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Review

Impact of Heat Stress on Broiler Chicken Production

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Abstract: Poultry farmers need to consider making adaptations now to help reduce cost, risk, and concern in the future; the industry's high and unstable input costs, which result in losses, need to incentivize manufacturers to concentrate on efficient management, welfare, and health improvements, thereby creating premium and value-added products. Heat stress, a significant concern, particularly affects broiler chicken, which is vital for global meat supply in the dynamic field of poultry farming. Despite advances in breeding and management, these pressures have a negative influence on avian development, well-being, and overall health, threatening the poultry industry's long-term viability. This study investigates the physiological reactions and production consequences of various heat conditions in the chicken business. It thoroughly investigates the complicated implications of heat stress, which has a negative impact on broiler performance and causes economic losses. This article investigates various dietary techniques, such as antioxidants, probiotics, amino acid balance, and vitamin supplementation, with the goal of improving chicken thermotolerance as part of a comprehensive stress reduction strategy. This assessment emphasizes the industry's continuous commitment to sustainable practices by highlighting the need for more research to enhance methodology, investigate creative tactics, and address regional variances in heat stress.

Keywords: heat stress; broiler chicken; poultry industry; meat supply; vitamin supplementation

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1. Introduction

In the scope of poultry farming, broiler chickens are primarily cultivated for their meat. The increasing demand for animal protein is directly related to the ever-increasing world population, making efficient poultry production more important [1]. The production cycle is relatively short, spanning 5 to 8 weeks, during which these birds undergo a remarkable transformation. Starting at a weight of 40–55 g as day-old chicks, they quickly gain weight and reach a remarkable 2.5 kg by the time they are ready to be sold. Broiler chickens are vulnerable to problems, such as heat stress (HS), due to their quick growth. Recent years have seen a drastic reduction in the time it takes for chickens to reach market weight, thanks to improvements in production methods made possible by breakthroughs in breeding techniques in response to the worldwide surge in demand for chicken meat. As a result of these innovations altering the preexisting relationships with the environment, the production of broiler chickens is greatly affected by environmental stresses, which have negative effects on their health, welfare, and performance [2,3]. The health of broiler chickens is greatly affected by environmental factors such as excessive humidity, air flow, and temperature. Among these stressors, the most serious one is heat stress caused by high temperatures, which is worsening due to ongoing global climate changes [4]. It has negative effects on feed consumption, feed efficiency, body mass index, meat quality, and mortality rates [4]. The proper development and general well-being of broiler chickens depend on controlling these environmental stresses.

To maintain the advancements made in poultry farming, it is crucial to make sure that broiler chicks can survive these shifting environmental circumstances. Handling the different challenges that broiler chickens encounter is essential for a prosperous poultry farm. Environmental, dietary, or even internal stresses can upset these birds' delicate physiological equilibrium [5]. The chicken production sector is still heavily impacted by environmental stress, despite advancements in housing and management systems that aim to reduce it [6].

The significance of tackling stress concerns and examining various techniques to alleviate stress in broiler production is emphasized in this review. Poultry producers must effectively manage many challenges that threaten the industry's productivity and the quality of goods such as meat and eggs. The poultry industry persists in its development despite encountering challenges, propelled by the imperative to accommodate global demand for chicken products and accommodate evolving circumstances.

2. Definition of Terms

An environmental stressor refers to a component or situation within the immediate surroundings that possesses the potential to trigger distress or detrimental effects in living organisms which influences the health, behavior, and well-being of animals within a particular ecosystem. Environmental stressors may include interactions with other organisms, oscillations in the availability of food, pollution, high temperatures, habitat destruction, and many others [7]. Stressors encompass various elements such as temperature, climatic change, oxidative stress, and immune response [8] with particular emphases on heat stress in this review. When the net amount of heat energy leaving the animal and entering the environment is less than what the animal produces, heat stress happens [9].

Heat Stress: Poultry are considerably affected in terms of performance, health, and overall welfare by heat stress (HS) [10]. The inability of the birds to keep up with high temperature results in production of more metabolic heat than they can release. A condition known as hyperthermia, in which the body's temperature rises abnormally, triggers HS [11]. Multiple physiological disturbances, including immune system abnormalities, hormone irregularities, respiratory difficulties, and electrolyte imbalances are observed in poultry exposed to HS [11–13]. Growth performance drops and intestinal barrier integrity is disrupted as a result of these domino effects of disturbances [14].

3. Factors Contributing to Heat Stress

Examination of Specific Environmental Factors Contributing to Heat Stress

A. Climatic factors:

Seasonal Variations: Seasonal variations in poultry production refer to the cyclical changes and fluctuations observed in the output of poultry over different seasons of the year. These variations can be influenced by factors like temperature, daylight duration, and breeding cycles. Seasons characterized by high temperatures present a series of obstacles for the poultry industry. In their study, ref. [11] elucidate on the many consequences that arise from these factors. They encompass diminished meat quality, poor feed efficiency, altered behavior, and increased death rates. As an illustration of the ubiquitous impact of seasonal heat stress, these elements collectively contribute to large economic losses for chicken producers. Heat stress further compounds the variety of difficulties that poultry breeders must overcome. Ref. [15] emphasize that broilers exhibit heightened water usage in an effort to adapt to the elevated temperatures. The increased burden on water supply systems results in the need for strategic water management. The genetic aspects of heat tolerance introduce an additional level of intricacy, necessitating meticulous breeding techniques and selection processes to improve overall resistance to heat stress [11]. The production of broilers is substantially impacted by seasonal heat stress, which has adverse effects on health, performance, and economic outcomes. When confronted with the complex dynamics of hot seasons, it is critical for farmers to implement comprehensive management strategies, smart genetic selection, and advanced ventilation systems in order to ensure the profitability and sustainability of broiler farming.

Temperature: Birds are homeothermic animals, possessing the capability to regulate their internal body temperature within a relatively constant range. This functional ability (temperature regulation) occurs effectively when the birds are kept within a thermoneutral zone, which ranges from 21 to 28 °C (around 70 to 82 °F) [9], allowing them to maintain a stable temperature for their internal organs. A fluctuation in the environmental temperature above upper limits of the thermoneutral zone leads to heat stress in animals [16] which affects the overall performance of the chicken and can result in mortality. However, due to their high level of production, fast-growing broilers with a substantial body weight are highly susceptible to heat stress in environments with high ambient temperatures, while in the absence of developed thermoregulatory organs, neonatal chicks are vulnerable to cold stress and cannot endure the severe conditions. The optimal temperatures at which the bird can function most effectively are determined by its age, body weight, housing system, feeding level, relative humidity, air velocity, and overall health [17]. In situations with a high ambient temperature, chickens have greater energy requirements than those grown in thermoneutral environments.

Humidity: Heat dissipation is an additional aspect of heat management that is subject to the influence of a number of variables, in addition to heat production. Significantly influenced by the relative humidity of the surrounding environment, evaporative heat dissipation is a critical mechanism. Elevated humidity reduces evaporative heat loss, which increases with temperature. Age and air temperature are variables that influence the effect of humidity on the thermal regulation response of broiler chickens [18]. Humidity significantly influences the performance of broiler chicks and turkeys that have been subjected to temperatures elevating to 28 °C and 30 °C, respectively [19]. Redistributing heat within the body at high temperatures, humidity influenced the thermoregulation of 1-week-old broiler chickens, resulting in a rise in peripheral temperature and a decrease in rectal temperature [18]. On 4-week-old broiler chicks, however, elevated humidity levels over 60 percent exhibited varying impacts at 35 °C and 30 °C, hindering heat transfer at 35 °C while promoting it at 30 °C [18]. It is extremely important to address the variable humidity needs of broiler chicken, particularly in hot and humid climates, despite the difficulty of humidity regulation in poultry homes. To optimize the thermal comfort and well-being of chickens under a variety of climatic situations, it is critical to comprehend and control these variables.

B. Management factors:

Housing Management: Numerous factors contribute to the overall heat stress on the chickens, which is reflected in the internal temperature of a poultry house. The proper management of poultry housing is critical in reducing heat stress, a possible stressor impacting productivity. Previous research has underlined the importance of ensuring adequate temperature regulation and ventilation controls in environmentally controlled housing for preventing heat stress [20,21]. In non-environmentally controlled situations, such as open-sided buildings, issues such as insufficient stocking density and ventilation can worsen heat stress [22,23]. Addressing these issues is critical for maintaining a healthy environment for chickens and avoiding heat stress-related problems. The aforementioned elements comprise heat produced by the avian species, ambient circumstances, the roof, the process of fecal matter biodegradation, and the exposed or shaded ground surface [24]. In equal environmental conditions, dark-colored surfaces absorb a greater amount of heat from direct sun radiation than light-colored surfaces [25]. Moreover, stagnant feces within the broiler house have the potential to release heat and a range of detrimental gases, including NH3, CH4, and H2S, as they decompose [26]. Achieving effective heat stress management in poultry production necessitates meticulous examination of the diverse heat generation sources present in the broiler house, as well as the development of solutions to alleviate the detrimental impacts these sources have on the birds (cool cell pads, sprinklers, fans, and tunnel ventilation are solutions to reducing heat stress). As a result, for maximum poultry welfare and productivity, the significance of the housing system is highlighted as an implementation to mitigate heat stress.

Nutritional Management: Poor nutritional management appears to have a more damaging effect on growth performance, health, and productivity of the young birds [27]. Heat stress causes broilers to limit their feed intake due to metabolic effort. Heat stress alters nutrient use, which in turn reduces hunger, which in turn slows growth and reduces feed conversion efficiency [28]. Consequently, the industry is experiencing losses in productivity and profitability, which threatens the economic viability of broiler production. In addition, broilers experience oxidative stress due to heat stress, which means there is a higher need for antioxidants to protect them from free radical damage [29]. When birds do not have enough to eat, their immune systems can become weakened and they become more susceptible to diseases caused by oxidative stress and the antioxidant defense mechanisms in their bodies. One popular way to reduce the physiological impact of heat stress on broilers is to restrict their feed intake [30]. Despite its good intentions, this method of heat stress relief makes feeding much more difficult. Broilers' capacity to satisfy their nutritional needs for ideal development and growth is further compromised when feed restriction reduces the availability of vital nutrients [31]. To sum up, broiler production faces a tangled web of problems caused by the interaction of heat stress and nutritional inadequacies. To tackle these problems in a balanced way, we need to find ways to feed broilers so they can survive heat stress, build their resilience, and make chicken farming a viable economic and environmental option.

Water: It is important to consider the availability, temperature, and quality of water when producing broilers, especially when thinking about the effects of heat stress. When broilers drink water that is polluted with harmful bacteria or other contaminants, it can affect their digestive systems and weaken their immune systems [32]. As a natural cooling mechanism, birds drink more water when they are hot, but any pollutants in that water might make their health problems worse and lower their productivity drastically. A rise in water temperature may also occur because of heat stress and strong ambient temperatures [33]. Hot water can cause birds to drink less water, which can make them even more dehydrated and adversely affected by heat stress [34]. Also, a major problem during heat stress is not having enough water [35]. Sufficient water is essential for broilers to regulate their temperature and keep their physiological functions running smoothly [35]. Lack of water intake because of heat stress can make it harder for nutrients to be absorbed, which in turn might affect growth and performance [36]. For broiler production, heat stress is already a major problem, but when water is of low quality, very hot, and not readily available, it becomes much worse. During the heat stress period, it is crucial to establish a reliable source of clean water, control the temperature of the water, and make sure there is plenty of water available to offset these harmful impacts. To ensure the survival and resilience of broilers in harsh environmental conditions, it is essential to use appropriate water management methodologies.

Welfare and Stocking Density: Heat stress affects the welfare of broiler chicken. Increase in the intensity of heat stress coupled with compromised stocking density due to overcrowding of broilers has serious consequences for the birds' health and well-being [37]. Despite the best intentions, overcrowding broiler chickens slows their growth, decreases their feed intake and efficiency, and endangers their health and well-being [38]. When broiler chicks are overcrowded in their house, their growth rate, feed consumption, and feed conversion ratio (FCR) all suffer [39]. Not only does overcrowding have a negative impact on broiler farmers' bottom lines and overall income [37], but it also puts the birds' health at risk. Research shows that broilers are more likely to experience effects of heat stress due to overcrowding, including decreased digestion and absorption, mucosal injury, and compromised intestinal processes [40]. Intestinal mucosal injury in broilers is closely linked to the increased release of corticosterone, which is caused by stress connected to high stocking density. This stress includes factors like competition for feed and water, elevated ambient temperature, and increased litter moisture content and ammonia levels [41]. One of the most important parts of rearing broilers at a high stocking density is the effect it has on carcass yield and meat quality [42]. Highlighting the need to resolve welfare concerns in chicken production methods, the convergence of heat stress and high stocking density intensifies these issues.

4. Economic Impact and Industry Resilience: Farmer, Industry, Country and Food Safety

The inadequate conversion of chicken feed into meat results in declines in productivity, ultimately causing considerable financial losses. For chicken producers in the United States, an annual cost reduction of about USD 50 million is anticipated for each one percent increase in feed conversion [12]. These obstacles are further compounded by heat stress, which in the chicken business alone results in annual economic losses of USD 128 to 165 million [43]. The ramifications of this phenomenon extend to the poultry business in the United States, where an estimated annual economic loss of USD 2.36 billion is incurred [11]. Chickens are susceptible to increased morbidity and mortality as a consequence of elevated ambient temperatures. Such practices endanger the well-being of chickens and have ramifications for human nutrition as well as poultry economic sustainability as a whole [9,44]. The financial repercussions highlight the critical nature of mitigating heat stress and improving feed conversion efficiency in order to ensure the long-term viability and profitability of poultry. Food safety is a top priority in today's food quality paradigm, and the global chicken sector is facing a significant problem in this regard—high heat stress [45]. The complicated relationship between stress and its potential negative impacts on food safety is becoming clearer. While multiple findings demonstrate a relationship between stress and disease carriage in farm animals, the particular mechanisms underlying this association remain unknown [11,46].

Transportation of broilers from farms to processing plants under high-temperature circumstances exacerbates the issue, leading to measurable decreases in meat quality [47]. The combination of stress and transportation underscores the varied character of the poultry industry's issues, which extend beyond on-farm factors. Foodborne bacteria such as Salmonella and Campylobacter colonize birds, posing a significant danger to both human health and the poultry and egg-producing industries. The spread of these diseases across the human food chain emphasizes the importance of resolving food safety issues in chicken husbandry. In the dynamic field of food quality concepts, food safety is a critical component. Recognizing the complex relationship between stress, transportation, and pathogen colonization is critical for developing comprehensive measures that protect both poultry health and the food supply chain's integrity [48]. As the industry faces these problems, a comprehensive approach that includes stress management, efficient transportation methods, and stringent disease control techniques is critical to ensuring the safety and quality of chicken products that reach consumers.

5. Impacts of Heat Stress in Broiler Production

5.1. Gut Health and Immune Function

a. Gut Health: The digestive tract of poultry contains a complex and diversified microbiota that interacts with the host in a bidirectional manner. Using the diet as a substrate and given the intimate interaction between the microbiota and the host, it is likely that a variety of host and environmental conditions, particularly heat stress, will have a major impact on the intestinal microbial community [49]. While it is becoming increasingly clear that heat stress has an impact on the structure and function of the gut microbiota, the precise mechanisms underlying these effects are still being studied and are not entirely known [50]. However, the intestinal tract is extremely sensitive to heat stress and all other forms of stress [51]. The efficient functioning of the intestinal tract is essential for the production of poultry since it greatly affects the birds' general well-being and productivity [52]. However, poultry farming places a premium on maintaining an intact intestinal barrier. The integrity of the intestinal barrier is compromised by heat stress leading to an increase in intestinal permeability. This is the process by which typically restricted molecules with large molecular weights (>150 Da) can diffuse immediately from the intestinal lumen to the bloodstream [53]. Heat stress causes morphological alterations and mucosal damage in the intestines of chickens because it reduces blood flow, nutrient and oxygen availability, and feed intake [54]. Ref. [55] reported that an increase in permeability and localized inflammation along the small intestine, which includes the duodenum, jejunum, and ileum, are significant consequences of heat stress on the intestinal barrier [56].

b. Immune Response: Numerous studies have explored the impact of stress on the immune response in animals, revealing intricate interactions between the central nervous system (CNS), endocrine system, and immune system [57,58]. The hypothalamic–pituitary–adrenal (HPA) and sympathetic–adrenal medullar (SAM) axes are the primary pathways through which the immune response can be influenced [59]. The presence of receptors for numerous neuroendocrine products of the HPA and SAM axes, such as cortisol and catecholamines, has been demonstrated to be present in lymphocytes, monocytes or macrophages, and granulocytes. These receptors have the ability to interfere with cellular processes, activity in the areas of trafficking, proliferation, release of cytokines, generation of antibodies, and cytolytic behavior [57,59,60]. Knowing how heat stress impacts the immune response in chickens has been the subject of recent research. Multiple studies have shown that heat stress weakens the immune systems of both broilers and laying hens. While different indicators have been used to identify this effect, such as lower thymus and spleen relative weights in laying hens, it has also been reported that broilers exposed to heat stress have lower lymphoid organ weights. Laying hens' liver weights are known to drop when they are subjected to prolonged heat stress. Broilers subjected to heat stress during either the main or secondary humoral reactions showed lower levels of total circulating antibodies and specific IgM and IgY concentrations [61–63]. Moreover, research has shown that heat-stressed laying hens have decreased humoral immune responses systemically and fewer intraepithelial lymphocytes and IgA-secreting cells in their digestive tracts [64,65]. Broilers that were heat stressed showed less antibody responses and were less able to phagocytize macrophages. Alterations in circulating cell levels were also brought about by heat stress, with an increase in the heterophil/lymphocyte ratio as a result of decreased lymphocytes and raised heterophils [66]. When birds experience severe heat stress, their bodies produce more reactive oxygen species (ROS), which causes oxidative stress. When there are too many reactive oxygen species (ROS) in the environment, it can harm hens and cause oxidative stress. This disorder develops when the bird's ability to deal with reactive oxygen species (ROS) is overwhelmed. Chickens experience oxidative stress when there is an overabundance of reactive oxygen species (ROS). Reactive oxygen species (ROS) overproduction causes this illness by taxing the bird's immune system to its breaking point. The immune system responds to these stresses by producing heat shock proteins (HSP). Members of this family include proteins like HSP70. These proteins aid in the correct folding of other proteins, stop misfolded proteins from clumping together, and speed up the breakdown of damaged proteins; they are essential for cell protection. Their primary function is to allow cells to deal with and recover from stress. When heat stress is applied to broilers and laying hens, research has revealed that their HSP70 concentrations rise. This suggests that their cells are responding by reducing the harmful effects of reactive oxygen species (ROS) [67]. The findings presented here highlight the multidimensional nature of heat stress's effect on chicken immunity.

c. Production Performance and Growth: A number of physiological reactions in chickens result from heat stress, all of which have a substantial effect on poultry output. As a consequence, avian neuroendocrine profiles are altered as the hypothalamic–pituitary–adrenal (HPA) axis is stimulated and feed intake is diminished. Although individual birds may exhibit differences in the duration and severity of these reactions to heat stress, the overall pattern remains consistent. The extent of these responses can be influenced by the severity and duration of the heat stress. Ref. [11] underscore the overall similarity of avian responses to heat stress, hence stressing the extensive ramifications of increased temperatures on the health and productivity of poultry. Several researchers in the poultry industry have investigated the influence of high temperatures on the health, physiology, and efficiency of chickens [68,69]. Ref. [70] discovered that broilers aged 42 days exposed to chronic heat had a 16.4 percent drop in feed intake, a 32.6 percent loss in body weight, and a 25.6 percent increase in the feed consumption ratio. Studies by [71] have shown that chronic heat stress in broilers can negatively impact fat metabolism, muscle growth, and meat quality due to electrolyte imbalance and activation of lipid peroxidation. Furthermore, ref. [72] observed that heat stress was associated with a decrease in protein content and an increase in fat deposits in birds. Increased mortality and welfare concerns have been associated with elevated ambient temperatures while transporting hens. There is frequently a correlation between increasing chicken weight and heightened death rates; specifically, heavier chickens are associated with more mortality. To address and reduce potential welfare difficulties and mortality risks, this highlights the significance of including environmental variables, particularly temperature, and the weight of broilers into transit protocols. Subsequent investigations and initiatives aimed at refining transportation conditions in light of these variables could potentially aid in the enhancement of poultry welfare enroute. The impact of heat stress on different commercial broiler strains is shown in Table 1.

Table 1. Impact of heat stress on different broiler strains. Each superscripts indicate the conclusion from each author and also the animal type/strain differs.

Strain	Sex	Housing Conditions	Negative Effects	References
Hubbard-Cobb	Male	Thermoneutral or heat-challenged condition	Increased feed intake and higher FCR in HS, mortality	[73]
Ross 308	Male	Thermoneutral group up to 35 days of age and then subjected to chronic HS (30 °C for 24 h/day)	[1] HS decrease in BW and feed consumption, [2] HS decreased daily weight gain, daily feed intake Increased FCR, increased mortality (5×), increase in rectal temperature	[1] [4] [2] [74]
	Mixed (males and female)	24 °C (control), 34 °C HS	HS decreased body weight gain in male but had no effect on body weight gain in females, reduced feed consumption	[75]
Cobb	Mixed (male and female)	20 °C (thermoneutral; TN conditions), or 27.8 °C (HS conditions)	Lower final BW, BWG, FI, and FE	[76]
Cobb500	Male	[1] Thermoneutral temperature at 24 °C or heat stress at 35 °C [2] Temperature conditions (thermoneutral and heat stress) [3] Cyclic heat stress (HS, 35 °C from 9:30 am–5:30 pm); however, the rest of the chamber were maintained at thermoneutral conditions (24 °C, TN)	[1] FBW, BWG, and FI reduced by 20, 29, and 16 percent [2] Lower feed intake, BW gain, and deteriorated feed conversion values [3] HS reduced feed intake and body weight, body part weights	[1] [14] [2] [77] [3] [78]

Table 1. *Cont.*

Strain	Sex	Housing Conditions	Negative Effects	References
	Female	23 °C (unheated), 34 °C for 7 h each day (cyclic heat), 34 (constant heat)	Reduction in feed intake and decrease in growth rate	[79]
Ross-708	Mixed sex	35 ± 2 °C from d 1 (HS) and thermoneutral conditions	HS-CONT unsupplemented group had 18.3% less BW gain on d 21 and 49.6% less on d 42 as compared with the CONT group	[71]
El-Salam strain, a white feather crossbred	Male	HS (38 °C and 60% RH)	BWG decreased, F:G was impaired. No effect on apparent digestibility of DM, OM, EE, and C HS + AA: increased BWG and FI and improved F:G	[11,80]
Ross PM3		High ambient temperature (35 to 37 °C for 8 h/d vs. thermoneutral for 16 h/d)	Decreased FI and weight gain	[81]
		33 °C as HS, 12 °C as cold stress, 23 °C (thermoneutral)	Lower feed intake, lower body weight, higher FCR and water intake	[82]

Health Challenges and Disease Susceptibility: Public health and economic implications in chicken production are substantial due to the colonization of birds by foodborne bacteria such as Salmonella and Campylobacter, which subsequently spreads along the human food chain. Foodborne illnesses [48,83] are frequently associated with consumption. Heat stress may have adverse effects on food safety via a variety of different mechanisms, according to an expanding body of literature. While evidence exists to correlate stress with pathogen carriage and shedding in farm animals, the precise mechanisms by which these processes occur are still unknown [84]. The occurrence of horizontal transmission, pathogen colonization, and increased fecal shedding are all associated with heat stress, which consequently increases the likelihood of contamination in poultry products [85]. In the past, the aforementioned characteristics of poultry infections were predominantly ascribed to the immunosuppressive effects of stress-associated hormones and mediators. In contrast, "microbial endocrinology", a new perspective that has evolved in recent years, proposes that stress-associated hormones and mediators have a direct impact on bacterial pathogens [86]. Salmonella and Campylobacter, among others, are able to boost their proliferation and pathogenicity by exploiting neuroendocrine abnormalities that emerge from the stress response of the host, according to recent research [86]. This revelation emphasizes the complex interaction among stress, the neuroendocrine system of the host, and the behavior of foodborne bacteria, thereby illuminating possible strategies to enhance chicken food safety. It is essential to recognize that heat stress has the ability to affect the interactions between hosts and pathogens. Particularly susceptible to stresses, the gastrointestinal tract undergoes numerous changes, including modifications in the protective microbiota and a reduction in the integrity of the intestinal epithelium [87]. An ex vivo investigation revealed that tissues derived from heat-stressed birds exhibited enhanced mucosal attachment of Salmonella Enteritidis. This finding suggests that elevated environmental temperatures might have an impact on the bacterial concentrations in bird feces, as well as influence the duration and magnitude of contamination in the vicinity [46]. Notwithstanding these results, a number of epidemiological investigations have documented seasonal variations in the prevalence of Salmonella and Campylobacter in broilers, as well as in chicken products sold at retail outlets [88]. This underscores the significance of taking environmental factors, such as heat stress, into account when examining pathogen dynamics in poultry production.

It further underscores the necessity for ongoing research to comprehensively comprehend the intricate relationship among pathogen behavior, host reactions, and heat stress [89].

Meat Quality and Carcass Characteristics: Modern broiler strains which have undergone rigorous breeding and genetic modifications are more susceptible to heat stress and oxidative damages than their ancestors [90]. HS drives up production costs and management, with an attentive decrease in the quality of the meat due to their susceptibility to heat as a result of quick metabolism and rapid growth therefore making their meat prone to oxidative reactions due to the presence of unsaturated muscle lipids [91]. Modern rapid-growing broiler strains are more vulnerable to heat stress and oxidative damage than their ancestors. Stress-induced effect on meat quality is occasioned by several contributing secondary factors and conditions such as lower pH, denatured muscle protein and increased drip loss, color (L*) value and shear force [92]. Muscle pH is the most broadly accepted chemical indicator that influences meat quality, and it fluctuates due to accelerating anaerobic glycolysis in muscle during and/or after slaughtering which results in decrease in muscle pH [92]. A sharp drop in pH results in changes in quality attributes of meat and is associated with low color (a* = redness), high drip (loss of proteins) and cooking losses in chicken breast meat [93]. The discoloration in meat occurs as a direct effect of myoglobin oxidation which results in lower redness [94] as increased lipid oxidation elevates the production of malondialdehyde aided by the presence of unsaturated muscle lipids in broiler meat. Acute heat stress significantly increases the amounts of malondialdehyde and carbonyls in muscle. Rapid postmortem glycolysis leads to accumulation of H + in muscle from adenosine triphosphate (ATP) hydrolysis. In heat-stressed chickens, the rate of anaerobic glycolysis to generate energy (ATP) by breaking down muscle glycogen is faster than in normal birds [95].

Responses induced by heat stress affect both ante- and post-mortem muscle metabolism, which result in a decreased pH, increased rate and extent of glycogen breakdown, and drip loss [96]. The accumulation of these events depresses the quality and shelf-life attributes of meat and its products. The creation of acute and chronic stress responses, a decrease in muscle glycogen and protein concentration, and a redistribution of fat storage are some of the major physiological and metabolic reactions linked to heat stress in poultry and their impact on meat quality. HS-induced oxidative stress results in a rise in reactive oxygen molecules and a fall in blood vitamin and mineral concentrations that support the immune system of an animal [97]. The continuous buildup of oxidation in the system harms cell membrane and mitochondrial integrity and causes cell damage through lipid peroxidation [98,99]. Oxidation of lipids leads to discoloration, drip losses, off-odor and off-flavor development in meat [100]. These effects of pre-slaughter stress are mainly attributed to alterations in the activities of adenosine triphosphate (ATP) and muscle glycogen reserves. Heat exposure can directly affect the metabolism of muscles and organs [101]. For example, when there is heat stress, there is a quick reduction in muscle pH resulting in a limited water-holding capacity which might exacerbate the risks of pale-soft exudative meat in broilers and turkeys [102]. Acute or brief heat stress in broilers from before to slaughter resulted in pale, mushy, and exudative meat alterations in meat quality [102]. It is well known that oxidative stress stimulates the production of reactive oxygen species (ROS), induces lipid peroxidation, and causes protein and DNA damage [103]. Additionally, heat stress increases the accumulation of lactate and lowers the pH; as pH declines, ROS production is accelerated resulting in protein oxidation. ROS can lead to diverse functions, including inhibition of enzyme activities, aging, loss of protein functions, and development of PSE conditions [104]. Elevated body temperature enhances the generation of ROS via accelerated rapid metabolic reactions in cells and tissues. Mitochondria is recognized to play a critical role in maintaining bio-energetic status under physiological conditions but becomes dysfunctional under acute heat stress leading to increased production of mitochondrial ROS in the skeletal muscle of chickens [105,106]. Previous studies have demonstrated that the production of reactive oxygen species (ROS) by high ambient temperature leads to oxidative stress. ROS cause lipid peroxidation in muscles, protein and liver damage, thereby triggering a serious impact on the growth of skeletal muscle [107]. Increased fat deposition and decreased muscle protein content are the results of high temperature differential disrupting lipolysis by suppressing enzymatic activities involved in lipid breakdown [108]. Reduced aerobic metabolism of fat and glucose and increased glycolysis as a result of ROS production compromising mitochondrial activity ultimately lead to low-quality meat with high drip loss and low pH [104]. Because it lowers the meat's acceptability, juiciness, and palatability, drip loss is associated with overall meat quality. It is one of the main problems with meat quality that animal scientists are working to fix, especially with chicken and pork [109]. Prior to bird slaughter, heat stress causes a rise in rigor mortis and metabolic rate, which denaturates proteins. Since protein plays a role in meat's ability to bind water, protein damage from a hot carcass inhibits protein's ability to do so, leading to a noticeable drop in meat content and insufficient water-holding capacity, as evidenced by increased cooking and drip losses [110].

5.2. Physiological Responses to Heat Stress

Physiological and Behavioral Responses: In order for animals to attain optimal production performance over long periods of time and in different environments, it is essential that they maintain a consistent body temperature. Intense thermoregulatory reactions are required for dispersing excess heat when ambient temperatures are high in the summer. Physiological changes include elevated heart rate, respiration rate, perspiration rate, and rectal temperature, and behavioral changes include stretching, sunning, drinking more, eating less, and panting [111]. Without endangering their well-being, these activities enable birds to triumph over the tremendous changes. The balance between heat loss and gain mechanisms is reflected in rectal temperature, which is a crucial physiological indicator for assessing thermal stress. Air sacs aid panting by increasing gas exchanges with air, which boosts evaporative heat loss through surface air circulation [112,113], thus panting is a good time to use them. Chickens are no different from any other animal in that they show changes in core temperature in reaction to outside stresses. In terms of core temperature, 41.2 degrees Celsius is the minimum acceptable for broilers and 42.2 degrees Celsius is the maximum. When birds are subjected to heat stress outside of their thermoneutral zone, though, these limitations become more pronounced. Under heat stress, broilers have a greater rectal temperature [114], which leads to an unintended rise in cloacal temperature [115]. A number of variables, including the birds' sex, age, strain, and weight, affect the rate at which their core body temperatures rise in response to heat stress [116]. The birds' level of heat stress can be determined by tracking their variations in core body temperature. Moderate heat stress is defined as a shift of 0.4–1 °C in core body temperature or severe heat stress as a change of >1 °C [117]. High temperatures affect poultry by activating the hypothalamic–pituitary–adrenal (HPA) axis and increasing corticosterone levels [118–120]. Triiodothyronine (T3) and thyroxine (T4), which are thyroid hormones, are vital to the physiology of chicken by controlling development and metabolic processes. T3 is the type that exerts direct biological activity on cellular metabolism, whereas T4 functions as a precursor that is transformed into T3 across different tissues. Hormones in chickens are of significant importance in processes such as feather formation, reproductive health, and body temperature regulation [121]. Their distinct physiological functions are influenced by their separate impacts, as illustrated by T3's function in cellular metabolism. The coordinated regulation of metabolic and developmental processes, which are essential for the optimal growth and overall health of chickens, is achieved through the combined activities of T3 and T4 [122]. The balance of thyroid hormones, triiodothyronine (T3) and thyroxine (T4), crucial for regulating body temperature and metabolism, is disrupted under heat stress. Studies consistently show decreased T3 levels in high temperatures, indicating thyroid dysfunction [119,123,124]. Effects on T4 levels vary across studies, with some reporting decrease, increase, or no change [11,125]. Disruptions in thyroid hormones, especially T3, impact the reproductive performance of chicken [126]. Chronic heat stress in broilers leads to endocrine changes, promoting lipid accumulation through increased de novo lipogenesis, reduced lipolysis, and enhanced amino acid catabolism [127].

Oxidative responses: In the poultry gut, oxidative stress is caused by pathogenic reasons, environmental variables such as heat stress, and dietary factors. Oxidative stress in the gastrointestinal tract (GIT) of chickens can be attributed to a multitude of variables, encompassing disease elements, dietary components, and environmental situations like heat stress. These pressures negatively affect the growth and production of broilers, in addition to the quality of the meat and eggs that are produced. Studies on heat-stressed broilers have revealed degenerative and oxidative changes in hepatic tissue, downregulation of antioxidant enzymes, and upregulation of HSPs and HSFs [127–139]. Chronic heat stress impacts the gene expression levels of key regulators such as Nrf2, NF-κB, HSP70, HSP90, and HSF3, leading to liver oxidative damage and an inflammatory response. Mycotoxins in poultry diets, such as aflatoxin B1, represent another stress factor causing hepatic oxidative damage, impaired mitochondrial function, increased ROS generation, and downregulation of Nrf2, SOD, CAT, and GPx [130]. The ramifications of heat stress on broilers are diverse, including modifications in feed consumption, impaired growth capabilities, immunosuppression, hypoxia, and heightened mortality [1]. Additionally, heat stress has a detrimental impact on the quality of chicken meat [8]. The adverse effects on intestinal morphology are evident in the reduced crypt depth, mucous area, and villus height observed in broilers subjected to cyclic heat stress. The modifications observed in the GIT underscore the complex correlation between environmental stressors, specifically heat stress, and the physiological welfare of poultry. This underscores the importance of implementing comprehensive management approaches to alleviate oxidative stress and its consequential effects on poultry production. These findings underscore the intricate interplay between environmental stressors, oxidative stress, and the regulatory pathways involved in cellular responses in poultry. The delicate balance between these factors determines the overall health, welfare, and performance of poultry in the challenging conditions of modern farming practices.

6. Mitigating Techniques and Strategies

Genetic and Breeding Approaches: Genetic selection is a promising tool in developing heat-resistant breeds. Interestingly, ref. [131] demonstrated that fine mapping with quantitative trait loci (QTL) can enable efficient screening of heat tolerance in birds. These results suggest that it is possible to use these genes to develop chickens that can withstand thermal challenges. The genetics of the commercial broiler business have primarily focused on achieving rapid weight gain and feed efficiency in the last 2–3 decades. Some of the genetic strategies include the following:

Marker-assisted selective breeding: Molecular markers have recently been developed to identify potential candidate genes associated with heat-tolerant characteristics for chicken bird selection to promote resistance to heat stress [132]. By boosting chickens' ability to survive in hot conditions, genetic potential can help the poultry industry improve overall poultry performance [133]. To establish thermotolerant breeds by marker-assisted selection, it may be necessary to identify and incorporate the appropriate biomarkers in breeding programs for thermal stress reactions in chickens [134]. For example, the HSP70 and HSP90 genes are known to protect the body from the negative effects of oxidative stress and are used as a marker for heat stress in chickens [135]. Heat shock proteins are widespread stress proteins found in all living cells. Living cells trigger a "heat shock response", which activates proteins to defend them from heat stress. The primary function of heat shock proteins is housekeeping; they maintain order in the cell by synthesizing other proteins while in a stressful environment or any pathological condition, their expression level increases, and they incline to attract immune cells at the respective site [136]. The molecular weight-classified HSPs were HSP40, HSP70, HSP90, HSP100, small HSPs, and chaperonins. HSPs are extracellular stress signals that activate immune cells in specific body areas amid stress and unwanted situations. Cell repair from HS damage requires

HSP70. HSPs are heat polypeptides created by high temperature, hence increased HSP expression during HS improves living cell tolerance to HS. One of the most studied heat shock protein families, HSP70 and 90, regulate cell cycle and cell tolerance [137]. In a heat stress environment, HSPs fix damaged proteins. As molecular chaperones, HSP 70 is low in normal climates, but muscle HSP levels rise rapidly during cellular stress (hyperthermia, oxidative stress, changes in pH). High HSP levels alter gene expression, remodeling skeletal muscles [138]. Many broiler chicken investigations have shown that the HSP family repairs damaged cells, and HSP70 is expressed in the muscles, liver, heart, kidney, and blood vessels during acute stress [139]. During AHS, broiler chicken muscle cells express HSP70 and 90. AHS also induces chicken kidney HSP70 and 90 protein and mRNA expression.

The naked neck gene: The naked neck (Na), dwarf (Dw), and frizzle (F) genes of chickens are thought to be candidates for thermal stress resistance. They represent a suitable, sustainable, and cost-effective solution to the heat stress problem. Utilizing favorable heat-resistant genes such as slow feathering (K), frizzle (F), and naked neck (Na) may increase heat tolerance, growth performance, and reproductive characteristics in chickens [140,141]. Homozygous chickens with the naked neck gene (Na) have roughly 40% less feather coverage than normal plumaged chicken, while heterozygous siblings have between 20% and 30% less [140,141]. When subjected to high ambient temperatures, their reduced plumage allows them to disperse heat. The Na chicken line has also exhibited improved immunity and output. When exposed to heat, birds with Na surpassed other feathered birds, according to research. This gene has been revealed to survive harsh environmental changes like high temperatures [142]. The lack of feathers on the neck increases the available space for heat dissipation and prevents heat insulation, allowing birds to survive the sweltering heat. Refs. [143,144] observed that in indigenous Egyptian breeds grown in hot stress, the gene improved thermotolerance via increasing HSP70 gene expression. Compared to other species, naked-necked birds exhibited significantly lower H/L ratios and total plasma cholesterol throughout the summer [145]. Under heat stress, laying chickens with the naked neck gene had higher egg weights, quality, and number [146]. The Na gene could be regarded as a marker gene because different genotypes can be identified by visual inspection of their feathers after hatching.

The frizzle gene (F): The frizzle gene is another potential target for creating heat-tolerant chickens. The frizzle gene (F) is a partly dominant gene that lowers feather intensity, boosting birds' ability to dissipate excessive heat [144]. According to [15,145], the frizzle (F) gene causes the form of the feather to curl, reducing its weight and increasing heat emission from the body. Adult frizzled birds' feathers (FF and Ff) are more brittle and curled than in the normal condition (ff). With the exception of sexual maturity under heat stress, ref. [146] discovered a significant interaction between environmental temperature and feathering genotype (FF) in all reproductive variables, including chick production, hatchability, and egg production. The scientists reported that regularly feathered chicken showed a notable drop in all reproductive indices at higher temperatures when compared to frizzle-feathered chicken. The findings of [147] demonstrated that frizzle layers outperformed conventional feathered chickens in a climate chamber at high temperatures. Commercialization of naked-necked and frizzled birds will benefit developing countries in tropical regions. The combination of the Na and F genes results in increased heat dissipation and low feather intensity, particularly when the Na gene is homozygous (NaNaF-), and the double heterozygous (Na/Na F/f) broiler has an additive effect [148].

Nutritional Interventions and Feed Modifications: Broiler feed conversion is prone to variability because of temperature fluctuations at both the seasonal and ambient levels. Research consistently indicates that elevated temperatures reduce the effectiveness of feed energy conversion into productive output. Although a reduction in feed intake does contribute to the diminished performance of broilers under high temperatures, the raised temperature itself is primarily responsible for a substantial percentage of the effect [149]. To address these obstacles, it is customary in the formulation of broiler feeds intended for hot climates to augment the energy content by the use of fat. In addition to increasing energy consumption, this lessens the specific dynamic effect of the diet, hence assisting birds in managing heat stress more effectively [149]. It is advisable to implement nutritional modifications, such as increasing protein intake and decreasing fat content, in order to mitigate the detrimental consequences of heat stress [150]. Vitamin supplementation, customized to specific needs and situations, is effective in minimizing the negative effects of heat stress on poultry, improving performance, and boosting immune function [149]. Proper management and awareness of each vitamin's role helps to improve the health of heat-stressed birds.

In addition to augmenting energy intake, the inclusion of fat in the diet also improves the energy content of other components present in the feed. It has been shown to enhance nutritional utilization by decreasing the rate of food passage in the gastrointestinal tract [151,152]. It has been demonstrated that lower protein diets supplemented with restricted amino acids produce superior effects during periods of high temperature than high protein diets. The objective of these dietary approaches is to enhance the efficiency of feed conversion while minimizing the adverse effects of heat stress on the performance of broilers (Table 2).

Table 2. An overview of nutritional strategies to reduce heat stress in birds.

Nutritional Strategies	Methods/Dosage	Benefits	Reference
Restricted feeding and watering	Increase water intake, restrict feed or intermittent feed. Feed withdraw from 9:00 am to 4:30 pm and provide cool water at this time.	Effective in lowering heat stress mortality. Starved birds produce 20% to 70% less metabolic heat than fed birds.	[153,154]
Vitamins and mineral supplementation	Supplementing poultry birds with vitamins C, E, and A, as well as minerals such as Fe, Zn, Se, and Cr in drinking water.	It reduces mortality and promotes growth during heat stress.	[155]
	Increasing Zn (0, 30, and 60 mg/kg) and vitamin E (0, 250, and 500 mg/kg) supplements to diet.	Enhanced FI consumption, development rate, and carcass quality in a linear fashion.	[156]
Vitamin A	Vitamin A (15,000 IU) supplementation with drinking water.	Enhanced live weight gain, feed efficiency, and carcass characteristics, as well as a reduction in serum MDA concentrations.	[157]
Vitamin C Ascorbic acid (AA)	High dose (1000 mg/kg) of AA supplementation in water.	Increases broiler performance by decreasing heat stress reactions and lowering plasma corticosteroid levels.	[158]
		Decreases the respiratory quotient in broiler chickens that are under a lot of heat stress by focusing on increasing fatty acid oxidation.	[159]
Vitamin E	High dietary supplemental level of Vitamin E (250 mg/kg diet) into feed.	Cell membrane damage and lipid peroxidation are prevented by vitamin E in the liver.	[160]
Prebiotics (Bospro, Lacto-Sacc)	Supplementation of 1 g/kg lactobacillus culture in the diet.	Antibiotics, probiotics, and postbiotics can all influence the gut microbiota under heat stress.	[98]
Probiotics	Use of prebiotic and probiotics.	Modify gut microbiota to improve health status and performance throughout the summer season.	[161]
Probiotic mixture	(*L. pentosus* ITA23; *L. acidophilus* ITA44).	Increased the number of enterococcus, bifidobacteria, and lactobacillus in the intestines of heat-stressed broilers. An increase in the antioxidant capacity of the liver.	[162]

Table 2. *Cont.*

Nutritional Strategies	Methods/Dosage	Benefits	Reference
Probiotic mixture	(*B. licheniformis*, *B. subtilis*, and *L. plantarum*).	Enhanced the viable populations of lactobacillus and bifidobacterium in the small intestine, while coliforms reduced in broilers subjected to heat stress. Intestinal barrier function is improved and jejunal villus height is increased.	[163]
Lactobacillus-based probiotics	(*L. plantarum*, *L. acidophilus*, *L. bulgaricus*, *L. rhamnosus*, *B. bifidum*, *S. thermophilus*, *E. faecium*, *A. oryzae*, and *C. pintolopesii*).	In the duodenum and ileum of broilers that had lost height, depth, and surface area due to heat stress, the changes were reversed. Kept the goblet cells performing their function.	[164]
Probiotic *B. subtilis*		Broilers exhibit an elevated antibody response to NDV subsequent to heat stress.	[165]
Herbal supplements and phytogenic	Using phytochemicals such as lycopene, anthocyanins, and gamma-glutamylethylamide, which can be found in papaya, guava, apricots, pink grapefruit, watermelon, and tomatoes.	Reduce heat stress and enhance performance. Increasing the level of serum growth hormone and alerting of heat shock genes in the immune system.	[166–168]
Ginger	The inclusion of ginger in the diet of broilers experiencing heat stress at a concentration of 2%.	Enhance biochemical blood parameters while bolstering performance and immunity.	[169]
	Adding 5 g of ginger per kilogram of feed to the diets of broilers.	The activities of GSHPx and SOD were enhanced and the MDA of broilers was decreased for a duration of 3–6 weeks.	[170]
Cinnamon powder	0.5% cinnamon powder into a system.	Blood variables are enhanced and performance is improved. It was found that cinnamon supplements helped keep balance because of the lower pH and DM levels caused by heat stress.	[171]
Black cumin (Nigella sativa) seeds (NSS)	Adding black cumin meal (10% to 20% of the feed), seeds (1% to 2% of the feed), or oil (0.5% to 1% of the feed) during very hot conditions.	Reduced oxidative stress, raised serum MDA levels, and improved the birds' performance. It also helped the health of brain and spinal cord tissues.	[172,173]

7. Climate Change and Future Projections

Amidst the increasing difficulties presented by climate change, the broiler chicken industry in the United States is devising strategies to achieve sustainable practices and transformative resilience. In anticipation of the anticipated consequences of increased frequency, intensity, and duration of heat stress, the poultry industry is actively adopting constructive future strategies. Infrastructure improvements and technological advancements emerge as critical components of this paradigm shift. Sophisticated ventilation systems, intelligent housing designs, and precise climate control mechanisms are being developed by the industry [174]. These advancements not only alleviate the consequences of heat stress on broiler chicks but also establish conditions that are favorable for their maximum development. The concept of genetic selection in relation to climatic resilience becomes a fundamental pillar of progress. Efforts are being made by scientists and breeders to generate broiler chicken lines that possess improved heat tolerance [175]. Adopting this proactive stance guarantees that forthcoming generations of broilers will be more adept at flourishing amidst the ever-changing environmental circumstances, thus promoting sustainability and adaptability. Environmental stewardship and sustainable practices are emerging as guiding principles. The agricultural sector's transition towards environmentally sustainable and resource-efficient practices demonstrates a dedication to accountable farming. The environmental well-being and longevity of broiler chicken production are enhanced by the implementation of sustainable measures such as optimized feed formulas and waste management systems [176]. Future investment in climate-resilient poultry breed research is crucial. Ongoing research contributes to the advancement of knowledge regarding the complex interplay among genetics, climate, and poultry health. This understanding not only strengthens the fortitude of broiler chickens but also provides insights for more extensive approaches to sustainable poultry agriculture. Fostering policy support and incorporating climate measures are fundamental components that establish a conducive milieu for the poultry sector. Policymakers are increasingly recognizing the imperative of harmonizing agricultural policy with measures for climate adaptation. To encourage the adoption of sustainable and climate-smart practices, they are offering vital incentives and tools.

8. Future Directions

The resolution of heat stress issues in broiler production necessitates the implementation of inventive approaches guided by comprehensive study and technical progressions. By combining intelligent sensors and real-time data analytics, precision agriculture optimizes environmental conditions for the comfort and performance of broiler chickens. The development of genetically resilient broiler strains that can endure various climate-related difficulties and maintain productivity is entirely dependent on genomic selection for multi-trait resilience, which extends beyond mere heat tolerance. The implementation of climate-adaptive housing designs, which incorporate innovative ventilation systems and modular structures, plays a crucial role in mitigating the adverse effects of severe temperatures on broiler welfare and fostering a favorable living environment. Nutritional techniques that prioritize the inclusion of immune-boosting components and antioxidants in broiler diets are of utmost importance in minimizing the physiological consequences of heat stress [11].

9. Conclusions

Broiler production faces heat stress, which requires scientific advances and adaptive solutions. Today, heat stress requires a complex approach, echoing Darwin's "Difficulties of the theory". A revolutionary resilience journey is built on precision agriculture, genetic selection, and sustainable practices. With sophisticated sensors and real-time data analytics, precision agriculture optimizes climate management for broiler well-being. Genomic selection helps broiler breeds withstand climate change's many difficulties.

Climate-adaptive housing delivers broilers with physiologically adjusted habitats in this environment. Nutritionally, antioxidants and immune-boosting ingredients protect broilers from heat stress. In broiler production, agroecological approaches offer harmony and sustainability. Comprehensive policies assist the industry's harmonized climate response at the crescendo. As the sector navigates heat stress, these coordinated efforts move broiler production toward resilience and sustainability. Innovation, genetics, nutrition, and policy help the broiler business push past adaptation and embrace climate change for sustainable growth.

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