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Enhancing Heat Stress Resilience in Broiler Chickens Through the Use of Probiotics and Postbiotics: A Review

S. Raknga[a], Y. Zhu[a], S. Okrathok[b], C. Pukkung[a], & S. Khempaka[a,*]
[a] School of Animal Technology and Innovation, Institute of Agricultural Technology, Suranaree University of Technology, Nakhon Ratchasima, Thailand
[b] Animal Production Innovation and Management Division, Faculty of Natural Resources, Prince of Songkhla University, Songkhla, Thailand
*Corresponding author: Khampaka@sut.ac.th
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ABSTRACT

The broiler industry is currently the most important and rapidly growing livestock sector worldwide. However, it faces critical environmental issues, especially heat stress (HS). HS adversely affects the bird's physiological and behavioural status, welfare, and growth performance, leading to numerous economic losses. Nevertheless, a limited understanding remains of the deep physiological and cellular responses related to energy formation and gut health. Therefore, the purpose of this review is to gain a better understanding of how HS affects broilers and to explore the potential of probiotics and postbiotics in mitigating HS effects, with a primary focus on antioxidant capacity, heat shock proteins (HSPs), gut health, and growth performance in HS-exposed broilers. HS induces various physiological and cellular responses related to energy metabolism, antioxidant defense, gut health, and inflammation. Probiotics and postbiotics, whether in single or mixed strains (such as *Saccharomyces cerevisiae, Bacillus subtilis, Lactobacillus acidophilus, L. plantarum,* and *Enterococcus faecalis,* etc.), have been shown to increase antioxidant enzyme activity, down-regulate HSP70 mRNA expression, and improve gut health through the enhanced gut morphology, strengthened barrier integrity, reduced inflammation, and restored gut microbial balance. Consequently, these benefits can lead to the enhanced growth performance in heat-stressed broilers. This indicates that probiotics and postbiotics hold promise as alternative feed additives to antibiotics for alleviating the negative effects of HS in the future. However, probiotics, being living microorganisms, are more sensitive and require conditions for viability and colonization in the gastrointestinal tract. Therefore, for practical application, postbiotics may offer greater effectiveness due to their safety, longer shelf life, and ease of storage, handling, and transportation.

Keywords: broilers; heat stress; gut health; postbiotics; probiotics

INTRODUCTION

Heat stress (HS) is defined as a condition where the birds are unable to maintain a balance between heat production and heat loss in their bodies (Wasti *et al.,* 2020). It is one of the most critical environmental stressors challenging agricultural and animal production systems worldwide, particularly for broiler chickens in tropical and arid regions (Kpomasse *et al.,* 2021; Thornton *et al.,* 2021; Oluwagbenga & Fraley, 2023; Apalowo *et al.,* 2024). HS induces the production and accumulation of reactive oxygen species (ROS) in cells beyond the capacity of the body's defense mechanisms for elimination. This predisposes cells to oxidative stress (OS), resulting in deleterious effects on damaged cells, such as gut barrier integrity and inflammation, and interferes with gut microbial homeostasis (Apalowo *et al.,* 2024). Consequently, it adversely affects nutrient utilization, growth performance, and survival rate (Attia *et al.,* 2017; Ranjan *et al.,* 2019; Vandana *et al.,* 2021; Oluwagbenga & Fraley, 2023; Iraqi *et al.,* 2024). Various feed additives, such as vitamins, minerals, phytogenics, prebiotics, probiotics, synbiotics, as well as antibiotics, have been widely used to resolve this problem (Roy *et al.,* 2015; Zhang *et al.,* 2017; Humam *et al.,* 2019; Vandana *et al.,* 2021; Attia *et al.,* 2023). However, the prolonged use of antibiotics as feed additives has resulted in the suppression of natural immunity, dysbiosis (by reducing gut microbiome diversity, which plays an important role in communicating with immune cells), the emergence of antibiotic-resistant bacterial strains, and increased the occurrence of antibiotic residues in animal products, which in turn facilitates the transfer of antibiotic resistance genes to consumers (Crisol-Martínez *et al.,* 2017; Bacanli & Başaran, 2019; Ma *et al.,* 2021). Therefore, in recent years, research has increasingly focused on finding safer alternatives to antibiotics, and natural products such as phytogenics

and probiotics have garnered significant attention (Kers *et al.*, 2018; Humam *et al.*, 2021; Danladi *et al.*, 2022; El-Sabrout *et al.*, 2023).

Probiotics are live non-pathogenic bacteria that benefit host animals by improving gut health, and positively influencing growth performance (Kers *et al.*, 2018). Several studies have reported that probiotics possess antioxidant capabilities and can alleviate the deleterious effects of HS in broiler chickens (Wang *et al.*, 2018; das D. Ribeiro *et al.*, 2023; Sumanu *et al.*, 2023ab). In addition, previous studies have indicated that dietary supplementation of probiotics obtained from *Bacillus subtilis* can enhance gut health by improving morphology and microbial population, antioxidant enzyme activity (glutathione peroxidase, GPx and superoxide dismutase, SOD), and growth performance of heat-stressed broilers including the downregulation of the hepatic mRNA expression level of heat shock protein (HSP) 70 (Cramer *et al.*, 2018; Wang *et al.*, 2018). Recent evidence suggests that feeding probiotics derived from *Saccharomyces cerevisiae* can reduce lipid oxidation in heat-stressed broilers (Sumanu *et al.*, 2023a). Likewise, the dietary inclusion of a mixture of multi-strain probiotics (*Lactobacillus acidophilus*, *L. plantarum*, and *Enterococcus faecalis*) has been shown to improve gut morphology, reduce pro-inflammatory cytokines (interleukin 6, IL-6 and tumor necrosis factor-alpha, TNF-α), and increase anti-inflammatory cytokine (interleukin 10, IL-10) in the blood of heat-stressed broilers, including the upregulation of genes associated with gut barrier integrity (Li *et al.*, 2020b, 2022). Nevertheless, the use of probiotics is still controversial regarding the risk of horizontally transferring antibiotic-resistant genes between organisms (Shazali *et al.*, 2014; Li *et al.*, 2020a; Xia *et al.*, 2024). In addition, the pelleting process, which involves high pressure, a temperature of 90 °C, and unsuitable storage conditions, can affect the viability efficacy of probiotic bacterial cells (Amerah *et al.*, 2013).

Postbiotic is a new technical term defined by the International Scientific Association of Probiotics and Prebiotics (ISAPP) in 2021. Postbiotics are non-viable products derived from beneficial bacteria composed of inanimate microbial cells, microbial cell fragments, and metabolites (Salminen *et al.*, 2021). Previous studies have demonstrated that postbiotics can exert relevant biological responses and contribute to restoring intestinal homeostasis, similar to probiotic bacteria (Liu *et al.*, 2020; Salminen *et al.*, 2021; Xia *et al.*, 2024). Especially, dietary postbiotic derived from *L. plantarum* have shown the ability to increase antioxidant activity (including total antioxidant capacity, T-AOC; catalase, CAT; glutathione, GSH, and GPx), improve gut morphology, reduce intestinal inflammation (by up-regulating IL-10 and down-regulating TNF-α genes), and improve the caecal microbial population of heat-stressed broilers when compared to antibiotic and vitamin C (Humam *et al.*, 2019, 2021). Additionally, postbiotics exhibit the ability to reduce hepatic mRNA expression of HSP70 (Humam *et al.*, 2021). Recently, *L. plantarum* postbiotics have been reported to promote growth performance and gut health in broilers under normal conditions by improving gut morphology, intestinal antioxidant capacity, microbial balance, and barrier integrity genes (Chang *et al.*, 2022). Similarly, Xia *et al*. (2024) demonstrated that *L. acidophilus* improves feed efficiency, digestive enzyme activity, and immunity, promotes gut health and microbiome balance and reduces inflammation by lowering pro-inflammatory cytokines in rabbits.

Therefore, the purpose of this review is to provide a better understanding of how HS affects broilers and to explore the potential of incorporating probiotics and postbiotics into diets to alleviate the HS effects, with a primary focus on antioxidant capacity, HSPs, gut health, and growth performance in broilers exposed to HS.

Challenges of Broiler Production Under Heat Stress Conditions

The increase in demand for broiler production aligns with the expected growth in the world population, which is projected to reach between 9 and 10 billion by 2050. The population expansion necessitates an increased focus on sustainable and efficient broiler farming to fulfill the growing demand (Kleyn & Ciacciariello, 2021). To date, breeder companies have consistently engaged in selecting and developing the genetics of breeder lines to achieve high feed efficiency and rapid growth within a short timeframe, aiming to meet the global demand (Tavárez & Santos, 2016). However, the broiler production sector is increasingly at risk of facing the challenges of severe global warming and climate change year by year, which adversely affects feed intake (FI), growth performance, and in extreme cases, compromised welfare or even death, leading to numerous economic losses (Nawab *et al.*, 2018; Kpomasse *et al.*, 2021; Thornton *et al.*, 2021). In addition, the improved broilers production traits are associated with a rapid metabolic rate (Hartcher & Lum, 2020), which causes an increase in the production of body heat, making it harder for birds to maintain core body temperature and more susceptible to various stressors such as climate change, ventilation and temperature control failures, high stocking density, and alternative production systems that create a challenge for efficient environment controls, and frequently predisposed to HS in poultry production (Kalmar *et al.*, 2013; Hartcher & Lum, 2020; Oluwagbenga & Fraley, 2023). HS causes physiological changes (such as OS, acid-base imbalance, and suppressed immunocompetence), neuroendocrine, and behavior changes as well as impaired gut health and microbiota (Wasti *et al.*, 2020; Liu *et al.*, 2022).

In-depth, under thermoneutral zone (TNZ) conditions, the activation of nuclear factor erythroid 2-related factor 2 (Nrf2), a transcriptional factor for stress responses, induces the synthesis of antioxidant enzymes that help to manage the ROS produced within cells. However, during HS exposure, there is an increase in the generation of free radicals in the mitochondria that the body's defense mechanisms are able to eliminate. This leads to a decrease in the effectiveness of the antioxidant defense systems, which damages all components of the cells, especially the most important and responsive organs like the intestinal tract. As the intestinal tract plays an important role in the digestion and

absorption of nutrients, it can also act as the first line of defense to prevent pathogens, toxins, and lipopolysaccharides (LPS) from passing into the bloodstream, and there is a risk of a deleterious effect on the overall health and growth performance of the birds (Wasti *et al.,* 2020; Oluwagbenga & Fraley, 2023). Therefore, HS represents a critical issue that requires effective solutions to combat and alleviate its impact. Among various strategies, nutritional management emerges as one effective and simple approach, such as restricting feed, reducing protein content, increasing fat in diets, and supplementing with vitamins, minerals, osmolytes, and phytogenics (Abdel-Moneim *et al.,* 2021). As HS extensively damages gut function, the use of probiotics or postbiotics may serve as an effective method to mitigate its deleterious effects (Humam *et al.,* 2021; Li *et al.,* 2022).

Physiological and Cellular Responses of Broilers to Heat Stress

The negative effects of HS have been widely reported on the behaviour, physiology, health, production, and welfare of poultry birds. In this review article, we will focus on the physiological and cellular responses related to energy formation and gut health under HS conditions.

The birds are endothermic homeotherm animals that lack sweat glands when exposed to HS and attempt to maintain body temperature through increased respiration, panting, and wing spreading, including reducing FI to minimize heat increments associated with nutrient metabolism, particularly protein sources, as the energy demands for thermoregulation escalate (Lara & Rostagno, 2013; Wasti *et al.,* 2020; Abdel-Moneim *et al.,* 2021). In addition, prolonged panting causes a relative loss of carbon dioxides (CO_2) and an increase in bicarbonate (HCO_3) in the blood, resulting in respiratory alkalosis (Vandana *et al.,* 2021). This alteration in blood chemistry modifies the ionic balance by decreasing levels of Na^+, K^+, Cl^- and pCO_2, which are crucial roles for regulating mineral and calcium (Ca^{2+}) balance, leading to a decrease in intracellular Ca^{2+} for adenosine triphosphate (ATP) synthesis (Chowdhury *et al.,* 2012; Vandana *et al.,* 2021).

Most cellular energy is produced through oxidative phosphorylation or the electron transport chain which occurs in mitochondria. When birds are exposed to severe and/or prolonged HS, there is a noticeable increase in cellular energy demand, which can be twice as high as normal (Teyssier *et al.,* 2022a). To meet this increased energy demand, the production of reducing equivalents such as NADH and $FADH_2$ rises, and the activity of enzyme subunits in the mitochondrial respiratory chain complexes is elevated. However, this heightened activity can lead to the increased proton (H^+) leakages across the mitochondrial membrane, which in turn increases the membrane potential and results in the overproduction of superoxide and the formation of ROS (Akbarian *et al.,* 2016). Excess ROS can cause damage to proteins, lipids, and nucleic acids, including reducing the efficiency of energy formation in the mitochondria and ultimately leading to the decreased ATP synthesis. In addition, ROS can act as a secondary messenger to trigger and modulate the cellular signaling pathway and transcription factors, of which activator protein 1 (AP-1), nuclear factor kappa B (NF-kB), and Nrf2 have been shown to undergo alterations in poultry under HS condition (Mujahid *et al.,* 2007; Yang *et al.,* 2019). The AP-1 functions modulate the expression of various genes (such as cytokines, growth factors, stress, etc.) in response to biological and environmental stimuli, whereas NF-kB is responsible for regulating various functions, including pro-inflammatory responses. Both transcription factors are involved in cell survival, differentiation, and growth (Akbarian *et al.,* 2016; Vandana *et al.,* 2021).

The HS condition affects the increase in body temperature and the bird's adaptive cardiovascular response, which increases blood flow to the external surface (skin) to promote body heat loss (Vandana *et al.,* 2021). However, a compensatory decrease in blood flow to intestinal organs, including the intestine, reduces oxygen availability and nutrient supply to the intestinal cells, which causes changes in morphology (Rostagno, 2020). The excessive production of ROS beyond the body's defense mechanisms leads to OS and inflammation (Belhadj-Slimen *et al.,* 2016), which causes damage to the intestinal mucosa and the tight junction proteins that play a crucial function in maintaining gut barrier integrity. Consequently, intestinal inflammation and leakage of toxins into the bloodstream can occur, thereby ultimately affecting nutrient digestion and utilization (Abdel-Moneim *et al.,* 2021). In poultry, several studies have noted that HS also alters the balance in intestinal microbial composition (Kers *et al.,* 2018; Metzler-Zebeli *et al.,* 2019), including growth performance (Cramer *et al.,* 2018; Ahmed *et al.,* 2019) as shown in Figure 1. It has been reported that broilers under HS showed increases in metabolizable energy intake (20.3%) and heat production (35.5%), alongside a decrease in energy retention (20.9%) and energy efficiency (32.4%) compared to a TNZ condition (Teyssier *et al.,* 2022a). Moreover, Teyssier e*t al*. (2022b) reported that HS decreased FI (47.1%), body weight (BW) (45.5%), and feed conversion ratio (FCR) (62.5%).

The Possible Mechanism of Action of Probiotics and Postbiotics to Alleviate Deleterious Effects on Heat-Stressed Broilers

Recently, numerous hypotheses have been discussed regarding how probiotics can mitigate problems caused by HS (Bai *et al.,* 2017; das D. Ribeiro *et al.,* 2023). For instance, it has been proposed that probiotics improve the activity of thyroid hormones, which are abnormally secreted during HS (Bayraktar *et al.,* 2021). Thyroid hormones, in general, play a significant role in regulating the body's metabolism. Triiodothyronine (T3) and thyroxine (T4) hormones are capable of maintaining intestinal tissues and enhancing the well-being of birds (Mullur *et al.,* 2014). Probiotics have been shown to downregulate HSPs mRNA expression, likely attributable to their enhancement of antioxidant enzymatic system and reduction in ROS accumulation, and this mechanism may assist cells in repairing damage, includ-

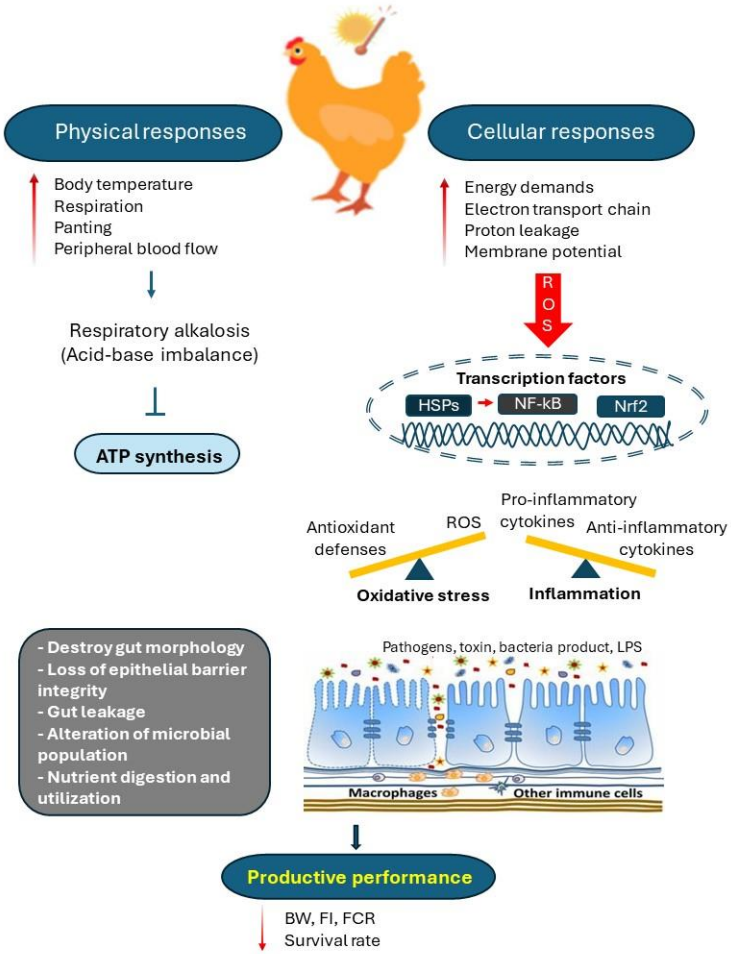

Figure 1. The physiological and cellular responses in heat-stressed broilers (modified from Koch *et al.*, 2019; Goel *et al.*, 2021).

ing the maintenance of gut barrier integrity (Deng *et al.*, 2012; Bai *et al.*, 2017). Furthermore, probiotics restore the composition of commensal gut bacteria, which play an important role in strengthening the gut barrier through various mechanisms, such as competitive exclusion and promoting undesirable conditions for pathogens. These beneficial mechanisms employed by commensal bacteria in colonization resistance include establishing a direct barrier against pathogens via competitive exclusion of both space and nutrients (Bauer *et al.*, 2018). Moreover, commensal bacteria continuously stimulate pathogens recognition receptors (PRRs), such as toll-like receptors (TLRs) on intestinal epithelial cells (IECs), which plays a crucial role in the first line of defense until more specific immunity develops, thereby promoting the production of mucins and antimicrobial peptides (AMPs) (Krysiak *et al.*, 2021). However, probiotic bacterial strains isolated from different parts (e.g., ileum and caecum) and poultry breeds (e.g., broilers, native chickens, laying hens), often exhibit varying adhesion abilities in the broiler's intestinal tract and may have different beneficial effects on gut health (Sirisopapong *et al.*, 2023). Therefore, the origin of the probiotics and their adhesion capabilities are important to consider for effective practical use.

Postbiotics have been reported to exhibit positive effects similar to probiotics, including immunomodulatory, antioxidants, and anti-inflammatory effects, as well as improvement in gut health and nutrient utilization, regulation of HSPs, and modulation of neuroendocrine responses (Piqué *et al.*, 2019; Zhu *et al.*, 2020; Humam *et al.*, 2021; Saeed *et al.*, 2023; Xia *et al.*, 2024). Based on the evidence and insights from previous publications, we propose two potential functions depending on the form of the postbiotics. The first function involves metabolites derived from beneficial probiotic bacteria, such as short-chain fatty acids (SCFAs), lactic acid, choline, antioxidants, enzymes, and AMPs. SCFAs such as acetate, propionate, and butyrate are important metabolites produced by probiotics, known for their effects such as serving as an energy source for the IECs, promoting gut health and integrity, and modulating the immune response during periods of stress (Shin *et al.*, 2023; Abd El-Aziz *et al.*, 2024). In addition, butyrate has anti-inflammatory properties and might reduce inflammation in the gut and other tissues during HS (Zmrhal *et al.*, 2023). Lactic acid, another metabolite produced by beneficial bacteria can also lower pH in the gut, creating an environment less favourable for pathogenic bacteria and promoting the growth of beneficial bacteria (Tang *et al.*, 2023). The second function is attributed to dead or non-viable cells produced from live probiotic strains, typically inactivated using various methods. These cells retain the capability to bind to the TLRs on IECs, thereby

stimulating mucin production similar to probiotics (Piqué *et al.,* 2019; Krysiak *et al.,* 2021). Furthermore, the inactivation of probiotics, often accomplished through heat treatment, enables these dead cells to release bacterial components such as peptidoglycans, lipoteichoic acids, and surface layer proteins, along with other cell fragments. These components exert direct immunomodulatory effects, reducing inflammation, and promoting gut health (Adams, 2010; Piqué *et al.,* 2019; Tsukagoshi *et al.,* 2020; Zhu *et al.,* 2020). Postbiotics offer several advantages over probiotics. Unlike probiotics, postbiotics do not require viability for colonization in the gastrointestinal tract and are less sensitive to heat and oxygen during feed processing and storage conditions (Saeed *et al.,* 2023). Additionally, there are no concerns about their safety when used in animal feed, as they are incapable of replicating and do not pose risks associated with organisms (Saeed *et al.,* 2023). These attributes make postbiotics a more stable and reliable option for enhancing gut health and promoting beneficial effects in animals. Unfortunately, research on postbiotics in poultry under HS remains limited, including birds, which are biological complexes. More research is needed to investigate how postbiotics function at the molecular levels, their interactions with antioxidant defense mechanisms, and the gut-brain axis. Using multi-omics approaches such as genomics, transcriptomics, proteomics, and metabolomics, including integrated muti-omics will be crucial in gaining deeper insights to clarify the precise role of postbiotics in promoting poultry health and performance. This approach is especially important under challenging environmental conditions and could serve as an effective strategy for poultry production in an era of disruptions.

Effects of Probiotics and Postbiotics on Heat Shock Protein and Antioxidant Activity in Broilers Exposed to Heat Stress

When birds are exposed to HS, it leads to an elevated production of ROS, which can have detrimental effects on cells. Nevertheless, birds employ a cellular defense mechanism by enhancing the activity of transcription factors to increase the expression of HSPs for protein refolding and antioxidant enzyme activity (Leonarduzzi *et al.,* 2010; Akbarian *et al.,* 2016). Both probiotics and postbiotics have been shown to possess antioxidant activity by activating the Nrf2, which translocated to the nucleus and binds to antioxidant response element sequences, promoting the expression of antioxidant enzymes to alleviate ROS formation during HS which may reduce activation of HSPs and NF-kB that play important roles in the expression of inflammatory cytokines (Karaca *et al.,* 2022; Saeed *et al.,* 2023; Rezaie *et al.,* 2024). Previous studies have demonstrated that dietary supplementation of beneficial probiotic bacteria obtained from *B. subtilis* in broilers exposed to cyclic HS at the age of 15-46 days, by using a heat stimulating temperature of 32 °C for 10 h daily, can improve GPx and SOD activity, along with the downregulation of HSP70 hepatic mRNA expression levels (Cramer *et al.,* 2018; Wang *et al.,* 2018). Similarly, adding *S. cerevisiae* to broilers exposed to summer temperatures (30-36 °C) from 15-35 days of age can increase SOD and GPx levels, comparable to the effects of vitamin C and/or a mixture of vitamin C and probiotics (Sumanu *et al.,* 2023b). In contrast, das D. Ribeiro *et al*. (2023) found that feeding a single strain probiotic, including *B. subtilis*, *L. lactis*, *L. delbrueckii*, and *S. boulardii* to broilers under HS (35-34 °C for 8 hr) did not affect the jejunal and liver SOD and HSP70 levels. However, *B. subtilis* reduced lipid oxidation in liver tissue. Feeding postbiotic in the form of metabolite derived from *L. plantarum* RI11 can increase T-AOC, CAT, GHS, and GPx in the blood of broiler chickens challenged with extreme environmental conditions (36 °C for 3 h daily) from 22-42 days of age, compared to RS5, UL4, antibiotics, and vitamin C as well as can also reduce the expression of hepatic mRNA of HSP70 (Humam *et al.,* 2020, 2021) (Table 1).

Effects of Probiotics and Postbiotics on Gut Health and Inflammation in Broilers Exposed to Heat Stress

The gut is one of the most important organs related to nutrient utilization efficiency and growth performance, representing the first internal organ to confront issues related to HS. Excess ROS production can damage intestinal cells and gut barrier integrity, which affects nutrient digestion, utilization, and gut leakage, as well as damage to protein misfolding (Rostagno, 2020). In general, birds employ a protective mechanism by increasing HSPs as previously mentioned. It should also be noted that HSPs can serve as a signal to activate the NF-kB transcription factor pathway, leading to the up-regulation of pro-inflammatory cytokines production and consequent contribution to the inflammation of the intestinal mucosa and the disruption of the gut microbial balance (Abdel-Moneim *et al.,* 2021). Al-Fataftah & Abdelqader (2014) demonstrated that dietary supplementation of *B. subtilis* improved gut morphology and surface area, reduced inflammation (indicated by reductions in hepatic protein concentrations of the IL-6 as pro-inflammatory cytokine and increased levels of the IL-10 as anti-inflammatory cytokine), and restored gut microbial population by increasing the population of beneficial bacteria (such as *Lactobacillus* and *Bifidobacterium*) and decreasing the population of harmful bacteria (*Clostridium* and *Coliform*) in broilers exposed to cyclic HS (35 °C for 5 h daily from 21-35 days of age). Moreover, feeding *S. cerevisiae* probiotics to broilers exposed to hot summer temperatures (30-36 °C) from 15-35 days of age can restore gut morphology and increase the number of goblet cells. This, in turn enhances mucin secretion, which provides protection and supports the immunoregulation of IECs (Samanu *et al.,* 2023). Dietary inclusion of a mixture of multi-strain probiotics (including *L. acidophilus*, *L. plantarum*, and *E. faecalis*) can also improve gut morphology, reduce pro-inflammatory cytokine (such as IL-6 and TNF-α), increase anti-inflammatory cytokine (IL-10) levels in the blood, and upregulates genes related to

gut barrier integrity in heat-stressed broilers exposed to temperature of 28 °C and 35 °C for 12 h daily during the grower period (22-42 days) (Li *et al*., 2020b, 2022). In addition, it has also been found that supplementation of probiotic *Lactobacillus* strains (*L. acidopillus* and *L. pentosus*) increased the caecal microbial population of *Lactobacillus* and *Bifidobacterium* in heat-stressed broilers raised under a constant temperature of 35 °C from 15-35 days of age (Jahromi *et al*., 2016). Similarly, dietary inclusion of postbiotics, as metabolite derived from *L. plantarum* RI11, can improve gut morphology and reduce gut inflammation (up-regulated IL-10 and down-regulated TNF-α genes) in broilers exposure to extreme environmental conditions (cyclic HS at the temperature of 36 °C for 3 h daily) from 22-42 days of age (Humam *et al*., 2019, 2020). Humam *et al*. (2019) also reported that postbiotic *L. plantarum* RI11 is effective in improving the caecal microbial population by reducing *Enterobacterium*, *Escherichia coli*, and *Salmonella* as well as increasing *Lactobacillus* and *Bifidobacterium*, similar to the effects observed in the antibiotic and vitamin C groups. Additionally, Rakngam *et al*. (2022, 2024) reported that feeding dead cell postbiotic *L. ingluviei* C37 can reduce caecal harmful bacteria (*Enterobacterium* and *E. coli*), and alleviate gut inflammation (down-regulated TNF-α and IL-6 genes) in broilers exposed to cyclic HS at a

Table 1. The effect of dietary probiotics and postbiotics on heat shock protein and antioxidant capacity in heat-stressed broilers

Species	Forms	Conditions	Results	References
Bacillus subtilis	Probiotic	Cyclic HS 32 °C, 10 h 15-46 days	Dietary inclusion of 0.025% *B. subtilis* (2.5×10^5 cfu/kg) improved endogenous antioxidant enzyme activity by increasing GPx and SOD in the breast meat of heat-stressed broilers.	Cramer *et al*. (2018)
Bacillus subtilis	Probiotic	Cyclic HS 32 °C, 10 h 15-43 days	Dietary inclusion of 0.025% *B. subtilis* (2.5×10^5 cfu/kg) decreased hepatic HSP70 mRNA expression and concentration levels in heat-stressed broilers.	Wang *et al*. (2018)
Bacillus subtilis *Lactobacillus lactis* *Lactobacillus delbrueckii* *Saccharomyces boulardii*	Probiotic	Cyclic HS 25-34 °C, 8 h 15-42 days	Dietary inclusion of 1×10^9 cfu/kg of a single strain of probiotics, including *B. subtilis*, *L. lactis*, *L. delbrueckii*, and *S. boudardii*, had no effect on jejunal and hepatic HSP70 gene expression in heat-stressed broilers. However, feeding *B. subtilis* did reduce MDA levels in the liver.	das D. Ribeiro *et al*. (2023)
Saccharomyces cerevisiae	Probiotic	Constant HS 30-36 °C 15-35 days	Dietary inclusion of 0.1% *S. cerevisiae* increased SOD and GPx in the breast meat of broilers exposed to the hot summer season as similar to vitamin C and/or a mixture of vitamin C and *S. cerevisiae*.	Sumanu *et al*. (2023b)
Lactobacillus plantarum	Postbiotic (metabolite)	Cyclic HS 36±1 °C, 3 h 22-42 days	Dietary inclusion of 0.3% *L. plantarum* RI11 increased blood T-AOC, CAT, and GHS activities and down-regulated hepatic HSP70 gene expression in heat-stressed broilers as compared to RS5, UL4, antibiotic, and vitamin C.	Humam *et al*. (2020)
Lactobacillus plantarum	Postbiotic (metabolite)	Cyclic HS 36±1 °C, 3 h 22-42 days	Dietary inclusion of 0.4-0.8% *L. plantarum* RI11 increased blood antioxidant enzyme activity (GPx, CAT, and GSH) in heat-stressed broilers as compared to antibiotic and vitamin C, in which the supplementation level of 0.6% showed the highest antioxidant activity in all groups.	Humam *et al*. (2021)

Note: GPx=glutathione peroxidase, SOD=superoxide dismutase, CAT=catalase, GSH=glutathione, T-AOC=total antioxidant capacity, HSP=heat shock protein.

Table 2. The effect of dietary probiotics and postbiotics on intestinal morphology in heat-stressed broilers

Species	Forms	Conditions	Results	References
Bacillus subtilis	Probiotic	Cyclic HS 35 °C, 5 h 21-35 days	Dietary inclusion of 0.1% *B. subtilis* PB6 (2.3×10^8 cfu/kg) improved VH, CD, VSA, and AECA in the SI (duodenum and ileum) of heat-stressed broilers.	Al-Fataftah & Abdelqader (2014)
Lactobacillus acidophilus *Lactobacillus plantarum* *Enterococcus faecalis*	Probiotic	Cyclic HS 28 °C, 12 h 35 °C, 12 h 22-42 days	Dietary inclusion of 0.015% a mixture of *L. acidophilus*, *L. plantarum* and *E. faecalis* (1.5×10^8 cfu/kg) improved VH and VH/CD in the SI of heat-stressed broilers.	Li *et al*. (2020b)
Bacillus subtilis	Probiotic	Constant HS 30 °C 22-35 days	Dietary inclusion of 3×10^7 cfu/kg *B. subtilis* PB6 improved duodenal VH, CD, VSA, and AECA of heat-stressed broilers.	Abdelqader *et al*. (2020)
Saccharomyces cerevisiae	Probiotic	Constant HS 30-36 °C 15-35 days	Dietary inclusion of 0.1% *S. cerevisiae* improved VH, CD, VH/CD, and increased goblet cells in the SI (duodenum, jejunum, and ileum) of broilers exposed to the hot summer season as compared to vitamin C and/or a mixture of vitamin C and *S. cerevisiae*.	Sumanu *et al*. (2023b)
Lactobacillus plantarum	Postbiotic (metabolite)	Cyclic HS 36±1 °C, 3 h 22-42 days	Dietary inclusion of 0.3% *L. plantarum* RI11 increased VH and VH/CD in the SI (duodenal, jejunal, and ileum) of heat-stressed broilers as compared to RS5, UL4, antibiotic, and vitamin C.	Humam *et al*. (2019)

Note: VH=villus height, CD=crypt depth, VH/CD=villus height per crypt depth ratio, SI=small intestine, VSA=villus surface area, AECA=absorptive epithelial cell area.

Table 3. The effect of dietary probiotics and postbiotics on gut barrier integrity and inflammation in heat-stressed broilers

Species	Forms	Conditions	Results	References
Bacillus subtilis	Probiotic	Cyclic HS 32 °C, 10 h 15-43 days	Dietary inclusion of 0.025% *B. subtilis* (2.5×10^5 cfu/kg) decreased hepatic inflammatory cytokine (IL-6) and increased anti-inflammatory cytokine (IL-10) protein levels in heat-stressed broilers.	Wang *et al*. (2018)
Lactobacillus acidophilus *Lactobacillus plantarum* *Enterococcus faecalis*	Probiotic	Cyclic HS 28 °C, 12 h 35 °C, 12 h 22-42 days	Dietary inclusion of 0.015% of a mixture of *L. acidophilus*, *L. plantarum,* and *E. faecalis* (1.5×10^8 cfu/kg) reduced inflammatory cytokine (IL-6, TNF-α) and increased anti-inflammatory cytokine (IL-10) in the blood of heat-stressed broilers.	Li *et al*. (2020b)
Lactobacillus acidophilus *Lactobacillus plantarum* *Enterococcus faecalis*	Probiotic	Cyclic HS 28 °C, 12 h 35 °C, 12 h 22-42 days	Dietary inclusion of 0.015% of a mixture of *L. acidophilus*, *L. plantarum,* and *E. faecalis* (1.5×10^8 cfu/kg) upregulated mRNA expression levels of tight junction protein (OCLD) in the ileum of heat-stressed broilers.	Li *et al*. (2022)
Lactobacillus plantarum	Postbiotic (metabolite)	Cyclic HS 36±1 °C, 3 h 22-42 days	Dietary inclusion of 0.6% *L. plantarum* RI11 upregulated anti-inflammatory cytokine (IL-10) and tight junction protein (ZO-1 and MUC2) and down-regulated pro-inflammatory cytokine (TNF-α) gene expressions in the ileal tissue of heat-stressed broilers as compared to antibiotic and vitamin C.	Humam *et al*. (2021)
Lactobacillus ingluviei	Postbiotic (dead cells)	Cyclic HS 32±1 °C, 5 h 15-42 days	Dietary inclusion of 0.1% (1×10^7 cfu/kg) downregulated pro-inflammatory cytokines (TNF-α, IL-6) gene expressions in the jejunal tissue of heat-stressed broilers similar to antibiotic.	Rakngam *et al*. (2024)

Note: IL-6/10=inflammatory cytokine 6/10, TNF-α=tumor necrosis factor alpha, OCLD=occludin, ZO-1=zoluna occludin 1, MUC2=mucin 2.

Table 4. The effect of dietary probiotics and postbiotics on gut microbial population in heat-stressed broilers

Species	Forms	Conditions	Results	References
Bacillus subtilis	Probiotic	Cyclic HS 35 °C, 5 h 21-35 days	Dietary inclusion of 0.1% *B. subtilis* PB6 (2.3×10^8 cfu/kg) improved the balance of harmful bacteria (*Clostridium* and *Coliforms*) and beneficial bacteria (*Lactobacillus* and *Bifidobacterium*) in the SI of heat-stressed broilers.	Al-Fataftah & Abdelqader (2014)
Lactobacillus pentosus *Lactobacillus acidophilus*	Probiotic	Constant HS 35 °C 15-35 days	Dietary inclusion of 0.1% a mixture of *L. pentosus* ITA23 and *L. acidophilus* ITA44 (1×10^8 cfu/kg) increased the population of *Lactobacillus* and *Bifidobacterium* in the caecum of heat-stressed broilers.	Jahromi *et al*. (2016)
Bacillus subtilis	Probiotic	Constant HS 30 °C 22-35 days	Dietary inclusion of *B. subtilis* (3×10^7 cfu/kg) improved the balance of harmful bacteria (*Clostridium* and *Coliforms*) and beneficial bacteria (*Lactobacillus* and *Bifidobacterium*) in the SI of heat-stressed broilers.	Abdelqader *et al*. (2020)
Lactobacillus plantarum	Postbiotic (metabolite)	Cyclic HS 36±1 °C, 3 h 22-42 days	Dietary inclusion of 0.3% *L. plantarum* RI11, RS5, and UL4 reduced caecal harmful bacteria (*Enterobacterium*, *E. coli,* and *Salmonella*) and increased beneficial bacteria (*Lactobacillus* and *Bifidobacterium*) in heat-stressed broilers. The RI11 showed the greatest potential than the other postbiotic strains (RS5 and UL4), antibiotic and vitamin C.	Humam *et al*. (2019)
Lactobacillus ingluviei	Postbiotic (dead cells)	Cyclic HS 32±1 °C, 5 h 15-21 days	Dietary inclusion of 0.1% (1×10^8 cfu/kg) *L. ingluviei* C37 reduced caecal harmful bacteria (*Enterobacterium*, *E. coli*) in heat-stressed broilers similar to antibiotic.	Rakngam *et al*. (2022)

Note: SI=small intestine.

temperature of 32 °C for 5 h daily from 15-21 and/or 42 days of age (Tables 2-4).

Effects of Probiotics and Postbiotics on Growth Performance in Broilers Exposed to Heat Stress

As mentioned previously, HS affects intestinal integrity and morphology and can also alter the gut microbial balance, which leads to the decreased nutrient digestion and utilization and impairs growth performance (Ranjan *et al*., 2019; Vandana *et al*., 2021). Probiotics and postbiotics have been demonstrated to alleviate the deleterious impacts of HS on the growth performance of broilers (Humam *et al*., 2019; Li *et al*., 2020b). Al-Fataftah & Abdelqader (2014) reported that dietary inclusion of probiotic *B. subtilis* PB6 improved growth and FCR of heat-stressed broilers, which were exposed to cyclic HS at the temperature of 35 °C for 5 h daily during 21-35 days of age. Similarly, Abdelqader *et al*. (2020) noted that dietary supplementation of *B. subtilis* PB6 effectively enhanced growth performance, as the PB6-fed groups showed improved growth and FCR in broilers challenged with constant HS (30 °C), similar to the TNZ (21 °C) during the period from 22-35 days of age. das D. Ribeiro *et al*. (2023) demonstrated that a single strain of probiotics, including *B. subtilis*, *L. lactis*, *L. delbrueckii*, and *S. boulardii*, in the diet of heat-stressed broilers (exposed to 35-34 °C for 8 h, from 15-42 days of age) restored growth and feed utilization to levels similar to those achieved with antibiotic feed. Similarly,

adding *S. cerevisiae* during the hot summer season improved growth compared to synthetic antioxidants like vitamin C and/or a combination of vitamin C and probiotics (Sumanu *et al.,* 2023b). Feeding a mixture of probiotics containing *L. pentosus* ITA23 and *L. acidophilus* ITA44 has also been shown to improve growth and FCR in broilers under constant HS (35 °C) for 3 weeks, starting from 15-35 days of age (Jahromi *et al.,* 2016). Attia *et al*. (2017) found that dietary inclusion of a combination of *S. cerevisiae* and *L. acidophilus* enhanced growth and FCR, which these probiotics were found to restore growth performance more effectively than vitamins C and E under HS conditions (36±2 °C for 7 hr daily from 25-42 days of age). Administration of multi-strain probiotics (*L. acidophilus*, *L. plantarum*, *L. brevis*, and *Bifidobacterium* spp.) improved the growth of heat-stressed broilers (Ahmed *et al.,* 2019; Li *et al.,* 2020b). Similarly, Li *et al*. (2020b) documented feeding a combination of probiotics (*L. acidophilus*, *L. plantarum*, and *E. faecalis*) promoted FI in broilers exposed to cyclic HS at the temperature of 28 °C and 35 °C for 12 hr daily during 4-6 weeks of age. In addition, a postbiotic diet derived from *L. plantarum* RI11 also improved the growth and FCR of heat-stressed broilers (subjected to cyclic HS at a temperature of 36 °C for 3 hr daily during 4-6 weeks of age) compared to groups supplemented with antibiotics and vitamin C (Humam *et al*., 2019), as shown in Table 5.

CONCLUSIONS AND FUTURE PERSPECTIVES

HS leads to changes in physiological and cellular responses, damages cells, disturbs energy formation, compromises gut barrier integrity, induces inflammation, and impairs gut microbial balance, ultimately resulting in deleterious effects on nutrient utilization, growth performance, and survival rate. Feeding probiotics and postbiotics can down-regulate HSP70 mRNA expression, boost antioxidant enzyme activity, promote gut health (by improving gut morphology, strengthening barrier integrity, and reducing inflammation), restore gut microbial imbalance, and enhance growth performance in heat-stressed broilers.

Both probiotics and postbiotics can serve as alternative feed additives to alleviate the negative effects of HS in the broiler industry. However, probiotics are more sensitive to heat, oxygen, and unsuitable conditions due to their living nature and the requirements for viability and colonization in the gastrointestinal tract. Furthermore, probiotic bacteria are at risk of transferring antibiotic-resistant genes. Therefore, considering practical applications in poultry feed, postbiotics may offer greater effectiveness in terms of safety, longer shelf life, ease of storage and handling, and transportation.

Table 5. The effects of dietary probiotics and postbiotics on growth performance in heat-stressed broilers

Species	Forms	Conditions	Results	References
Bacillus subtilis	Probiotic	Cyclic HS 35 °C, 5 h 21-35 days	Dietary inclusion of 0.1% *B. subtilis* PB6 (2.3×10^8 cfu/kg) improved BW (17.84%), ADG (34.94%), FCR (27.94%), and survival rate (60%) in heat-stressed broilers.	Al-Fataftah & Abdelqader (2014)
Lactobacillus pentosus *Lactobacillus acidophilus*	Probiotic	Constant HS 35 °C 15-35 days	Dietary inclusion of 0.1% of a mixture of *L. pentosus* ITA23 and *L. acidophilus* ITA44 (1×10^8 cfu/kg) improved FI (4.46%), ADG (10.85%), and FCR (5.29%) in heat-stressed broilers.	Jahromi *et al*. (2016)
Saccharomyces cerevisiae *Lactobacillus acidophilus*	Probiotic	Cyclic HS 36±2 °C, 7 h 25-42 days	Dietary inclusion of 0.2% of a mixture of *S. cerevisiae* and *L. acidophilus* improved BW (6.96%) and FCR (6.32%) in heat-stressed broilers. In addition, these probiotic strains not only restored performance but also outperformed vitamins C and E.	Attia *et al*. (2017)
Lactobacillus acidophilus *Lactobacillus plantarum* *Lactobacillus brevis* *Bifidobacterium spp.*	Probiotic	Constant HS 32-35 °C 22-42 days	Dietary inclusion of 0.1% of a mixture of *L. acidophilus*, *L. plantarum*, *L. brevis*, and *Bifidobacterium spp.* (2×10^7 cfu/kg) improved BW (23.84%) in heat-stressed broilers.	Ahmed *et al*. (2019)
Lactobacillus acidophilus *Lactobacillus plantarum* *Enterococcus faecalis*	Probiotic	Cyclic HS 28 °C, 12 h 35 °C, 12 h 22-42 days	Dietary inclusion of 0.015% of a mixture of *L. acidophilus*, *L. plantarum*, and *E. faecalis* (1.5×10^8 cfu/kg) improved FI (2.78%) in heat-stressed broilers.	Li *et al*. (2020b)
Bacillus subtilis	Probiotic	Constant HS 30 °C 22-35 days	Dietary inclusion of 3×10^7 cfu/kg *B. subtilis* PB6 improved BW and FCR in heat-stressed broilers as similar to TNZ condition.	Abdelqader *et al*. (2020)
Bacillus subtilis *Lactococcus lactis* *Lactobacillus delbrueckii* *Saccharomyces boulardii*	Probiotic	Cyclic HS 25-34 °C, 8 h 15-42 days	Dietary inclusion of 1×10^9 cfu/kg a single-stain probiotics including *B. subtilis*, *Lacto. lactis*, *L. delbrueckii*, and *S. boudardii* improved BWG and FCR in heat-stressed broilers similar to antibiotic.	das D. Ribeiro *et al*. (2023)
Saccharomyces cerevisiae	Probiotic	Constant HS 30-36 °C 15-35 days	Dietary inclusion of 0.1% *S. cerevisiae* improved BWG in broilers exposed to the hot summer season as compared to vitamin C and/or a mixture of vitamin C and *S. cerevisiae*.	Sumanu *et al*. (2023b)
Lactobacillus plantarum	Postbiotic (metabolite)	Cyclic HS 36±1 °C, 3 h 22-42 days	Dietary inclusion of 0.3% *L. plantarum* RI11 improved BW (9.12%), ADG (14.12%), and FCR (6.40%) in heat-stressed broilers. In addition, it exhibited superior performance restoration compared to both the antibiotic and vitamin C.	Humam *et al*. (2019)

Note: ADG=average daily gain, BW=body weight, FI=feed intake, FCR=feed conversion ratio.

CONFLICT OF INTERESTS

We certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript.

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