Review Article

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Sustainable Poultry Production: Enhancing Heat Stress Resilience through Nutritional Management

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Poultry production is a vital aspect of agricultural economy worldwide providing affordable and high quality protein source. However, heat stress acts as a significant threat to poultry production. Heat stress can be defined as a physiological condition in which an animal is unable to adequately dissipate excess body heat due to the combined effect of environmental factors such as high ambient temperature, humidity, solar radiation and low air movement resulting in impaired welfare, health and productivity. Unlike mammals, birds lack sweat glands, so they rely on evaporative cooling through the respiratory system to dissipate excess heat. Relative humidity along with ambient temperature plays an important role to assess thermal stress. Their combined effect expressed as Temperature- Humidity Index (THI), serve as a reliable indicator of thermal load and physiological stress. Thus, heat stress is classified based on THI and duration of exposure. Heat stress induces significant behavioural, morphological and physiological changes in poultry, leading to substantial economic losses. Hence, development and implementation of effective mitigation strategies are important. Among various mitigation strategies of heat stress, nutritional management seems to be easy, affordable by farmers and most effective. Supplementation of electrolyte helps maintain acid-base balance and hydration, while vitamins A, C and E improve egg production, hatchability and overall health. Probiotics such as *Bacillus spp*. improve gut health and stress resilience. Dietary plant extracts, such as rosemary and boldo leaf, provide antioxidant support. *In ovo* feeding can improve thermo tolerance by promoting optimal embryonic growth before hatch. Additional approaches such as controlled feed restriction, wet mash feeding, dietary fat supplementation and specific amino acid fortification further help reduce negative impact of heat stress. Strengthening nutritional and management strategies is essential to improve poultry adoptability and sustain productivity with rising global temperature.

Keywords: Poultry, Heat stress, THI, Nutritional management

Introduction

Poultry production is an essential component of global agriculture, contributing significantly to food security by providing an affordable and dependable source of high quality protein worldwide. However, the sustainability of the sector is increasingly threatened by heat stress (HS) due to rising global temperature in the tropical and subtropical regions of the world including India (Wasti et al., 2021). Poultry are very prone to HS due to their feather covered bodies, high metabolic heat production and the absence of sweat gland which limit their ability to dissipate heat efficiently (Akbarian et al., 2016). HS occur when bird struggle to maintain a balance between heat generation and heat loss and it can impair growth, reproductive and immune function of poultry while also raising production and management cost (Nawaz et al., 2021). High humidity intensifies the effect of heat stress in poultry which further reduces feeding, growth, production and quality of eggs (Awad et al., 2019).

The thermoregulatory capacity of poultry depends on multiple factors such as relative humidity, feeding schedule, age, sex, breed characteristics, body weight and growth rate (Farag and Alagawany, 2018). Generally, the normal body temperature of chickens ranges from 41–42°C while their optimal thermo neutral zone is 18-21 °C ensuring maximum growth and performance (Kumari and Nath, 2018). Exposure to temperature above this range, whether acute or chronic, can disrupt normal physiological function reducing gut immune defense and impairing nutrient digestion. This can trigger gastro intestinal inflammation negatively affecting overall health and increasing mortality risk (Kadykalo et al., 2018). Therefore, understanding and mitigating HS is critical for maintaining poultry health, welfare and sustainable production under changing climatic condition.

Effect of Heat Stress on Growth, Reproduction and Immune Status of Chicken

The hypothalamus plays a central role in coordinating energy balance through complex neuroendocrine signaling pathways. When animals are exposed to HS, the neurogenic system gets activated. During the initial phase of HS, the Sympathetic Adrenal Medulary Axis (SAM) plays an important role in maintaining homeostasis. In contrast, in case of chronic HS, the Hypothalamo Pituitary Adrenal Axis (HPA) becomes activated (Fernandes et al., 2023).

The physiological mechanisms and effect of HS in poultry are shown in Figure 1.

High environmental temperature disturb normal functioning of the hypothalamus which in turn lowers Luteinizing Hormone (LH) levels in the blood stream and reflects disruption of the reproductive hormonal axis (Kala et al., 2017). Ambient temperature adversely influences key reproductive traits in both laying hens and breeder

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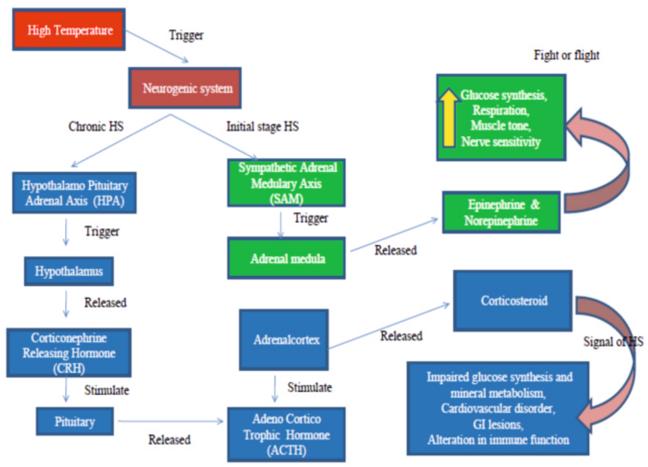


Figure 1. Physiological responses initiated during the initial phase of HS (green section) and prolonged HS (blue section) along with their respective consequence in poultry exposed to HS

flocks including egg weight, egg output, shell quality, hatchability and fertility (Yousaf et al., 2017). Male breeders are generally more sensitive to heat induced infertility than females (Bonato et al., 2014). Exposure to temperature beyond thermo neutral zone, triggers excessive generation of reactive oxygen species which leads to oxidative stress and lipid peroxidation causing damage to testicular tissues. Consequently, semen characteristics decline with reduction in semen volume, testicular size, sperm concentration, motility and viability along with impaired development of spermatogenic cells (Türk et al., 2016).

Beyond reproductive impairment, HS also compromises immune system which is crucial for maintaining poultry bird health and productivity. Figure 2 depicts impact of HS on poultry growth and productivity. During HS, major lymphoid organs such as spleen, thymus and bursa of fabricus shrink in size indicating suppression of the immune system in chickens (Awad et al., 2019).

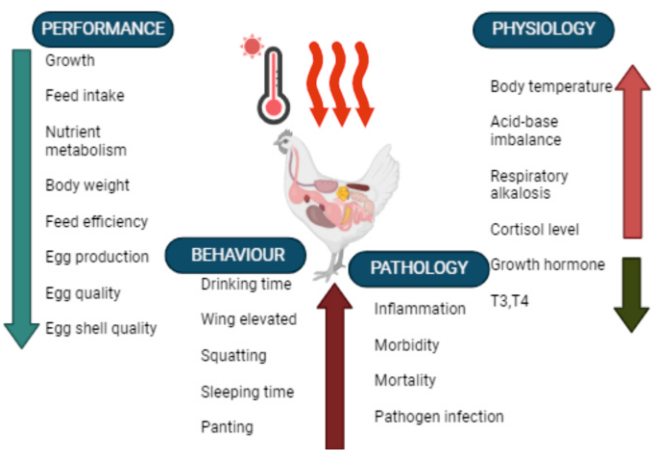


Figure 2. Impact of HS on poultry growth and productivity

Influence of Heat Stress on Heat Shock Protein

HS affects immune efficiency in poultry by increasing production of heat shock proteins (HSPs). HSPs are a group of proteins produced by organisms when they are exposed to extreme heat. These proteins work as molecular chaperones, helping maintain cellular stability by recognizing proteins that have become misfolded or damaged and guiding them either towards proper folding or degradation (Balakrishnan et al., 2023). Repeated cyclic chronic HS generally increases the activity of HSPs and antioxidant enzymes. However, acute or continuous long term HS weakens antioxidant defense system, lowers mitochondrial function and enzyme activity, increases protein breakdown and disrupts normal cellular process (Ma et al., 2021; Madkour et al., 2022)

Cytochrome P450 (CYP450), heme oxygenase-1 (HO-1) and nuclear factor erythroid 2 related factor (Nrf-2) are key components of the cellular defence system that detoxify reactive species and mitigate oxidative stress. In HS condition, Nrf-2 activates antioxidant pathways and up regulates HO-1, enhancing cellular protection (Men et al., 2021; Miao et al., 2020). Acute HS in broilers (26, 29, 32 and 35 °C for 6 hours increases hepatic Nrf-2 and HO-1 expression (Miao et al., 2020), where as constant chronic HS suppress their levels (Yilmaz and Gul, 2023a).

CYPP450 enzyme, which function as a heme dependant mono oxygenases, also respond variably- generally increasing under chronic HS, but decreasing during acute exposure (Li et al., 2023; Yilmaz & Gul, 2023b). HS furthers alters poultry behaviour, such as increased resting, moving away from other birds in the flock, extending and dropping their wings enhance heat dissipation. As HS intensifies, birds rely on more pronounced thermoregulatory behavior like panting and gular fluttering to dissipate excess heat (Li et al., 2015). The primary physiological response to HS is the activation of heat shock factors which trigger HSP formation in different tissues. These proteins are highly conserved and can also be induced by various non thermal conditions such as hormonal changes, restricted feed intake, hormonal regulation, tissue growth and immunological challenges including bacterial infection, inflammation and fever (El-Hack et al., 2018).

Based on molecular weight, HSPs are categorized into HSP 100, HSP 90, HSP 70, HSP 60, HSP 40 and small HSPs. Among these, HSP70 is widely regarded as a reliable indicator of thermal stress, particularly when body temperature exceeds 38.6°C (Berger et al., 2016). It enhances cytoprotection, supports proper protein folding and contributes significantly to maintaining epithelial integrity by strengthening tight junctions and improving gut barrier function under high temperature exposure (Chauhan et al., 2014). HSP70 expression is markedly up regulated across multiple tissues during thermal stress in a range of poultry species including quail, turkey and chickens (Kennedy et al., 2022).

Nutritional interventions can modulate these stress response as evidenced by reduced HSP70 expression in broilers supplemented with vitamin E and selenium. The lowest HSP70 expression were observed in birds ssupplemented with vitamin E (100 mg/L) combined with selenium (0.2 mg/L) and vitamin E (200 mg/L) combined with vitamin C (200 mg/L), suggesting improved cellular protection and better thermo tolerance under HS condition (Singh et al., 2023). The major effect of HS on poultry has been given in Table 1.

Table 1: Symptoms of heat stress in various species of poultry

Species	Temperature & Humidity	Symptoms of heat stress	Reference
Broiler (42days age)	34 °C	Decrease in feed intake (16%) and body weight gain (29 %).	Alaqil et al., 2022
Broiler chicken	30 °C	Decrease in body weight, reduced insulin-like growth factor 1 (IGF-1), rise in cholesterol and glucose level, reduced villus surface area, height, crypt depth and high FCR.	Abdelqader et al., 2020
Laying Hen (32 weeks Hen)	33 °C and RH - 66 %	Lower in egg production (11%), Decrease in feed intake (30%).	Kim et al., 2024
Jinding duck	12 hour of HS at 40°C	Prolonged HS caused an initial rise followed by a decline in antioxidant activity and HSP expression. After 12 hrs of HS, increased gut permeability and compromised barrier integrity were shown. Digestive enzyme activity markedly reduced and there was significant decline in intestinal immune cell population.	Liu et al., 2025
Turkey (35 days)	35 °C and 75 % RH and control group in 32 °C and 60 % RH	No significant change occurred in feed intake and body weight gain in HS birds compared to control. But respiratory alkalosis and panting observed in HS birds.	Crespo and Grimes, 2024

Nutritional Management to Mitigate Heat Stress

Vitamins such as A, B- complex, C, D, are widely used to enhance immune function and antioxidant defense in poultry exposed to HS (Akinyemi and Adewole, 2021). Evidence suggests that combining vitamins is more effective than supplementing them individually in mitigating HS. In particular, the synergistic action of viatamin C and E improved feed efficiency, growth performance and immune response in heat stressed chickens (Attia et al., 2018). Similarly dietary inclusion vitamin E with organic selenium in the diet has been reported to lower mortality while enhancing growth and carcass traits in broilers under HS (Calik et al., 2022). Furthermore, dietary supplementation of vitamin E and selenium significantly improved haematological and biochemical parameters, liver enzyme activity, serum chloride levels, antioxidant status and heat shock protein response in broilers compared to the control group ($P<0.05$) (Singh et al., 2023). In addition, broiler chicken meat can be effectively enriched by supplementing the diet with 0.30 mg/kg selenium and 200 mg/kg vitamin E without adversely affecting bird performance while also, enhancing immune response (Sridhar et al., 2022).

Moreover, zinc, manganese, chromium and selenium, along with other trace elements such as calcium, phosphorus, copper, iron, sodium, potassium, magnesium and iodine, have been extensively studied and shown to play a beneficial role in mitigating the adverse effects of HS in poultry (Mir et al., 2018).

Plant-based supplements further extend these protective effects. For example, dietary rosemary extract may enhance HSP70 and CRYAB gene expression, protecting birds before and during heat exposure (Tang et al., 2018). Boldo leaf extract improves growth, blood health and antioxidant activity under HS (Abo Ghanima et al., 2019). Other supplements, such as *Morinda citrifolia* (Noni), also offer protective effects (Flees et al., 2017), while resveratrol supports intestinal health by strengthening gut morphology, increasing goblet cells and regulating tight junction genes (Zhang et al., 2017).

Oxidative stress and poor gut health affect broilers critically especially under HS in tropical and sub tropical regions (Tripathi et al., 2025). Traditionally, antibiotic growth promoters were used to manage these issues, but concerns over antibiotic resistance and antibiotic free poultry products have driven the shift to phytochemicals (Moustafa et al., 2021). Quercetin, a plant derived flavonoid has shown strong anti-inflammatory and antioxidant properties. It helps in neutralizing free radicals, increase antioxidant enzyme and reduces oxidative stress, ultimately supporting better growth and overall health in broilers (Tan et al., 2022). A recent bibliometric study indicates that compounds such as flavonoids, probiotics, curcumin, resveratrol, essential oils and plant extracts can alleviate HS in poultry (Uyanga et al., 2023). Bioactive compounds such as curcumin, resveratrol, quercetin have been reported to stimulate vitagene expression and modulate the antioxidant defence system particularly through activation of the Nrf2 signaling pathway, thereby reducing oxidative damage induced by HS (Madkour et al., 2022). Consistent with these findings, dietary supplementation of resveratrol has been shown to enhance growth performance, reduce hepatic injury and improve antioxidant status by increasing the activities of the enzyme Superoxide Dismutase (SOD) and Glutathione Peroxidase (GPx) along with regulating the Nrf 2 keap 1 pathway in broiler chickens (Ding et al., 2023). Furthermore, polyphenols, possess strong free radical scavenging properties, limit lipid peroxidation, regulate antioxidant enzyme activity and alleviate oxidative stress making them sustainable nutritional approach for managing HS in poultry (Mas et al., 2023).

Probiotics supplementation

It was also observed that, inclusion of probiotic, especially with mannan-oligosaccharides and *Lactobacillus* strains has been found to increase serum tri iodo thyronine (T3) and thyroxine (T4) levels in broilers suffered from HS (Sohail et al., 2010). As thyroid hormones helps in the synthesis of essential proteins, enzymes and hormones, so, an increase in their levels due to probiotic supplementation may contribute to better digestion and metabolic activity in poultry under HS (Aluwong et al., 2013). Lowering down of corticosterone level may be one primary mechanism behind this effect. Given the sensitivity of probiotics to environmental conditions, their inclusion in poultry diet is helpful in ensuring their survival and activity within the digestive tract, thereby maximizing their positive effects (El-Moneim et al., 2020).

Sahin et al. (2018) observed that, in laying hens, exposure to acute stress can significantly affect gut health by altering villus morphology and intestinal epithelial integrity. Likewise, HS also hamper gut integrity and suppress immune function in broiler birds leading to decreased overall performance (Abdelqader et al., 2020).

In poultry production, supplementation of probiotic in broilers subjected to chronic HS helped to mitigate the adverse effects of oxidative stress, thereby improving semen quality and increasing breast meat yield (Cramer et al., 2018). Dietary inclusion of *Bacillus subtilis* in poultry feed; inhibit the growth of pathogenic microorganisms, thereby enhancing dietary protein utilization making it a valuable probiotic option for enhancing health and production capacity of poultry (El-Moneim et al., 2020).

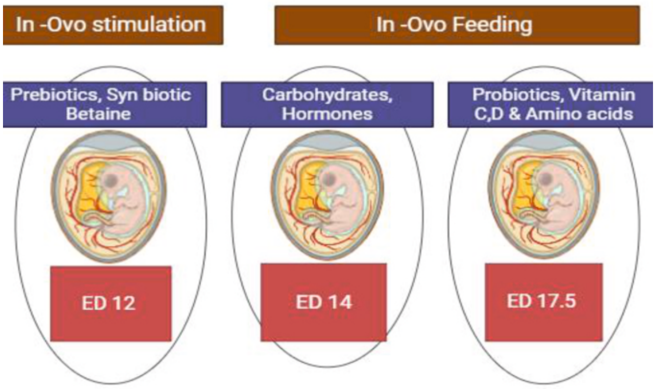
Furthermore, *Bacillus licheniformis*, improves gut function by enhancing nutrient absorption and promoting the growth of beneficial microorganisms such as *Aspergilus awamori*, *Lactobacillus* and *Bifidobacterium* making it valuable in poultry diet (Abdelqader et al., 2020). Researchers also observed that probiotic bacterium supplementation helps sustain goblet cell numbers in the ileum and caecum of heat stressed hens (Deng et al., 2012). This contributes to better gut health and overall resilience against environmental challenges.

Probiotics improve feed digestibility by breaking down complex compounds and producing enzymes like phytases, lipases, amylases and proteases, while also stimulating the bird's own enzyme production, which support better nutrient absorption and feed utilization (Flint et al., 2012).

Probiotics, beyond enzyme production also support the synthesis of antioxidants, vitamins, exopolysaccharides, thereby improving the overall nutritional profile of the feed. Cholesterol metabolism is also regulated by some probiotic strains contributing towards better health outcomes in poultry (Wealleans et al., 2017). Moreover, efficient utilization of nutrient is important because the accumulation of undigested feed in the gut can disturb microbial balance and increase the risk of digestive disorders (LeBlanc et al., 2017).

In-ovo feeding in poultry (IOF)

Embryonic interventions such as temperature adjustments during incubation and in ovo feeding (IOF) have shown promising results in developing heat-tolerant birds (Al-Zghoul et al., 2019). In IOF, nutrient and growth promoting substances are administered to the poultry embryo highlighting that nutrition before hatching is as critical as provided after hatch. More number of studies is being conducted in IOF as; incubation period significantly affects embryonic growth, hatchability and performance of chick post hatch. Recently in-ovo administration of amino acid has been explored to access their impact on HS in chickens. Studies have



(Figure. 3: The optimal time for in-vivo inoculation varies depending on type of bio-active compound being administered. For in ovo stimulation bioactive additives such as prebiotics, synbiotics and betaine are generally administered around embryonic day 12 (ED-12) whereas, in ovo feeding carbohydrates, hormones and similar substances are introduced in ED-14 and probiotics, vitamins, amino acids are preferably administered on ED-17.5)

shown that supplementing embryo with L-Leu or methionine can enhance the thermo tolerance in chickens by regulating body temperature, increasing feed intake, enhancing the expression of immunity-related genes and positively influencing antioxidant status in chicken (Elnesr et al., 2019).

Zhu et al. (2020) observed that, Vitamin C plays a crucial role in enhancing DNA and histone demethylation, thereby influencing liver epigenetics by regulating gene expression. The same researchers also claimed that *in vivo* feeding of Vitamin–C at embryonic day 11 led to increased expression of genes HSP-60, Pyruvate Dehydrogenase Kinase 4 – (PDK-4) and secreted frizzled related protein 1 (SFRP-1) which contribute to embryonic protection against HS. However, finding from other studies have not consistently supported this epigenetic adaptation in response to HS during embryonic development (Sgavioli et al, 2019).

Other nutritional management practices

Feed restriction and feed withdrawal

Withholding feed for at least six hours during HS has been found to reduce body temperature, decrease mortality rates and lower the heterophil-to-lymphocyte ratio suggesting a mitigation of HS effects (Lozano et al., 2006). However, finding regarding growth performance of broilers have been inconsistent, with some studies reporting improvements (Mohamed et al., 2019) while others observed reduction in growth of birds (Lozano et al., 2006), likely influenced by timing and severity of feed restriction (Özkan et al., 2003). Removing feed a few hours before peak heat exposure may help prevent increased heat production caused by anticipatory feeding behaviour, as seen in birds undergoing intermittent fasting (Fondevila et al., 2020).

Wet feeding

In heat-stressed broilers, when feed was mixed with an equal amount of water enhanced dry matter intake (DMI), body weight gain (BWG), carcass weight and protein deposition. However, this approach also led to greater abdominal fat and higher lipid content relative to carcass weight, alongside a reduction in dry matter conversion efficiency (DM intake/BWG) (Kutlu., 2001). Despite some benefits, practical application of wet feeding remains limited, primarily due to the heightened risk of fungal contamination and mycotoxin exposure, which can negatively impact bird health (Wasti et al., 2020).

Form of feed (mash/crumble/pellets) and feed particle size

It has been observed that, under thermo neutral condition, pelleted form of feed enhanced body weight gain and feed intake along with improving digestibility in chicken (Massuquetto et al., 2019). Further, adding pelleted feed to chicken ration led to 8.3% rise in BWG, 10% increase in feed intake and improved crude protein (CP) digestibility by 2.3 % (Cardoso et al., 2022).

Feeding broilers, pelleted diets under HS improves intestinal morphology, increasing villus length and the villus-to-crypt depth ratio in the jejunum (Hosseini and Afshar, 2017b). Pelleted feed also lowers breast HSP70 and creatine kinase levels, reduces mRNA expression and decreases the heterophil-to-lymphocyte ratio, collectively mitigating HS (Hosseini and Afshar, 2017a). Additionally, feed particle size affects HS responses: broilers and laying hens consuming coarser corn particles show higher panting, elevated body temperature and reduced eggshell quality compared to finer particles (Santos et al., 2019).

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Lipid supplementation through feeding

In animals, exposed to HS, incorporating fats and oils into diet helps improve feed intake, supports better productivity and reduces overall heat load (Attia et al., 2021). The type of dietary fat significantly affects broiler performance under HS. Broilers fed isocaloric diets with coconut oil or beef tallow showed better body weight gain (BWG) and feed conversion ratio (FCR) than those receiving olive or soybean oil, likely due to their shorter-chain saturated fatty acids, which are rapidly absorbed and produce less heat during digestion (Seifi et al., 2020). Short and medium chain fatty acid (SCFAs and MCFAs) have likewise been reported to aid mitochondrial function and support the electron transport chain, often impaired under HS (Hecker et al., 2021; Akbarian et al., 2016). To compensate for reduced energy intake during HS, higher metabolizable energy (ME) diets are commonly used, which can improve BWG by up to 17%, FCR by 10% and lower skin and rectal temperatures (Attia et al., 2011, 2018; Wasti et al., 2020).

Supplementation of individual amino acids

Methionine is the primary limiting amino acid (AA) in poultry and along with cysteine (Cys), plays a crucial role in meeting the sulphur AA requirements of birds. Research indicates that Met supplementation can influence inflammation related gene expression in the liver of broilers exposed to high temperatures (Liu et al., 2019).

Lysine (Lys) is the second limiting amino acid in corn and soybean meal based broiler diets is crucial for muscle protein deposition (Ishii et al., 2019). However, studies suggest that providing Lys above the requirements for thermo neutral conditions does not prevent the growth reduction associated HS. Interestingly, when Lys was supplemented alongside Met in a reduced CP diet, broilers exhibited growth performance and carcass traits similar to those fed higher CP diets in hot climates (Attia et al., 2021).

In laying hens, increasing diatary threonine (Thr) from 0.43% to 0.66% did not improve performance but resulted in reduced HSP 70 expression in the ileum (Azzam et al., 2019) and increased superoxide dismutase (SOD) levels in serum and liver (Azzam et al., 2012), indicating potential antioxidant benefits of Thr under HS conditions.

Unlike mammals, poultry have limited ability to synthesize arginine (Arg) due to reduced activity in the de novo synthesis pathway (Castro and Kim, 2020). Increasing dietary Arg has been linked to improved growth, reproduction, immunity, antioxidant capacity and maternal antibody transmission in quails (Kalvandi et al., 2022). Arg also serves as the sole nitrogen donor for nitric oxide production, which supports vasodilatation and may aid in thermoregulation during HS (Uyanga et al., 2021).

Recently, researchers are more interested in citrulline (Cit), which is formed during catabolism of Arg and synthesis of nitric acid. Supplementation of Cit may be more effective than supplementation of L-Arg in increasing systemic Arg levels (Agarwal et al., 2017). Furthermore, as temperature changes, Cit concentration in blood also fluctuates (Chowdhury, 2019), and supplementation of this Cit could help to increase the synthesis of nitric acid which will provide anti-inflammatory effect and aid in regulation of central body temperature (Uyanga et al., 2021, 2022).

When Tryptophan (Trp) was supplemented in high dietary concentration in both broiler (Badakhshan et al., 2021) and layer (Dong et al., 2012) it did not show any improvement in performance. However, Trp supplementation found to decrease rectal temperature and alleviate corticosterone response to broilers affected in HS (Badakhshan et al., 2021).

Among non-essential AAs, glycine (Gly) has shown promise in improving FCR under both normal and HS conditions when included in low CP diets (Awad et al., 2018). Emerging research indicates that Gly and serine (Ser), often evaluated together as Gly equivalents, may be co-limiting or even more limiting than some branched-chain AAs (BCAA) in low CP diets under thermo neutral conditions (Chrystal et al., 2020). This suggests that Gly equivalents could play a critical role in alleviating the negative effects of HS-induced reductions in feed intake.

Effect of dietary protein level in diet

To meet digestible Amino Acid (AA) requirements while minimizing heat production from AA oxidation, reduced CP diets are often supplemented with feed grade AAs. Unlike intact protein sources, feed grade AAs does not require enzymatic digestion, thus preventing additional heat production during nutrient metabolism. However, the decline in performance seen with reduced crude protein diets are consistent with findings that broilers fed a high CP diet (220 g/kg) exhibit high heat production compared to those fed a low CP diet (160 g/kg) under cyclic HS condition (Soares et al., 2020).

Some studies suggest that broilers exposed to HS can achieve better performance when fed diets with both high metabolizable energy (ME) and CP levels (Attia and Hassan, 2017). However, in an experiment where broilers were reared under either thermo neutral or cyclic HS conditions from day 19 to 42 and provided with diets containing either 3,152 kcal/kg ME with 194.8 g/kg CP or 3,253 kcal/kg ME with 210.3 g/kg CP, no performance benefits were observed with the higher density diet. Furthermore, economic evaluations indicated reduced profitability with the increased nutrient density (Cardoso et al., 2022).

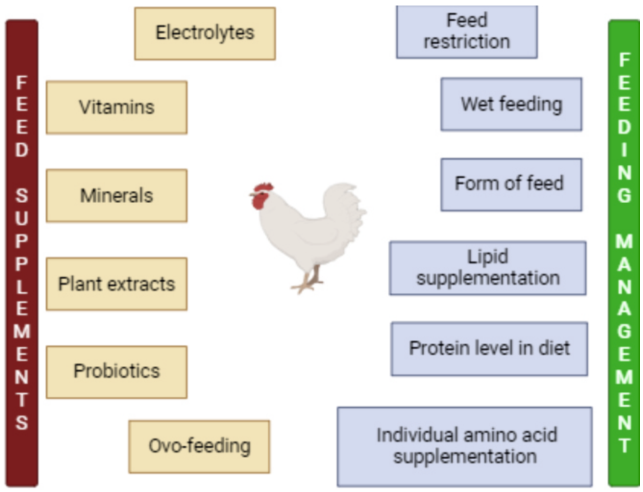

Figure-4: Dietary supplementation of feed additives and other feeding management practices to reduce heat stress in poultry birds

Conclusion

Birds naturally reduce feed intake to lower heat production, but this also limits growth and productivity. Nutrition offers a practical way to alleviate these effects. Although some feeding strategies can be difficult in intensive systems, targeted dietary adjustments show promise. Further research on nutrient partitioning and dietary optimization under heat stress is needed to develop cost-effective strategies that support performance, health and welfare in hot climates.

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