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Responses of Poultry to Heat Stress and Mitigation Strategies During Summer in Tropical Countries: A Review

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ABSTRACT

The poultry industry faces increasing challenges from heat stress caused by global warming, particularly in tropical regions. Heat stress, caused by rising environmental temperatures, undermines the health and productivity of poultry, resulting in significant economic losses. This review comprehensively addresses the physiological and behavioural responses of poultry to heat stress and explores the key mitigation strategies, categorized under genetics, management and feeding. Genetic approaches, like utilizing specific genes in breeding, show promise but require wider adoption. Management practices such as housing design, including orientation, insulation and ventilation, controlled lighting and thermal manipulation are critical to maintaining poultry in their thermoneutral zone. Furthermore, feeding strategies like feed restriction, dual feeding and nutritional manipulation have shown promise in reducing heat stress effects. In addition to feeding strategies, water management is also crucial for mitigating heat stress, especially in tropical areas. Ensuring sufficient water space, maintaining operating waterers, and keeping water cool are essential to encourage adequate drinking. Despite progress, further investigation is required to explore the synergistic effects of combined strategies to improve the resilience of poultry. This review highlights the urgent need for comprehensive approaches to mitigate heat stress in poultry to ensure sustainable productivity under the challenges of global warming.

Keywords: heat stress, mitigation, management, poultry

INTRODUCTION

Rising global temperatures in recent years have had a significant impact on the agricultural sector, particularly in tropical regions, by reducing crop yields and increasing the vulnerability of livestock (1,2). The impact of global warming due to climate change on livestock is a significant concern, with industrialized farming systems potentially losing up to 25% of their production. This could be an even greater issue in tropical regions, where extensive farming is the dominant practice. Without significant reductions in greenhouse gas emissions, global warming is expected to surpass 2°C this century (3,4). Poultry, which plays a vital economic role in many developing countries by providing essential food (meat and egg) and livelihoods, has been particularly affected (5). Poultry meat is valued for its high-quality protein and lower fat content in comparison to other meats, which contribute to its global popularity as a healthy and accessible choice. Likewise, poultry eggs are the most cost-effective source of animal protein, rich in vitamins, particularly vitamin D, but also in carotene and essential minerals like calcium, iron, and phosphorus (6,7). The increasing demand for poultry products in these regions is driven by two key factors: affordability and the absence of religious restrictions (8,9). As global poultry meat and egg consumption has doubled over the past decade and is projected to double again by 2050, advancements in chicken genetics have significantly increased production. However, these improved broiler chickens and laying hens have higher metabolic rates, leading to increased body heat and making them more susceptible to heat stress (10,11). Heat stress is a major constraint to poultry productivity particularly in hot and humid tropical regions characterized by elevated temperatures and humidity. These regions, which are generally located close to the equator, experience consistently warm climates throughout the year, which makes it all the more difficult to manage poultry in their thermoneutral zone which is 19-22°C for laying hens and 18-22°C for growing broilers (12–14). Poultry in tropical countries are reared in open sheds and thus they are often raised under stressful conditions like extreme heat. The recent rise in global temperatures has further complicated this issue, impacting farming in both tropical and subtropical regions (15). In light of this, the poultry industry must adopt environmentally friendly technologies and resilient production systems to withstand the increasing frequency of extreme weather events (4). Different poultry breeds or strains respond in a different manner according to age, sex, stage of production, and reproduction (16). Heat stress significantly impairs growth, reproduction, and meat quality and increases mortality, leading to substantial economic losses globally (17,18). In tropical regions, summer heat waves can be particularly damaging, causing heat stress that results in major financial losses for the poultry industry. Over time, researchers have suggested a number of potential intervention strategies with the aim of reducing the adverse effects of heat stress on poultry (19–21). These strategies encompass genetic improvements, management practices, feeding strategies with nutritional manipulation (14,21–24). Embracing multifaceted strategies is crucial for effectively managing heat stress in poultry and ensuring industry sustainability amidst global warming challenges (10,12). Considering that extensive research has been published on the detrimental effects of heat stress on poultry health and performance and possible mitigation strategies, it is important for researchers and the poultry industry to summarize these findings. The objective of this review is to provide a summary of two key areas: firstly, the behavioral and physiological changes observed in poultry under conditions of heat stress; and secondly, the potential mitigation strategies that could be employed to alleviate heat stress in broiler chickens and laying hens.

UNDERSTANDING HEAT STRESS IN POULTRY: CAUSES AND TYPES

Poultry are exposed to a variety of environmental stresses, of which heat stress is the most common and affects their performance, particularly in meat and egg production (25). Heat stress occurs when chickens are unable to regulate their body temperature, normally between 40.5-41.5°C, due to elevated ambient temperatures (10). This condition results from a combination of high ambient temperatures, humidity, radiant heat and air speed, with high ambient temperature being the most important factor (12). In chickens over two weeks old, heat stress begins when temperatures exceed 26-28°C, leading to increased panting as they attempt to dissipate excess heat (12,26). The situation is aggravated by high humidity, resulting in serious adverse effects on both egg-laying and meat-producing chickens by reducing overall production quality including reduced comfort, efficiency, growth rate, feed conversion and weight gain, and ultimately increased mortality (27). For broilers, heat stress lowers meat quality by reducing protein content, resulting in softer and less juicy meat. In laying hens, it decreases egg quality, leading to thinner shells and smaller eggs. Additionally, heat stress impacts nutrient absorption in both types, contributing to poorer overall health and production (12,22).

In poultry production, heat stress can be divided into acute and chronic heat stress. Acute heat stress refers to short and sudden periods of extremely high temperature, while chronic heat stress refers to prolonged periods of high temperature. Acute heat stress can last for one week with a temperature above 30°C (28) or one day with a temperature of 36°C for 6 hours, whereas chronic heat stress can last for more than three weeks with a temperature above 30°C or more than three days with a temperature of 32°C for 6 hours (28,29).

BEHAVIORAL AND PHYSIOLOGICAL RESPONSES OF POULTRY BIRDS TO HEAT

Due to high environmental temperatures, poultry undergo many changes in their behavior and physiology to restore thermal balance with their environment. Poultry spend less time in feeding, but more time in drinking and panting, with spread of wings when the ambient temperature exceeds the comfort zone (above 25°C). They also spend more time resting rather than moving and walking (10,12).

Social behavior (e.g. huddling) and posture changes in heat-stressed birds are also less frequent. Birds prefer a cool, shaded area in a natural environment. To promote heat loss, the thermoregulatory response in chickens shifts splanchnic blood flow (blood supply to the gastrointestinal system, liver, spleen, pancreas, and kidneys) to dilated blood vessels in peripheral skin tissue (30,31). This peripheral vasodilation causes a reduction in blood flow, resulting in hypoxia in the gut, poor nutritional digestibility (due to gut barrier malfunction), and stunted growth (31,32). Poultry (4 weeks of age) first reduce their energy intake by decreasing their feed consumption when the temperature exceeds 24°C (33). With the reduction in performance, birds remove heat mainly by convection, conduction and radiation. Other reactions are also observed such as increased heart rate, dilation of blood vessels in the skin and exchange areas where insulating feathers are missing (legs, comb, etc.), search for cooler and more ventilated areas, spreading of the wings to increase the surface area for heat exchange and present less feathered areas (34).

At 25°C and above, thermal control begins with an increase in heat exchange surface area and latent heat loss, and respiratory evaporation becomes a very important mode of heat loss (35). Heat loss by the sensible method decreases as ambient temperature approaches body temperature, and latent heat loss represents the only means of maintaining poultry life (36). In a thermo-neutral environment, respiratory movements can be as low as 25 movements/minute, whereas under heat stress conditions, movements can be exceed 200 movements/minute (37). According to (36), when the internal temperature reaches about 44°C the respiratory rate exceeds 140 to 170 movements per minute. This phenomenon, called "panting", is usually observed when the ambient temperature reaches 29°C, but can start as early as 27°C with high humidity. In this case, the increased respiratory rate leads to a change in the acid-base balance of the blood (38,39). However, it should be mentioned that increased panting leads to a decrease in carbon dioxide and partial pressures of CO_2 in arterial blood (capnia or $PaCO_2$), an increase in the concentration of bicarbonate ions excreted by the kidneys and a reduction in the concentration of hydrogen ions (H^+) to maintain acid-base equilibrium and thus increase the pH of the blood. If the respiration rate is too high, there are limits to the removal of heat produced by the respiratory muscles. As a result, the body temperature suddenly rises to a maximum of 47°C leading to death by cardiac or respiratory arrest (34,36,40). Mainly as a result of heat stress, the metabolic function of chickens is altered, and glucose production is induced to maintain homeostasis in the presence of stressors. During periods of high temperature, air sacs play an essential role in gas exchange by increasing the flow of air to the surface and consequently, heat is dissipated by evaporation. This causes respiratory alkalosis with electrolyte imbalance and ultimately death of the bird (40–42).

MITIGATION STRATEGIES TO ALLEVIATE HEAT STRESS IN TROPICS

There are three main strategies to mitigate heat stress in poultry: genetic, management, and feeding. The following sections discuss specific approaches to genetic selection, effective management techniques, and strategic feeding interventions.

Genetic Strategies for Enhancing Thermo-Tolerance in Poultry

In tropical and hot regions, enhancing the genetic traits of poultry to improve their heat tolerance is critical to maintaining productivity and overall health. Genetic selection to improve thermotolerance in poultry can be effective in different housing systems, including open, semi-open and closed houses. In open and semi-open houses, where environmental control is limited, selection for heat tolerance can help birds cope better with temperature fluctuations. In closed poultry houses, where conditions are better controlled, genetic selection can complement other management practices to optimize overall heat resistance (43). Recent genetic strategies have focused on combining indigenous and high-yielding breeds and exploiting specific thermo-tolerant genes such as frizzled, naked-neck and dwarf genes. These approaches aim to create poultry strains that are better adapted to high temperature environments (14,44,45).

Combining native and high-yielding breeds

Mating high-yielding commercial breeds with native breeds is a common strategy to improve environmental adaptation and heat tolerance in poultry (46). Native breeds are typically better adapted to local conditions, including heat stress, while commercial breeds offer higher productivity. This combination can produce offspring that maintain robust performance in challenging climates. This approach helps preserve genetic diversity and local adaptability, essential for long-term sustainability (44,47).

Naked-neck gene

The naked neck gene (Na) is an important genetic trait that increases heat tolerance in chickens by reducing neck plumage, which aids in heat dissipation. Heterozygous (Na/na) and homozygous (Na/Na) birds show a 20% and 40% reduction in neck plumage, respectively, compared to normal siblings (48,49). This gene correlates with increased body weight, breast muscle development, and reduced abdominal fat in broilers (50–52). In addition, naked neck chickens have a lower heterophil/lymphocyte ratio and total plasma cholesterol levels, indicating better health in hot climates (10). Furthermore, the presence of the Na gene has been observed to positively influence egg mass, quantity, and quality in laying hens exposed to high temperatures (53). The results of these studies indicate that such genes could be incorporated into the development of a chicken breed that is capable of tolerating heat stress.

Frizzled gene

The frizzle (F) gene induces a distinctive curvature in feather outlines, which reduces feather weight and enhances heat dissipation, thereby improving egg production and quality in laying hens compared to heterozygous carriers and normal-feathered hens (15,26). There is a marked interaction between the FF genotype and environmental temperature in the event of heat stress, affecting reproductive traits such as egg production, hatching and chick production, although sexual maturity is unaffected (54). However, at higher temperatures, normally feathered hens exhibit reduced reproductive traits compared to frizzle-feathered hens, while lower temperatures delay sexual maturity but reduce egg production and chick numbers in FF genotypes (55). Although the beneficial effect of the F gene is lower in broilers at high temperatures, there is an additive effect in double heterozygous broilers (Na/Na F/f), indicating the potential of the frizzle gene in developing heat-tolerant chickens (10,56).

Dwarf gene

The dwarf gene (dw) is a sex-linked recessive gene in chickens that reduces body size and metabolic heat production, which is beneficial for heat tolerance in hot climates (55). Chicken that is carrying this gene weigh significantly less, with homozygous females and males weighing around 30% and 40% less than normal, respectively (57). While its benefits in heat-stressed laying hens have been debated, recent studies recommend its inclusion for the development of heat-tolerant poultry breeds (10,58). However, in fast-growing broiler chickens, the dw gene was found not to improve heat tolerance under chronic stress conditions (59).

Management Strategies

Effective management strategies for poultry heat stress include housing design for optimal ventilation and temperature control, thermal manipulation methods like early heat treatment, litter management to regulate humidity, and lighting management to ensure adequate rest and activity periods (22). These strategies are critical to maintaining poultry health and productivity in hot climates, are discussed below.

Housing management

Effective management of environmental conditions and housing systems is essential to reduce heat stress in poultry, as failures in temperature control and ventilation can worsen the problem (60,61). In tropical countries, open poultry houses are common due to their simplicity and low cost. However, these buildings have limited options for regulating the internal climate. They are also vulnerable to pests like rats and wild birds, which can spread diseases (62). In order to mitigate heat stress, poultry house must be well designed to limit heat penetration from the external environment (63). The type of poultry housing system is crucial for protecting chickens from harsh environmental conditions, affecting their performance and productivity (14,62). In tropical regions, poultry houses are typically open-sided and naturally ventilated to manage internal temperatures effectively (64). To minimize heat production, it is crucial to maintain maximum insulation and orient the houses in an east-west direction to avoid direct sunlight. Adequate ventilation is achieved by placing windows on the north and south sides, ensuring the building's long axis runs east-west (62).

To avoid the need for interior supports that could interfere with operations, the width of these houses must be less than 12 meters. This design is suitable for various poultry types, including broilers and laying hens (64). It's crucial to consider the various tasks performed by farmers, such as chicken transfer, feeding, and waste management, as lengthy pen houses can pose maintenance challenges, particularly with manual operations. To ensure efficient circulation and service delivery, doors should be strategically placed at intervals of 15-30 meters (65).

The optimal roof slope for a poultry shed is recommended at 45° to minimize heat accumulation and maximize air exchange (14,65). Roof overhangs can effectively shade sidewalls from solar radiation, reducing heat gain by up to 30% when implemented correctly at a 45° slope. Ridge openings facilitate ventilation through natural airflow but may be ineffective in insulated poultry houses due to temperature uniformity. Adequate spacing between buildings is necessary to ensure proper airflow and circulation in poultry houses. Each house should be separated from the others by at least 10 meters by small trees or bushes. In addition, large, knotless deciduous trees beyond the roof ridge provide shade on the roof (14,62,65).

Rooftop sprinklers are effective for cooling roofs but require materials such as metal roof coatings that are resistant to constant water exposure. Evaporative cooling, achieved by fogging or spraying, can reduce heat stress in birds by lowering the temperature inside the barn. However, maintaining optimal humidity levels is essential to prevent adverse effects on bird health. Recirculating fans enhance cooling by increasing air velocity, which promotes convection cooling throughout the room. Installing these fans strategically, at an elevated position and tilted downward, ensures effective airflow distribution (62,65). Furthermore, the incorporation of evaporative cooling techniques, such as cooling pads and sprinklers, can be pivotal in farms with extreme external temperatures and low humidity levels (66).

To increase insulation in buildings, natural materials such as palm branches, reed stalks, or wheat straw are recommended because of their ability to reduce radiation (65). Reflective roofing materials can significantly reduce the amount of heat absorbed by the house. Painting the roof with reflective colours, such as aluminium, green, or white, can enhance this effect, with white providing the highest radiation reflection at 75% (67). Cost-effective solutions such as whitewashing can be used when traditional insulation materials such as polyurethane foam are unavailable or expensive. This involves mixing 25 kg of hydrated lime with 50 liters of water, letting it sit for 12 hours, then adding 2 liters of sour milk or curd, and organic glue or alum before spraying it on roofs and walls. This method can lower building temperatures by 1.5-2°C (68,69). Additionally, incorporating vegetation such as shrubs and tall trees can provide natural shading and convective cooling, further enhancing the overall cooling system while reducing reliance on mechanical cooling methods (14,62).

In hot climates, it is optimal to maintain a stocking density of 10-12 birds per square meter for broiler chickens in open-sided poultry houses and a maximum of 9 birds per square meter for egg-laying hens in non-cage housing systems during the summer (70,71). Exceeding this density negatively affects broiler growth performance, as observed in the study by (72), where stocking densities above 12 birds per square meter resulted in higher feed conversion ratios and lower body weights. Increased metabolic rates in summer intensify heat generation in poultry houses, hindering heat dissipation and increasing overall temperatures (73).

Thermal manipulation

Thermal manipulation (TM) refers to the process of exposing embryos or young chicks to elevated temperatures for a specific duration to induces long-term thermo-tolerance during the subsequent heat period (74). During incubation, exposing embryos to 39°C from days 16 to 18 can enhance hatchability and lower metabolic rates, which helps in developing heat tolerance (75). Another effective TM strategy is exposing embryos from days 7 to 16 at 39.5°C and 65% relative humidity for 12 hours daily, which improves heat resilience later in life (76). Post-hatch

TM also contributes to long-term heat tolerance; chicks exposed to 35-38°C for 24 hours from 3 to 5 days of age show increased body weight and reduced mortality under heat stress (77,78). This treatment can boost feed intake and growth despite initial delays (77). Incubating eggs at slightly higher temperatures can further enhance heat tolerance, reflecting a broader application in poultry management (75). These TM strategies hold promise for improving poultry resilience to climate change, though their impact on productivity compared to current breeds is still being evaluated. Overall, TM at both embryonic and post-hatch stages significantly benefits poultry thermotolerance (76,77,79).

Litter management

During hot weather, it's crucial to manage litter temperature in poultry houses by keeping the litter moderately wet. Litter that is over-dry can cause overheating and reduced humidity, while overly wet litter increases humidity and forms cakes that stick to the floor after drying (63,80,81). Wet litter also produces bad odors and ammonia, which can hinder bird growth, attract flies, and increase bird stress (80). Maintaining litter quality and thickness is vital in summer, especially on cement floors. To avoid excessive heat, litter should not exceed 6 cm in thickness, and any caked or wet litter should be promptly removed (82). The quality and type of litter is particularly important for young chicks. Bedding material, such as straw, should be clean and free of mold. In order to reduce dust formation, straw should not be cut into pieces, but should be spread out over its entire length. Wood shavings are the most important component of healthy litter, but they must be dust-free and made from soft, untreated wood. Once the floor has reached an adequate temperature after heating the house, the bedding should be placed. Spreading the litter early can lead to condensation (wet and sticky litter) due to temperature differences between the floor and the house (83,84).

Lighting management

During periods of heat stress, the building temperature should be maintained in a thermo-neutral zone (18-24°C), and the lighting schedule (hours of light and darkness), as well as lighting intensities, should be maintained to create a distinct period of rest and activity (85,86). Continuous photoperiod (daylight) in broilers induces sleep deprivation, provoking severe physiological responses to heat stress, while the addition of dark periods increases melatonin production, which is important for immune system development (87). Intermittent lighting regimes can enhance feed efficiency and broiler production efficiency due to reduced heat production during both light and dark periods, with heat production fluctuating according to the light-dark cycle (88,89). Studies indicate that broilers on an intermittent lighting schedule of 1 hour light followed by 3 hours darkness, repeated three times per night, show improved body weights and feed conversion ratios compared to those under continuous lighting. This improvement is observed in broilers from 3 to 42 days of age (90). Reverse lighting during heat stress in broilers can be beneficial by creating a period of darkness during the warm hours of the day. A period of 10h-19h darkness and 19h-10h light in broilers during heat stress (33±2°C) decreases blood corticosterone concentration and increases IgG, IgA and IgM (increased immunity) (91). Besides, blue light has been shown to have a calming effect by reducing the negative impact of heat stress. A study by (92) on 21-day-old ROSS and COBB broiler strains exposed to 33°C and 70% humidity demonstrated that monochromatic blue light (25 lux for 5 hours daily over 4 days) reduced malondialdehyde (MDA) levels and increased the activities and gene expression of superoxide dismutase (SOD) and catalase (CAT). These enzymes protect cells from free radicals and reduce oxidative stress. Additionally, blue light minimized degenerative changes in liver tissue due to heat stress.

It is important to comply with local legislation regarding light intensity and duration, but specific recommendations for light intensity during heat stress depend on the poultry's comfort level.

Feeding Strategies

To alleviate the adverse effects of heat stress in poultry production under humid tropical conditions, various feeding strategies such as feed restriction, dual feeding, wet feeding and nutritional interventions are used. These strategies aim to optimize nutrient intake, promote thermoregulation and improve bird performance, providing cost-effective solutions for farmers facing environmental challenges (67).

Feed restriction

Fasting during periods of heat stress allows for controlled feeding times for poultry, promoting rest and digestion when temperatures are high. This practice reduces metabolic heat production and helps mitigate the adverse effects of heat stress (93,94). Chickens fed two hours before the hottest part of the day have shown improved weight gain compared to those without dietary restrictions. Feed restriction, typically from 8 AM to 5 PM, lowers birds' metabolic rates, decreases rectal temperature, and reduces mortality and abdominal fat (24,95). Nevertheless, this practice is not widely adopted due to its impact on growth rates and the subsequent delay in the market age of chickens (96). To mitigate heat stress, it is recommended to limit feeding to cooler times of the day, such as mornings, evenings, or nighttime, to avoid the peak heat load that occurs between 9:00 to 11:00 AM when feeding at 6:00 AM. This strategy minimizes the negative effects of heat stress by reducing the heat generated from feed digestion, absorption, assimilation, and excretion (61,97).

Dual feeding

Dual feeding programs comprise the administration of a protein-rich diet during the cooler hours of the day and an energy-rich diet during the warmer hours (4). Research findings suggest that the feeding of broilers a protein-rich diet from 4 p.m. to 9 a.m. and an energy-rich diet from 9 a.m. to 4 p.m. during periods of high temperature can result in a reduction in body temperature and mortality in birds experiencing heat stress (98,99). Given that dietary proteins have a higher thermogenic effect compared to carbohydrates, it is hypothesized that feeding high protein diets during cooler periods can improve thermotolerance in birds (24,100). Dual feeding did not improve growth performance or feed efficiency in heat-stressed broilers (99). While it might be feasible in tropical or less-intensive systems, dual feeding is generally impractical for most commercial operations due to its cost and logistical challenges (101).

Wet feeding

Wet feeding, which involves mixing feed with water, is beneficial for poultry, especially under heat-stress conditions, as it helps improve feed conversion compared to dry mash or pelleted diets (102). During summer, laying hens provided with wet feed show enhanced laying performance, evidenced by higher yolk index, shell weight, yolk percentage, moisture percentage, and feed conversion efficiency (103,104). For broilers reared in tropical conditions, a 50:50 feed-to-water ratio improves feed intake, weight gain, carcass yield, and overall growth potential (105). Wet feeding aids digestion by increasing nutrient uptake and promoting faster digestive enzyme action (102). Additionally, it mitigates heat stress by increasing water intake, which is crucial for thermoregulation (4,106). However, despite these benefits, the risk of fungal growth and mycotoxicosis limits its widespread application (10).

Supply of cool water

Water is crucial for poultry during heat stress as it helps regulate body temperature and supports essential metabolic processes. High temperatures increase water intake significantly due to elevated water loss through respiration, which is necessary for efficient evaporative cooling (106). Proper water intake prevents dehydration, which can impair their overall health and productivity. Additionally, water aids in maintaining electrolyte balance, which is essential for cellular function and overall well-being (107). Providing cold water helps reduce body temperature, improve physiological responses, and support metabolism and homeostasis, thereby enhancing heat tolerance and performance (108). Cool water, ideally between 10-12°C, is beneficial, and it's essential to protect water tanks and pipes from direct sunlight to ensure birds consume it (109). This can be achieved by painting tanks in light colors, insulating them, or placing them indoors or underground. Additionally, water pipes should be positioned away from heat sources such as roofs (110). The use of nipple drinkers positioned slightly above chick eye level enhances water intake (111). Wider and deeper drinkers can also help in heat dissipation by allowing the immersion of the beak and face (65). Overall, ensuring access to cool, clean water below 25°C, possibly with ice, and systematically refilling with fresh cold water, can help maintain poultry body temperature during heat stress (109).

Nutritional intervention

Nutritional manipulation is a cost-effective way to reduce the negative effects of high humidity and temperature on livestock in hot, humid tropical regions, as climate-controlled facilities are often beyond the reach of many low-income farmers (67). Reducing dietary crude protein and increasing fat content can minimize the thermal effect on animals. Adding fat and protein to broiler diets at high ambient temperatures has significant benefits and considerations (112). High fat diets (up to 5-8%) improve growth performance, feed intake and nutrient absorption, while reducing heat production and mortality due to their lower heat increment compared to carbohydrates and proteins (65,113). Fats such as palm oil and sunflower oil are particularly effective in improving survival and performance under heat stress (114). High energy diets with increased fat content also result in better feed conversion and protein utilization, helping broilers to cope more efficiently with heat stress (102,115). In a study conducted by (116) it was found that the inclusion of oil supplementation in high-protein diets was effective in mitigating the adverse effects of chronic heat stress on the performance, meat quality, and physiological and immunological health, although it also caused a significant increase in abdominal fat (113). On the other hand, protein supplementation must be carefully balanced; high protein diets may exacerbate heat stress due to increased heat production from protein catabolism (102). Low protein diets (17-20%) supplemented with essential amino acids can help maintain performance without the negative effects of high protein under heat stress (117). Adjusting the protein-to-energy ratio and ensuring adequate supply of essential amino acids, especially methionine and lysine, are critical for optimizing broiler performance during heat stress (118,119).

Electrolytes are essential compounds that dissolve into positive and negative ions in solution, crucial for maintaining fluid balance and acid-base equilibrium in poultry. Key electrolytes include sodium (Na^+), potassium (K^+), and chloride (Cl^-). The balance of these electrolytes, known as dietary electrolyte balance (DEB), is vital for poultry health, especially during heat stress (107). Under heat stress, DEB needs to be increased to around 250 mEq/kg to optimize performance. Sodium bicarbonate ($NaHCO_3$) and potassium chloride (KCl) are also recommended for balancing electrolytes, improving feed efficiency, and mitigating the effects of heat stress (120). The National Research Council suggests 0.20% sodium and chloride and 0.30% potassium in starter feeds, with adjusted levels for finisher phases and heat stress. Higher levels of these electrolytes can enhance growth but may lead to increased water intake and litter moisture. The supplementation of 1.5-2.0% potassium from potassium chloride (KCl) and up to 0.5% sodium bicarbonate (NaHCO3) has been demonstrated to be particularly effective in the context of chronic heat stress (39,121). For layers, maintaining electrolyte balance is also of great importance in order to prevent a decline in eggshell quality and laying performance. The inclusion of electrolytes such as sodium bicarbonate ($NaHCO_3$), potassium carbonate (K_2CO_3) and ammonium chloride (NH_4Cl) in layer diets has been found to be an effective method of managing heat stress (122).

During hot weather, poultry require more vitamins, including vitamin C and E, which can be added to their feed or water to help regulate body temperature and reduce stress levels. While chickens primarily synthesize vitamin C in their kidneys, this may not be enough during hot and humid seasons, making supplementation necessary (123,124). Vitamin C supplementation not only combats heat stress, but also improves immune response, feed consumption, weight gain, fertility, hatchability of fertile eggs and several other factors that affect bird health and productivity (123). Vitamin E (alpha-tocopherol) is a fat-soluble vitamin with antioxidant properties that scavenges free radicals and modulates inflammatory signaling, resulting in enhanced phagocytic activity of macrophages and lymphocyte proliferation in broiler chickens (125). Supplementing the diets of heat-stressed laying hens with vitamin E has been shown to enhance egg production, increase egg weight, improve shell thickness and specific gravity, and raise the Haugh unit, with an optimal dose of 250 mg/kg feed (126,127). Broilers supplemented with 250 mg/kg of vitamin E under heat stress exhibited lower liver and serum malondialdehyde (MDA) levels, along with higher serum and liver concentrations of vitamins E and A (128).

Probiotics, which contain live beneficial microorganisms, have been shown to have beneficial effects in reducing the negative effects of heat stress in poultry. The addition of probiotics, including Bifidobacterium, Lactobacillus, and Bacillus spp. to the diets of broilers has been found to enhance growth performance, feed conversion ratio (FCR), and immune response, particularly in the context of high temperatures (13,14). Probiotics facilitate the modulation of the microbiota–gut–brain axis, the reduction of stress-related inflammation, and the amelioration of gut health. This results in enhanced nutrient absorption, increased egg production, and improved overall poultry performance during periods of heat stress (129,130). For example, the administration of Bacillus licheniformis to laying hens subjected to heat stress has been demonstrated to enhance egg production, feed intake, and intestinal health (131). Probiotics also contribute to the maintenance of gut structural integrity, which is essential for optimal nutrient absorption. These benefits contribute to improved body weight, feed intake, and overall health in birds subjected to heat stress (132).

Prebiotics, defined as selectively fermented food ingredients that induce specific changes in the composition or activity of the gut microbiota, are increasingly recognized for their benefits in mitigating heat stress in poultry (133). They promote beneficial bacteria in the colon, thereby enhancing host health. In poultry, various oligosaccharides such as mannan oligosaccharides (MOS), inulin, and fructo-oligosaccharides (FOS) are commonly employed as prebiotics. These compounds are fermented by intestinal microbiota to produce short-chain fatty acids and other antimicrobial substances, which help suppress harmful microbes and improve gut health (134,135). The addition of prebiotics to the diet of heat-stressed broilers has been shown to improve several performance metrics (133). For example, the combination of chicory root, seaweed, and Enterococcus faecium, when added to broiler diets, has been shown to improve intestinal health and growth performance under conditions of heat stress. This is evidenced by increases in ileum villus length, crypt depth, body weight, feed conversion ratio, and carcass yield (136). Furthermore, the inclusion of mannan oligosaccharide prebiotics and Lactobacillus-based probiotics has been shown to reduce stress markers such as cortisol and cholesterol while simultaneously increasing thyroxine levels, humoral immunity, and gut morphology (137). The administration of mannan oligosaccharides (0.5%) and probiotics (1%) resulted in further improvements in villus length, surface area, and crypt depth in broilers subjected to heat stress (138,139).

In conclusion, the increasing incidence of heat stress due to global warming presents a significant challenge to poultry production, particularly in tropical regions. Heat stress adversely impacts growth, productivity, and reproductive efficiency in poultry, leading to considerable economic losses. Addressing this issue requires a multifaceted approach, focusing on advanced mitigation strategies and innovative research to develop more resilient poultry breeds. Future research should prioritize developing genetic selection methods to breed heat-tolerant poultry while maintaining productivity and health. This approach could offer a cost-effective solution, especially beneficial for tropical regions in developing countries. Additionally, there is a need for comprehensive studies on the synergistic effects of combined mitigation strategies, such as optimizing housing designs with better insulation, ventilation, and orientation, alongside nutritional interventions. The development of more effective environmental management practices, such as controlled lighting schedules and advanced cooling systems, will also be critical. Implementing intermittent and reverse lighting schedules can help reduce heat production and improve feed efficiency. Additionally, enhancing litter management and employing evaporative cooling techniques, such as cooling pads and rooftop sprinklers, can significantly mitigate the adverse effects of high temperatures. Overall, managing heat stress in poultry production requires an integrated approach that combines genetic, nutritional and management strategies. Continued research and innovation in these areas will be essential to ensure the sustainability and productivity of the poultry industry in the face of global climate change.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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