry production[47]

week until a stable housing temperature of 70°F (21°C) is achieved[36].

Because birds lack sweat glands, thermoregulation in poultry is inherently challenging, particularly under high ambient temperatures, which may adversely affect production efficiency (Fig. 3). As homeothermic organisms, birds must maintain thermal balance by equating metabolic heat production with heat dissipation[37]. When ambient temperature is lower than body temperature, heat is lost through conduction, convection, radiation and evaporation. However, under conditions of elevated environmental temperature, poultry rely predominantly on behavioral and physiological adaptations to dissipate excess heat.

Common behavioral responses to heat stress include panting[38,39], gasping, wing spreading, eye closure, recumbency and , in extreme cases, cannibalistic behavior[40]. The optimal thermal range for poultry performance, referred to as the thermoneutral zone, varies slightly among production types; laying hens perform optimally between 19-22°C, whereas broilers exhibit optimal growth between 18-22°C[41]. Heat stress in poultry is typically classified according to duration and intensity as acute (27-38°C for 1-24 hrs), moderate (27-38°C for up to seven days) and chronic or severe (38-50°C for more than seven days)[42-44]. When ambient temperature exceeds the bird's body temperature, evaporative heat loss becomes the sole effective mechanism for maintaining thermal equilibrium and preventing hyperthermia[45,46].

Birds regulate heat exchange with their environment through four principal mechanisms, conduction, convection, radiation and evaporation. Evidence indicates that poultry actively seek cooler areas within housing systems during periods of heat stress[48]. They may also scratch or burrow into the litter to access cooler underlying layers, an adaptive behavior that enhances conductive heat loss. In addition, heat-stressed birds increase water intake, which facilitates conductive cooling as ingested water equilibrates with body temperature[49]. Convective heat loss is determined by the temperature gradient between the bird and the surrounding air, the exposed surface area and airflow velocity. Air movement enhances heat dissipation through a wind chill effect; however, in many intensive production systems, limited bird mobility necessitates mechanical ventilation to optimize convective cooling[48].

Radiative heat exchange occurs between birds and surrounding surfaces, including walls, floors, ceilings and conspecifics[50]. The magnitude of this exchange depends on the temperature differential between the bird's body surface and its environment. Studies on naked-neck genotypes have demonstrated that Sensible Heat Loss (SHL), encompassing conduction, convection and radiation, is greatest from the neck and face regions, whereas the body trunk contributes minimally to heat dissipation[51]. Birds enhance SHL through behavioral adaptations such as wing spreading to increase surface area for convective heat transfer and seeking cooler substrates to augment conductive heat loss. Infrared thermography has been shown to provide more accurate assessments of SHL compared to conventional thermocouple techniques[51]. Furthermore, heat transfer from internal tissues to the body surface is facilitated by peripheral vasodilation, which increases blood flow to the skin and respiratory surfaces, thereby promoting heat dissipation.

Evaporative cooling represents a critical thermoregulatory pathway, occurring through the evaporation of water from body and respiratory surfaces. The latent heat required for evaporation is primarily derived from the bird's body surface rather than the surrounding air, making this mechanism highly effective under appropriate conditions[52]. Panting enhances evaporative heat loss by increasing airflow across moist surfaces of the nasal and buccal cavities, thereby accelerating evaporation and heat dissipation[53]. However, the efficiency of evaporative cooling declines markedly under conditions of high relative humidity, which restricts moisture evaporation and impairs thermal balance[54]. In both broiler and layer production systems, appropriate housing design and effective ventilation are essential for mitigating heat stress[46]. Birds experiencing thermal stress frequently exhibit elevated rectal temperatures, indicating a compromised ability to maintain homeostasis[55,56].

Effects of heat stress on hormonal regulation: The neuroendocrine system plays a central role in maintaining homeostasis and regulating physiological functions in birds, particularly under conditions of heat stress. During the early phase of heat exposure, the Sympatho-adrenal Medullary (SAM) axis is rapidly activated as a primary adaptive mechanism. Thermal stress is detected by the central nervous system, which stimulates the hypothalamus and subsequently activates the pituitary gland[57]. This process leads to the secretion of adrenocorticotropic hormone (ACTH), regulated by corticotropin-releasing factor released from the hypothalamus (Fig. 4).

Activation of the adrenal medulla results in increased secretion of catecholamines, notably epinephrine and norepinephrine, which are critical for stress adaptation. These hormones elevate blood glucose concentrations, promote hepatic glycogenolysis, reduce muscle glycogen reserves,

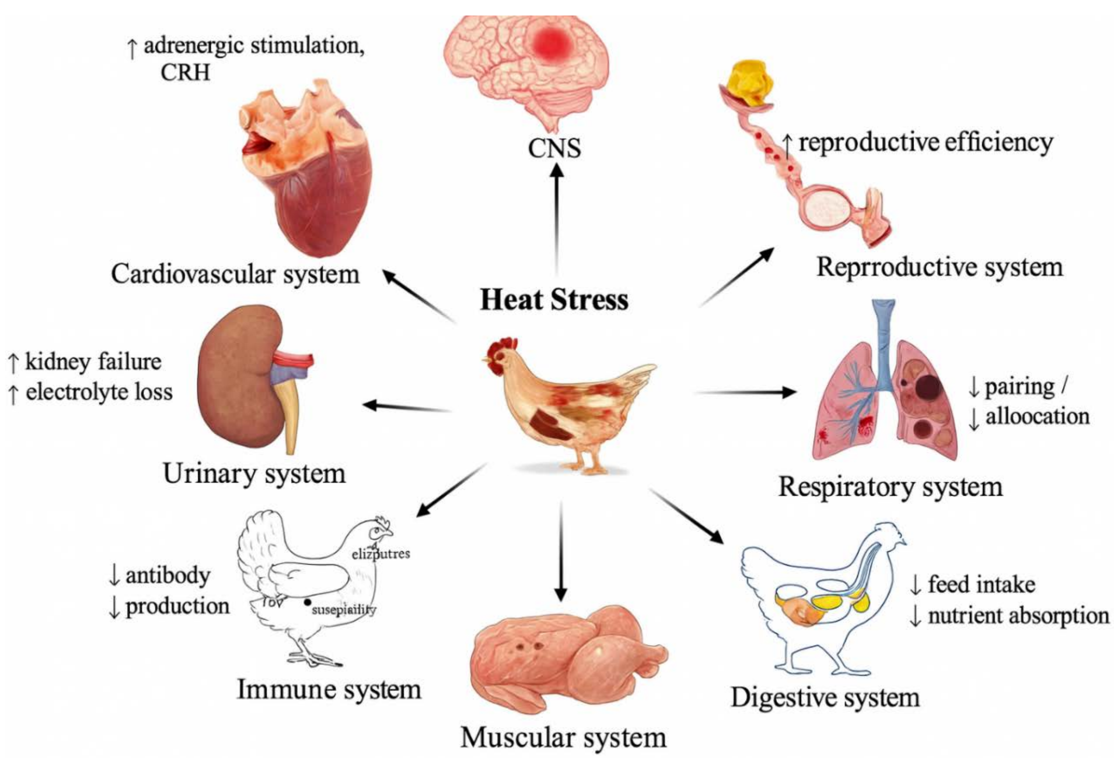

Fig. 4: Hormonal response due to heat stress in poultry[63]

increase respiratory rate, induce peripheral vasodilation and enhance neural responsiveness to mitigate the effects of heat stress[58,59]. In addition, catecholamines influence metabolic and cardiovascular functions, including increased glucose utilization[60], enhanced skeletal muscle perfusion[61,62], elevated heart rate and blood pressure, vasomotor regulation and improved neural sensitivity under thermal challenge.

Concurrently, the Hypothalamic Pituitary Adrenal (HPA) axis is activated as part of the integrated stress response. The hypothalamus secretes Corticotropin-releasing Hormone (CRH), which stimulates the anterior pituitary to release ACTH. This, in turn, promotes the synthesis and secretion of corticosteroids, primarily cortisol and aldosterone, from the adrenal cortex[64]. These hormones facilitate gluconeogenesis, enabling the production of glucose from lipids and proteins[16,59,65] and play vital roles in regulating thermoregulation, circulatory dynamics and overall metabolic homeostasis. Furthermore, they contribute to the maintenance of osmotic balance by modulating sodium retention and potassium excretion via renal mechanisms, thereby ensuring fluid balance during stress conditions[66].

Thyroid hormones, particularly triiodothyronine (T3) and thyroxine (T4), are also integral to metabolic regulation in heat-stressed birds. Empirical studies indicate that plasma T3 concentrations generally decline under heat stress[67-69], whereas T4 levels exhibit variable responses in laying hens exposed to elevated temperatures[16,67,69]. The reduction in T3 is primarily attributed to decreased peripheral conversion of T4 to T3 under thermal stress conditions[70]. Genetic variation among poultry breeds further influences thyroid hormone metabolism. For example, the presence of the dwarf gene in *Gallus gallus* has been shown to impair the peripheral conversion of T4 to T3[71]. Similarly, Naked Neck laying hens exhibit lower T3 concentrations compared to New Hampshire and Lohman White breeds[72].

Heat stress also disrupts reproductive endocrinology by reducing circulating levels of gonadotropin-releasing hormone, testosterone, progesterone and estradiol in laying hens, leading to diminished egg production and reproductive efficiency[16,37,73]. These endocrine alterations contribute significantly to reduced growth performance[74] and impaired reproductive function in heat-stressed poultry[73].

Biochemical effects of heat stress: Heat stress exerts substantial effects on the physiological status of poultry, influencing a wide range of biochemical and hematological parameters[18,75]. Alterations in blood biochemical indices are among the primary indicators used to evaluate the impact of thermal stress[61]. Heat stress has been shown to modify serum cholesterol and triglyceride concentrations, reflecting underlying metabolic disturbances[76]. In addition, exposure to mild to moderate heat stress has been associated with increased leukocyte counts, as reported by Maxwell *et al.*[65]. Similar elevations in white blood cell counts in laying hens exposed to high ambient temperatures have been documented by Tanor *et al.*[77].

Further investigations have demonstrated that heat-stressed birds typically exhibit lymphocytopenia accompanied by heterophilia, indicating a shift in immune cell distribution and an altered immune response profile[78]. Moreover, broilers subjected to elevated temperatures show a reduction in the weight of lymphoid organs, which is associated with compromised immune function[79]. Heat stress also impairs systemic humoral immunity, decreases intraepithelial lymphocyte populations and reduces the number of immunoglobulin A-secreting cells within the gastrointestinal tract[79]. These immunological impairments are further characterized by diminished antibody responses and reduced macrophage phagocytic activity, thereby weakening the birds' ability to resist infectious diseases[80,81].

Under high-temperature conditions, birds display a range of behavioral adaptations, including panting, gasping, wing spreading, eye closure, recumbency and, in severe cases, cannibalistic behavior[40]. Santos *et al.*[82] reported no significant differences in feed intake among naked neck broilers subjected to heat stress, suggesting the presence of adaptive behavioral mechanisms that help mitigate thermal challenges. Panting, a primary thermoregulatory response, can increase respiratory rate by 10 to 20 times, resulting in excessive loss of carbon dioxide (CO_2) via the lungs. This elevated CO_2 excretion leads to increased blood pH and disruption of acid-base homeostasis, ultimately impairing physiological function and productivity[5,83].

Prolonged panting under heat stress induces respiratory alkalosis due to excessive CO_2 elimination. This condition reduces bicarbonate availability for eggshell formation and increases the concentration of organic acids, thereby lowering free calcium levels in the bloodstream. Decreased concentrations of CO_2 and HCO_3^- limit the availability of carbonate ions necessary for eggshell mineralization. Consequently, this imbalance results in thinner and more fragile eggshells, a common characteristic of heat-stressed laying hens. Tanor *et al.*[77] similarly reported that elevated environmental temperatures negatively affect eggshell thickness in White Leghorn hens, leading to reduced shell quality.

As CO_2 levels decline, concentrations of carbonic acid (H_2CO_3) and hydrogen ions (H^+) decrease, whereas bicarbonate ions (HCO_3^-) accumulate, resulting in an alkaline shift in blood pH. To restore acid-base equilibrium, birds compensate by excreting excess HCO_3^- and retaining H^+ through renal mechanisms. This compensatory response can lead to metabolic acidosis and is closely associated with declines in overall production performance in poultry[84-86].

Impacts of heat stress on poultry production and behaviour: Convective heat loss in birds is influenced by several factors, including the temperature gradient between the body surface and the surrounding air, the extent of exposed surface area and the velocity of air movement. Airflow, whether natural or mechanically induced, enhances convective heat dissipation by increasing the rate of heat transfer. The comb and wattles of poultry play a critical role in thermoregulation due to their extensive vascularization and relatively large surface area, which facilitate heat exchange[87]. Evaporative cooling represents another essential mechanism, achieved through the evaporation of water from body and respiratory surfaces, with panting being a prominent response to elevated temperatures[18]. Collectively, these physiological and behavioral adaptations to heat stress have adverse consequences for animal welfare and productivity, thereby posing significant economic challenges for the poultry industry, particularly under conditions of global climate change[88].

The behavioral response of birds to heat stress varies with age. Experimental evidence indicates that younger chicks exhibit a greater tendency to remain recumbent under heat stress compared to older birds[89]. As birds mature, the duration of lying behavior under thermal stress generally decreases. Mack *et al.*[49] reported that heat-stressed birds display increased resting behavior and reduced locomotor activity. In contrast to adult birds, which tend to spend more time standing during heat exposure, chicks more frequently adopt a recumbent posture. However, under prolonged heat stress, birds across all age groups increase the time spent lying down relative to standing. Sgavioli *et al.*[89] observed that although young chicks typically exhibit higher feed intake than older birds under normal conditions, their intake declines more markedly during heat stress. Similarly, Chowdhury *et al.*[38] demonstrated that broiler chickens reduce feed consumption as an adaptive strategy to minimize metabolic heat production. Notwithstanding reduced feeding duration, Mack *et al.*[49] reported no significant differences in total feed intake, crop fill, or body weight, suggesting compensatory improvements in feed efficiency under certain conditions.

Poultry enhance convective heat dissipation by elevating and spreading their wings, thereby increasing the effective surface area available for heat exchange[90]. This behavior exposes the apteria, regions beneath the wings with reduced feather coverage, which facilitate efficient heat transfer to the environment. These areas are highly vascularized, further promoting heat loss[91]. De Queiroz *et al.*[92] emphasized the importance of wing-spreading as an adaptive response in naked-neck broilers exposed to high ambient temperatures.

Heat stress is also associated with alterations in social and stress-related behaviors. Birds exposed to elevated temperatures exhibit increased pecking activity directed toward feeders, drinkers, enclosure surfaces and conspecifics, a behavior that may escalate to cannibalism[49,93]. Additional behavioral indicators of thermal stress include heightened restlessness, increased scratching, tonic immobility, wing flapping and intensified pecking activity[89]. Kim *et al.*[94] reported that laying hens exposed to temperatures of 32°C spent more time with their wings elevated to facilitate heat dissipation from featherless regions beneath the wings. Furthermore, heat-stressed birds demonstrate increased water intake alongside reduced feed consumption, consistent with previous findings[49,89].

Effect of heat stress on the performance of birds: The optimal ambient temperature range for maximum performance in laying hens is approximately 19-22°C[46]. Deviations above this thermoneutral range, particularly at elevated temperatures, markedly impair poultry productivity and may reduce survival rates and egg output[20]. Chickens maintain a normal body temperature of approximately 41°C (106°F); however, an increase exceeding 4°C above this level can be lethal[4]. Owing to their high metabolic rate, dense feather coverage and absence of sweat glands, laying hens are especially susceptible to thermal stress[18,37,95]. Furthermore, their prolonged production cycle, extending up to 75-80 weeks, increases cumulative exposure to heat stress and exacerbates its adverse effects[96].

When ambient temperatures exceed 80°F, typically up to 85°F, birds reduce feed intake while increasing water consumption as a compensatory response[2]. As temperatures further rise within the range of 86-95°F, significant declines in egg production and eggshell quality are observed[28]. In laying hens, the Feed Conversion Ratio (FCR), expressed per unit of egg mass or per dozen eggs, deteriorates with increasing temperature. Under severe heat stress, chickens increase evaporative heat dissipation through panting and gular fluttering mechanisms[97,98]; however, prolonged exposure to such conditions can result in high mortality rates. Severe heat stress is also associated with clinical signs including depression, nervousness, tremors, incoordination and convulsions.

Sohail *et al.*[43] reported that broilers exposed to chronic heat stress exhibited a 16.4% reduction in feed intake, a 32.6% decrease in body weight and a 25.6% increase in FCR by 42 days of age. Numerous studies have consistently demonstrated the detrimental effects of heat stress on broiler growth performance[79,99-101]. In addition to thermal stress, stocking density represents a critical interacting factor that further influences productivity and welfare outcomes. Star *et al.*[102] documented a 31.6% decline in feed efficiency, a 36.4% reduction in egg production and a 3.41% decrease in egg weight in heat-stressed laying hens.

Heat stress also adversely affects egg quality parameters. Lin *et al.*[30] reported that elevated temperatures result in thinner eggshells and increased egg breakage. Quantitatively, heat stress has been associated with reductions in egg weight (-3.24%), eggshell thickness (-1.2%), eggshell weight (-9.93%) and eggshell percentage (-0.66%). One of the primary mechanisms underlying these effects is reduced feed intake, which leads to decreased calcium consumption, a critical mineral for eggshell formation[103,20]. Additionally, high ambient temperatures are associated with reduced serum calcium concentrations[16].

Excessive panting induced by heat stress disrupts acid-base balance by increasing blood pH (respiratory alkalosis) due to enhanced carbon dioxide loss. This condition reduces the availability of bicarbonate ions required for calcium carbonate deposition in the eggshell while simultaneously increasing organic acid concentrations, further lowering the availability of free calcium in the bloodstream. These physiological alterations are particularly critical in breeder and laying hens, as they directly compromise eggshell quality and structural integrity[18,104].

CONCLUSION

Heat stress represents a critical constraint in layer production systems, adversely affecting bird health, productivity and overall welfare. Beyond its detrimental impact on physiological well-being, heat stress imposes substantial economic losses on poultry operations. Accumulated evidence indicates that exposure to elevated temperatures elicits a complex cascade of endocrine and biochemical responses, including increased catecholamine secretion, altered thyroid hormone dynamics, suppression of reproductive hormones and disruption of acid-base homeostasis. Collectively, these changes impair growth performance, reduce feed efficiency and compromise egg quality. Behavioral adaptations, such as panting, wing elevation and decreased physical activity, reflect physiological attempts to enhance heat dissipation; however, these responses also redirect energy away from productive processes. This dual impact underscores that heat stress functions both as an acute survival challenge and a chronic constraint on production efficiency. Effective mitigation of heat stress requires an integrated approach encompassing environmental and nutritional interventions. Key strategies include optimization of ventilation and housing design, implementation of thermal management practices, supplementation with antioxidants, provision of balanced amino acid profiles and adequate mineral nutrition. In the context of increasing climatic variability, the adoption of adaptive, evidence-based management strategies is essential to sustain productivity while ensuring animal welfare across diverse poultry production systems.

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