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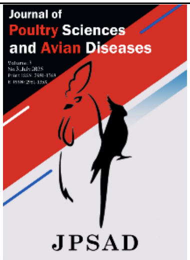

Innovative Strategies to Mitigate Heat Stress in Broiler Chickens

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ABSTRACT

Heat stress remains a major challenge for the poultry industry, particularly in tropical regions and warm seasons, where it negatively impacts poultry welfare and performance, leading to economic losses. Although heat stress has been a long-term concern for the poultry industry, existing solutions only partially alleviate the negative impacts on overall productivity. Enhancing our understanding of this challenge and available solutions can aid in shaping future initiatives to develop more robust solutions for managing heat stress. This review explores recent strategies developed to mitigate heat stress in broiler chickens, including genetic selection, nutritional approaches such as vitamins (C, E, A, and B groups), amino acids, electrolytes, environmental modifications, and improving behavioral monitoring systems. Furthermore, we discussed the challenges in reducing heat stress's impacts. Integrating these diverse strategies can improve poultry resilience, ensuring better welfare and sustainable production systems. Therefore, this review contributes to advancing adaptive strategies to safeguard poultry in a warming world.

Keywords: *Heat stress, welfare, genetics, nutrition, environmental*

1 Introduction

1.1 Overview of Heat stress

Heat stress causes a significant challenge in poultry production by increasing mortality rate or lowering product quality, particularly in broilers (1) (Figure 1). When chickens are exposed to elevated environmental temperatures (+30°C), often compounded by high humidity (+60%), they are unable to regulate their body temperature effectively, leading to physiological disorders (2-4). In this

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situation, chickens try to manage their body temperature by eating less feed to reduce the heat generated by their body during digestion. The decline in nutrient intake adversely affects growth rates (5) and product quality (6). Furthermore, chickens try to respond to heat stress through several other mechanisms, including increased panting, spreading of wings, reduced activities like walking and staying in cooler areas (7). These behaviors could temporarily alleviate discomfort, but when chickens are exposed to heat for longer periods, it overwhelms their coping mechanisms, leading to exhaustion, reduced product quality, or increased mortality under extreme conditions (3).

Heat stress increases oxidative damage and alters electrolyte balance in poultry (8). When broilers are exposed to high temperatures, their bodies generate high amounts of reactive oxygen species (ROS) as their mitochondria are impaired, which can damage cellular components like lipids, proteins, and DNA (9). Mitochondria are the primary source of ROS production and play a major role in tissue health (10-12). Heat stress also impairs the antioxidant defense system by impacting superoxide dismutase, catalase, and glutathione peroxidase activities (13). Heat stress also leads to compromised gut integrity (14), increasing susceptibility to external pathogens and impaired immune function. Several negative factors listed below are the consequences of chickens' exposure to heat stress. Therefore, an integrated understanding of physiological mechanisms and mitigation strategies is essential to maintain broiler health and productivity under climate stress.

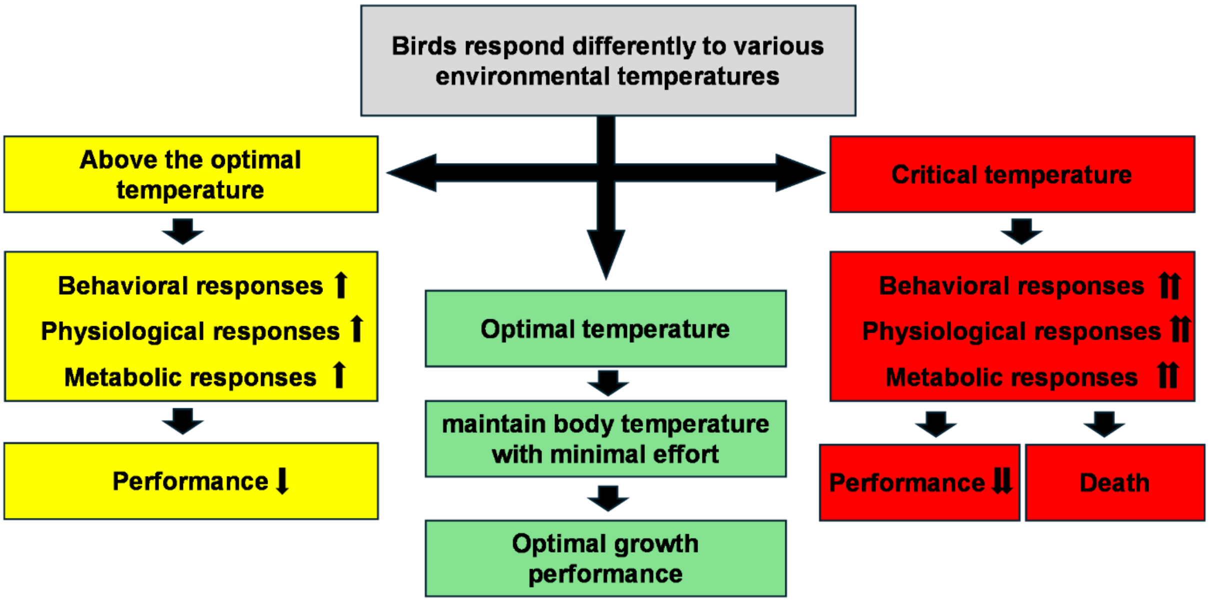

Figure 1. Chickens respond differently to various environmental temperatures. They exhibit normal growth performance when the temperature is optimal (18-22°C). However, performance declines when temperatures exceed the optimal range, with more severe effects occurring as temperatures reach critical zones above 35°C.

1.2 Economic Impacts of Heat Stress

Under hot thermal conditions, broilers exhibit poorer performance due to reduced feed intake, which directly compromises profitability and results in financial losses for the industry. Such declines in productivity not only reduce profitability but may also disrupt downstream processing and market availability. Additionally, mortality significantly increases during high environmental temperatures, which is a substantial economic burden (15). Large-scale mortality happens during extreme heat (16), especially when immediate interventions are unavailable. Each bird lost represents a financial loss, including the cost of rearing without return.

1.2.1 Higher Operational Costs

Several current strategies for mitigating heat stress require significant infrastructure investment, such as higher-capacity cooling systems and equipping a house with climate-controlled systems (17). Although the systems are effective, they are not practical for all farms (especially smaller farms) as they are expensive and require ongoing maintenance. Modern housing systems may cost 30–50% more than traditional floor-based housing (18). Furthermore, such equipment's energy demands significantly increase operational expenses, particularly during warm seasons.

1.2.2 Additives Expenses

During heat stress, chickens need a specialized diet to ensure their body receives adequate nutrition despite lower feed intake, such as vitamins, to enhance heat tolerance and minimize oxidative damage (3, 14). However, including these additives raises feed costs, impacting overall profitability.

1.2.3 Disease Management Costs

Heat stress alters chickens' immune system and increases infection susceptibility (19). The immune system alteration increases the costs of biosecurity measures to maintain bird's health. Outbreaks of illness due to weakened immunity can lead to further productivity losses and additional costs for treatment and recovery.

2 Physiological Consequences of Heat Stress

2.1 Metabolism and Feed Intake

Heat stress disrupts metabolic efficiency (Figure 2), forcing the chickens to spend additional energy to maintain/or reduce their body temperature. This redirection of energy away from essential functions such as growth and immune response leads to noticeable declines in productivity (5). During heat stress, protein synthesis is significantly impaired, resulting in reduced muscle development and lower body weight gain in broilers (20). Disruption of metabolic efficiency leads to the generation of high amounts of ROS, causing cellular damage, including DNA, proteins, and lipids, leading to long-term physiological strain (21). Hormonal imbalances, particularly elevated corticosterone levels, further suppress normal metabolic functions (22), weakening the chickens' ability to respond to external stressors and increasing vulnerability to infections and diseases.

Heat stress directly impacts the feeding behavior of poultry, with chickens instinctively reducing their feed intake to minimize the internal heat generated during digestion (23). Reduced nutrient absorption due to lower feed intake impairs growth, immunity, and productivity (3). Nutritional deficiencies affect chickens' overall health, making them more vulnerable to illnesses. Additionally, disrupting normal feeding patterns can cause energy and protein levels imbalances. Therefore, a comprehensive approach to coping with heat stress must be required to reduce the negative effects of impaired metabolism and nutritional deficiencies under heat stress conditions, including dietary adjustments, environmental modifications, and technological interventions. For instance, upgrading cooling systems can reduce environmental temperatures, while nutritional supplements improve energy levels and immune function. Addressing these interconnected challenges is essential for sustaining poultry welfare and productivity under heat-stress conditions.

2.2 Oxidative Stress and Immune System

Oxidative stress occurs when the production of ROS exceeds the chicken's natural antioxidant defenses, creating an imbalance that leads to cellular damage (24) (Figure 2). Oxidative damage interferes with several physiological processes, such as energy metabolism, protein synthesis, and reproductive functions, impacting overall productivity (25). During heat stress, the heightened metabolic rate in poultry results in excessive ROS production, which overwhelms their ability to neutralize these harmful compounds. ROS damages cellular components, causing lipid peroxidation, membrane integrity loss, and cell death in extreme situations. Being metabolically active and rich in polyunsaturated fatty acids, muscle tissue is particularly vulnerable to lipid peroxidation under oxidative stress, resulting in poor carcass quality.

Oxidative stress weakens immunity in broiler chickens by disrupting barrier integrity (compromising the protective barrier and increasing susceptibility to infections) and gut dysbiosis (altering gut microbiota composition and leading to digestive issues) (26, 27), leaving chickens more vulnerable to infections. The heat stress response is mediated by hormonal changes, particularly an increase in corticosterone levels, which suppress immune functions by reducing the production of immune cells such as lymphocytes and macrophages, impairing the chickens' ability to respond to external pathogens effectively. The gut, a critical immune system component, is particularly affected during heat stress (28). Increased intestinal permeability allows pathogens and toxins to enter the bloodstream, compromising immunity. Using immune-boosting feed additives helps enhance gut health and restore the immune system.

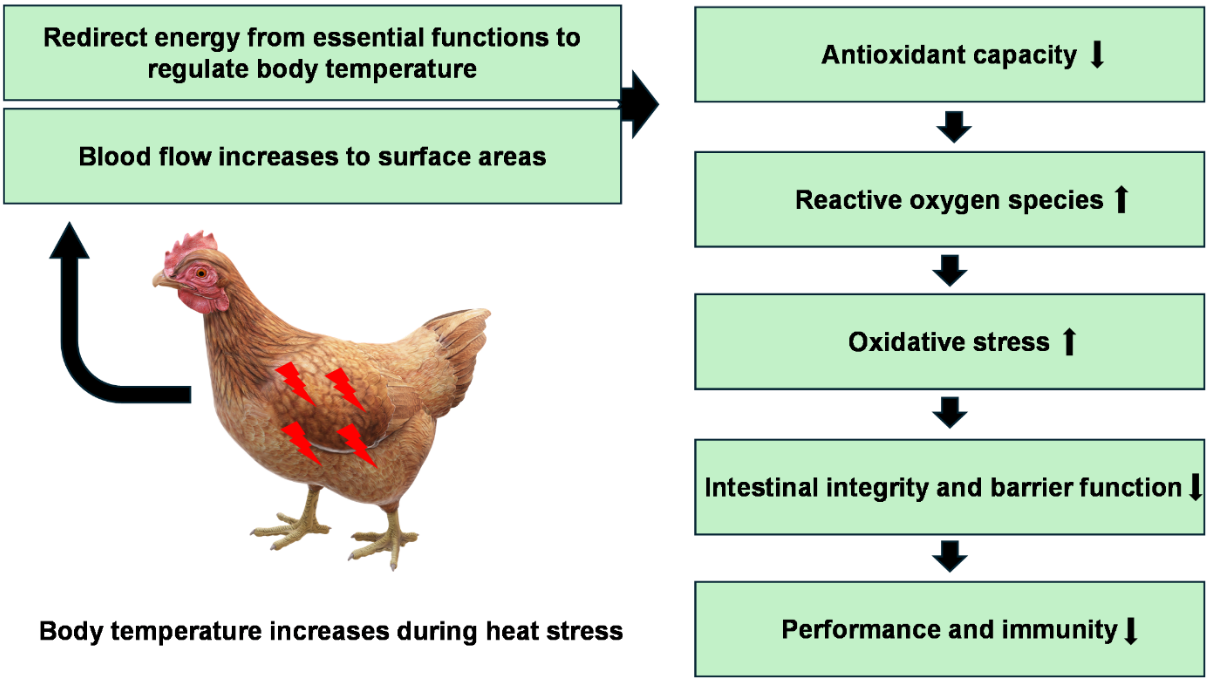

Figure 2. Chickens use several mechanisms to lower their body temperature. While these strategies help with thermoregulation, they become insufficient under prolonged heat stress, negatively impacting health and performance.

3 Strategies to Mitigate Heat Stress

3.1 Genetic Selection

Genetic selection is crucial in developing poultry breeds that can thrive under heat stress (29). Selective breeding programs target traits such as efficient thermoregulation and higher tolerance to elevated temperatures. For instance, local breeds, which have adapted to the local climate over the years, can be crossbred with high-yield commercial strains (Ross and Cobb) to combine heat resilience with improved productivity. Some local broiler strains have developed adaptations to cope with heat stress, such as Naked Neck (fewer feathers on their necks, allowing better heat dissipation), Red Jungle Fowl (strong thermoregulatory abilities), Indigenous African strain (efficient panting and blood flow redistribution), and Thai Indian Native strain (lower metabolic heat production). Genomic technologies have accelerated the identification of genetic markers associated with heat tolerance in poultry (29). For instance, CRISPR-based editing of heat shock protein genes has shown promise in enhancing thermoregulatory efficiency.

Broiler chickens have several heat resistance genes that help them cope with heat stress, such as heat shock proteins (protecting cells from heat-induced damage by stabilizing proteins) and heat shock factors (regulate the expression of heat shock proteins) (30), antioxidant enzymes (superoxide dismutase and catalase help neutralize oxidative stress) and immune-related genes (Toll-like receptors and cytokines to protect against infections) (31).

3.2 Nutritional Management

Nutritional strategies such as osmolytes, amino acids, and natural phytochemicals have shown synergistic potential in restoring redox balance, maintaining gut integrity, and enhancing mitochondrial function under heat stress (32). Including the additives in feed individually or in combination helps neutralize ROS and maintain osmotic balance (33), improving growth performance and meat quality in broilers under heat-stress conditions (Table 1).

Table 1. Summary of nutritional strategies to mitigate heat stress in broilers.

Additive	Function	Recommended	Ref.
Betaine	Methylation and hydration	0.5–2 g/kg	(34, 35)
Taurine	Membrane stabilizer	6g/kg and 0.1%	(36, 37)
Glutamine	Gut integrity, immune booster	0.5–1.0%	(15, 38)
Vitamin C	Corticosteroid	120–200 g/1000L water	(3)
Vitamin E	Membrane protection	100–250 mg/kg	(3, 39)
Vitamin A	Mucosal health, immune support	4.5 mg/kg	(40)
Vitamin D	Calcium metabolism	1600-2000 IU	(41)
Vitamin B group	Energy metabolism	20 and 40 µg	(42)
Arginine	Immune modulator	1–2%	(43)
Lysine	Produces antibodies	excess level*	(44)
Methionine	Reduces oxidative damage	excess level*	(45)
Polyphenols	Anti-inflammatory	2–10 g/kg	(23)
Electrolytes	Osmotic pressure regulation	different levels#	(46, 47)

* Level is higher than NRC recommendations.
\# Vary depends on what electrocyte was added to the diet.

3.2.1 Osmolytes

Osmolytes such as betaine are small organic compounds that help broiler chickens maintain cellular homeostasis and combat the effects of heat stress (14), as well as support mitochondrial function and energy production (48), which are essential for cellular health (49).

Betaine, as a methyl donor, converts homocysteine to methionine through a process mediated by betaine-homocysteine methyltransferase, which is crucial for maintaining cellular detoxification by converting homocysteine and supporting metabolic pathways by synthesizing methionine, an essential amino acid involved in various metabolic functions (14). Several studies have shown that supplementing a bird's diet with betaine (0.5-2 g/kg) improves broiler chickens' overall performance and health under heat stress (34, 35). The effects are consistent across different betaine levels, with higher doses showing slightly greater improvements in growth rate (50).

Certain osmolytes, such as taurine, have antioxidant properties that could neutralize ROS and protect cellular components like lipids and DNA (36) by supporting antioxidant enzymes such as superoxide dismutase (51). Furthermore, taurine protects mitochondria membranes (preventing ROS production) and regulates Akt/mTOR, which is important for cellular stress response (51). The Akt/mTOR (Akt: protein kinase B, mTOR: mammalian target of rapamycin) regulates cell functions (52). Akt inhibits tuberous sclerosis complex two protein, preventing suppressing Ras homolog enriched in the brain. The Rheb stimulates mTORC1, enabling mTOR to regulate various cellular processes, including protein synthesis, autophagy, and cell cycle progression. Taurine (0.1%) is an effective additive to improve broiler chickens' health under heat-stress conditions (53, 54), while 6 g/kg taurine significantly improved growth performance, oxidative stress resistance, and gut health in broilers (37).

Some osmolytes, such as glutamine, protect the gut lining, reduce inflammation, and improve absorption in the gut (38), resulting in improved performance. Glutamine acts as an energy source for enterocytes, essential for maintaining the integrity and function of the gut barrier (55). Glutamine produces energy through the Krebs or citric acid cycle (56) by converting it into glutamate (glutaminase enzyme) and α-ketoglutarate. The energy generated by glutamine also helps strengthen tight junctions, reducing gut cell permeability (57). Furthermore, glutamine promotes the production of mucus, which acts as a protective layer over the gut lining (55) by managing energy metabolism, which helps with thermoregulation (58). Studies showed that glutamine (0.5-1%) could improve broiler chickens' gut health and performance under heat stress (15, 38). A study suggests that increasing glutamine levels beyond 1% may benefit broilers when stressed, however, results could vary from one study to another study depending on environmental conditions and bird health (59).

3.2.2 Vitamins

Vitamins play a vital role in helping broiler chickens combat heat stress by boosting immune function, reducing oxidative damage, and supporting metabolic processes (3).

Vitamin C (ascorbic acid) reduces oxidative stress and supports immune function (3) by neutralizing ROS, regenerating other antioxidants, and facilitating the production of immune cells like lymphocytes and macrophages. Vitamin C is also involved in the secretion of corticosteroids (60), which improves metabolic activities during heat stress. Under heat stress conditions, chickens release adrenal corticosteroids (primarily corticosterone) as a stress response (61). Corticosterone is a hormone produced during stress conditions by activating the hypothalamic-pituitary-adrenal axis in response to stress to boost the immune system (62). During stress, the hypothalamic-pituitary-adrenal axis releases corticotropin-releasing hormone, producing adrenocorticotropic hormone, which helps release stress hormones (63). Additionally, vitamin C improves gut health by improving mucus production, improving the health and function of epithelial cells (secretion of mucus), which protects the gut cells against pathogens and irritants (64). Vitamin C improves epithelial cells' health by boosting collagen synthesis, which upholds the structural integrity of epithelial cells. Different doses of vitamin C in drinking water (120 and 200 g/1000L) are essential during heat stress for broiler chickens (3). A study indicated that higher doses of vitamin C may have a limited impact on broiler performance, particularly under certain conditions (65).

Vitamin E protects cell membranes from damage, enhances antioxidant defense (3), and shields cellular membranes by neutralizing lipid peroxidation. Vitamin E is available in the lipid layers of cell membranes, which stops free radicals (stabilizing them by donating electrons) to initiate a chain reaction of lipid peroxidation, leading to compromise the membrane's integrity (66). Unlike some antioxidants, vitamin E remains stable and does not become a pro-oxidant, so it protects cells and stays stable. Vitamin E can be regenerated by vitamin C, which allows it to continue neutralizing free radicals (67). Different doses of vitamin E (100 and 250 mg/kg) are helpful for chickens during heat stress (3, 39). While a study showed no improvement in growth performance for higher doses of vitamin E (68), under certain conditions, the higher doses might provide better outcomes (69).

Vitamin A (retinoic acid) supports mucosal integrity by maintaining the activity of goblet cells (produces mucus) (70), which prevents external pathogens from entering the body. Goblet cells produce proteins essential for mucus secretion (glycosylated proteins) (71). The proteins are synthesized in the endoplasmic reticulum and transferred into secretory granules. The granules are released through exocytosis, forming mucus that protects epithelial surfaces. Furthermore, vitamin A regulates immature cells to develop into specialized epithelial cells as a protective lining of organs such as the gut, ensuring the tissues function effectively against external pathogens (72). Vitamin A improves the production of keratin and collagen, which are both important for maintaining the strength and elasticity of the tissues. Vitamin A boosts the immune system through several pathways, including promoting the differentiation of T cells into regulatory T cells (maintaining immune tolerance), maturation of B cells into plasma cells (producing antibodies), boosts the activity of macrophages, and promotes the development of ILCs (maintaining gut barrier integrity) (73, 74). It has been recommended that vitamin A should not be used in high doses as it could have adverse effects in broiler chickens (75), while a level of 4.5 mg/kg could alleviate the negative impacts of heat stress (40).

Vitamin D plays a crucial role in protecting chickens during heat stress by supporting calcium metabolism and bone health (76), counteracting the negative effects of stress on skeletal development, and modulating immune function. Vitamin D helps calcium absorption in the intestines by increasing calcium-binding proteins such as calbindin production. The proteins transport calcium across the intestinal cells, allowing calcium to enter the bloodstream more efficiently (77). Therefore, without vitamin D, calcium absorption may be interrupted, leading to calcium deficiency in the body. Calcium is essential for the immune system as it activates immune cells, which helps chickens deal with infections and diseases (78). A study showed that adding vitamin D (1600-2000 IU) could improve performance and meat quality (41). Higher doses of vitamin D could cause adverse effects for broiler chickens, such as metabolic imbalances and organ calcification (79).

Vitamin B (B1-6, B9, and B12) improves energy metabolism by assisting in carbohydrate, protein, and fat utilization and neurological function, mitigating stress-induced metabolic disruptions (80). Vitamin B1 (decarboxylation of pyruvate to acetyl-CoA in the Krebs cycle), B2 (electron transport chain using flavin adenine dinucleotide and flavin mononucleotide), and B3 (glycolysis through the synthesis of nicotinamide adenine dinucleotide and nicotinamide adenine dinucleotide phosphate in the Krebs cycle) help convert food to energy for the body, especially during heat stress when bird's body requires more energy to cope with the condition (80). Vitamins B5 and B6 synthesize stress hormones such as cortisol, which help chickens cope with the physiological challenges of heat stress by providing sufficient energy for the body, enabling chickens to adapt to environmental stressors and maintain homeostasis. Vitamins B9 (formation of DNA and RNA) and B12 (DNA synthesis) produce red blood cells and immune cells, ensuring oxygen transport and a robust immune response (81). Supplementing a diet with B12 (20 and 40 µg) has been shown to positively impact performance in broiler chickens (42).

3.2.3 Amino Acids

Amino acids play a crucial role in helping broiler chickens cope with heat stress by enhancing protein synthesis, boosting antioxidant defense, improving gut health, regulating osmotic balance, and supporting immune function (82). Amino acids such as lysine and methionine are critical for maintaining efficient protein synthesis and ensuring muscle development and growth (83). Lysine produces antibodies, heat shock proteins, and immune cells, helping the immune system broilers to cope with stress (84). Methionine helps chickens during stress conditions by synthesizing glutathione (protects cells from oxidative damage), regulating metabolic processes supporting cellular defense systems, and boosting the expression of stress-related genes (45, 84, 85). In addition to methionine, glutamine, and cysteine also produce glutathione, which protects cells from oxidative damage caused by ROS (15, 86). Furthermore, glutamine strengthens intestinal health by repairing the intestinal lining, reducing inflammation (which produces heat shock proteins) in gut tissues, and improving nutrient uptake efficiency (87). Certain amino acids, such as glycine and proline, help regulate the osmotic balance within cells, preventing dehydration caused by heat stress (88, 89). At the same time, arginine enhances immune responses by stimulating the production of nitric oxide, which supports immune cell activity and promotes lymphocyte proliferation and defense mechanisms (43).

3.2.4 Polyphenols

Polyphenols, a group of plant-based compounds with powerful antioxidant and anti-inflammatory properties, are effective in modulating physiological responses to heat stress (23). Polyphenols improve blood flow, helping chickens control their body temperature more effectively by improving vascular health and promoting the dilation of blood vessels (90). Polyphenols improve blood flow by promoting nitric oxide production in the inner sides of blood vessels by activating endothelial nitric oxide synthase enzyme (converts L-arginine into nitric oxide) (91). Furthermore, the anti-inflammatory properties of polyphenols help reduce ROS production (less oxidative damage) in blood vessels, improving blood flow by preventing plaques. Additionally, Flavonoids scavenge ROS and modulate inflammatory and apoptotic signaling cascades, protecting intestinal epithelium and mitochondrial function under heat-induced inflammation (92). Supplementing a diet with polyphenols (2-10 g/kg) enhanced overall performance and reduced oxidative stress (23). High doses of polyphenols might have varied effects on growth depending on the source, dosage, and environmental conditions. Studies indicate that excessive polyphenol did not enhance growth performance or feed efficiency, while others highlighted potential benefits on performance when chickens were subjected to heat stress (93, 94).

3.2.5 Electrolytes

Electrolytes maintain physiological homeostasis during thermal stress by stabilizing key physiological functions such as acid-base balance, osmotic pressure regulation, and thermoregulation (95). Heat stress leads to respiratory alkalosis due to increased panting, which causes excessive loss of carbon dioxide. Electrolytes like sodium, potassium, and chloride help restore the acid-base balance by controlling buffer changes in blood pH (95). Electrolytes stabilize pH levels through a phosphate buffer system (donating or accepting hydrogen ions) and a protein buffer system (interacting with proteins such as hemoglobin) by binding with hydrogen ions (96). Some electrolytes like sodium and potassium are essential for maintaining cellular activity and ensuring the proper function of ion channels, which are critical during periods of heat stress. These electrolytes act as signaling molecules and bind to specific receptors on ion channels, which help activate or inactivate the channels (97). Optimal dietary electrolyte balance is crucial for growth performance and physiological stability (47). However, excessively high electrolyte levels may not provide additional benefits and could lead to metabolic imbalances or increased litter moisture (98).

3.3 Environmental Modifications

Housing design plays a vital role in mitigating heat stress (99). Evaporative cooling systems lower the temperature by increasing air circulation. Reflective roofing materials, such as white or metallic coatings, reduce heat absorption and prevent excessive thermal buildup. Proper insulation and shading prevent direct heat exposure, and low stocking densities ensure better air circulation within poultry flocks. Maintaining dry litter reduces microbial heat generation and enhances thermal comfort. In addition to temperature reduction, maintaining optimal humidity (<60%) is critical for effective evaporative cooling and microbial control.

Countries use various housing systems to minimize heat stress in poultry, adapting to their climate and infrastructure. In the United States and Middle Eastern countries, mechanical ventilation, evaporative cooling systems, and fogging systems are commonly used in the poultry industry (100), while in Australia, farmers use controlled-environment housing with automated cooling systems (101). In India and Malaysia, open-sided housing with shade structures is commonly used for raising chickens (101, 102).

3.4 Thermal Conditioning

Thermal conditioning is a preconditioning technique that exposes chicks to mild heat stress during their early life stages (103). This practice helps them acclimate to higher temperatures as they grow, improving their thermoregulation in later heat stress events. Short periods of elevated temperatures during the first few weeks of life have enhanced physiological and behavioral adaptability in poultry (104). Previous studies have shown that thermal conditioning enhances chickens' response to heat stress at later ages when they are exposed to 24 hours of heat as young chicks (105) and improved meat quality (106).

3.5 Emerging Technologies

Advances in behavior and health monitoring systems can help farmers detect early signs of heat stress in poultry (107, 108) (Table 2). Sensors and cameras can track changes in activity levels, flock distribution, panting, and wing-spreading behaviors. These systems provide real-time information, allowing farmers to intervene promptly. Predictive analytics based on the obtained data can forecast heat stress risks and recommend proactive measures, ensuring better flock management.

Table 2. Emerging technologies to cope with heat stress in broilers.

Systems*	Equipment	Function
Thermal monitoring	Infrared cameras Automated thermal monitoring	Detect temperature Real-time adjustments to cooling systems
Smart cooling	AI-driven climate control Evaporative cooling pads	Optimizes airflow and temperature Enhance heat dissipation
Nutritional Innovations	Yeast postbiotics Precision feeding systems	improve gut health and resilience against heat stress Adjust nutrient intake to support thermoregulation
Wearable and IoT-Based Monitoring	Smart sensors Automated alerts	Track bird activity, hydration, and stress indicators Notify farmers of heat stress risks in real-time
Physiological Adaptations	Embryonic thermal programming	Conditions chickens to withstand heat stress later in life

* These advanced technologies help maintain bird health and productivity by improving heat management and adaptation to rising temperatures.

4 Challenges

4.1 Costs of Emerging Technologies

One of the major challenges is the cost associated with implementing advanced technologies and infrastructure. Although cooling systems and monitoring devices can significantly improve productivity and bird welfare (109), they require substantial investments, which may be inaccessible to small poultry farms. Furthermore, these systems' ongoing maintenance and operational costs can strain farm finances. Even when farms can afford initial investments, maintaining these advanced systems efficiently requires specialized training and expertise, which may not be readily available in certain regions. Even the most advanced innovations remain underutilized without proper support, preventing widespread adoption in smaller farming operations.

4.2 Genetic Limitations

Despite progress in breeding heat-resistant broiler chickens, genetic selection is a time-intensive process that may not yield immediate results. Moreover, balancing heat tolerance with productivity can be challenging, as some beneficial traits for heat stress mitigation, such as woody breast myopathy and spaghetti meat (110), may compromise meat quality.

4.3 Limited Research and Data

Although significant progress has been made in understanding heat stress in broiler chickens, there is still insufficient available data on the long-term effects of heat stress and the effectiveness of various interventions. Most studies focus on short-term physiological responses, such as reduction of feed intake, panting behavior, and immediate productivity declines (5, 46). However, comprehensive long-term studies on metabolic adaptations, genetic resilience, and multi-generational impacts are limited. Furthermore, although many strategies, including nutritional supplementation and housing modifications, have been explored, their sustained effectiveness under diverse environmental conditions is still not well-documented. The interaction between genetic selection, climate adaptation, and stress tolerance remains understudied, making it difficult to develop universally applicable solutions.

Additionally, data collection and analysis gaps pose challenges in developing predictive systems for managing heat stress in poultry production. Traditional poultry farms often lack standardized monitoring tools, resulting in inconsistent reporting of environmental conditions, bird health, and performance variations. Without comprehensive data integration, it becomes difficult to identify critical risk factors and implement effective, proactive strategies.

5 Conclusion

As climate variability intensifies, heat stress emerges as one of the foremost challenges in global poultry production. A multidisciplinary and integrated strategy—encompassing genetic selection, dietary innovation, environmental engineering, and technological foresight is essential to ensure animal welfare, economic viability, and sustainable productivity. While traditional solutions offer partial relief, the convergence of precision nutrition, early-life thermal adaptation, and real-time behavioral analytics holds transformative potential. Future research should prioritize scalable interventions, cost-effective technologies, and policy support to empower producers globally, especially in low-resource settings.

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Conflict of Interest

The authors declare no competing interests.

Author Contributions

M.Sh. wrote the original draft, reviewed it, and edited it; H.L.H. and A.Kh. reviewed and edited it. All the authors have read and approved the work.

Data Availability Statement

All data have been included in the article or referenced in the article.

Ethical Considerations

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