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THE BENEFICIAL EFFECTS OF MICROALGAE IN PROMOTING GROWTH PERFORMANCE OF POULTRY UNDER HEAT STRESS CONDITIONS – A REVIEW

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Abstract

Heat stress can seriously impair broiler chicken development and meat quality, so scientists are looking for sustainable additives like microalgae that might mitigate these impacts. Poultry health and productivity are seriously impacted by heat stress, which is a major concern. Incorporating compounds rich in antioxidants into the feed of chickens is crucial for addressing the problem of heat stress and maintaining the appropriate operation of the redox system. Animal and human health both benefit from the high antioxidant content of microalgae. Many researches have demonstrated that, when handled properly, microalgae can enhance immunity, nutrition, stress relief, aquatic bioremediation, disease resistance, and inhibit bacterial quorum sensing. Microalgae's anti-cancer, anti-inflammatory, antibacterial, and antioxidant qualities contribute significantly to its ability to reduce the bad effects of heat stress. As a result, we can advise using microalgae instead of protein sources in chicken feed to lessen the harmful effects of heat stress because it has excellent properties and is reasonably priced to maximize profit.

Key words: poultry, heat stress, antioxidant, microalgae, growth promoter

The world's constant climate change greatly affects the chicken industry (Chaudhary, 2023). According to Nawaz et al. (2021), acute heat stress lasts only a few hours, while chronic heat stress lasts several days. Either way, the heat stress causes the cell to develop reactive oxygen species (ROS) and reactive nitrogen species (RNS), which are free radicals that can lead to oxidative stress (Maibam et al., 2018; Ghanima et al., 2020). ROS and RNS induce lipid peroxidation, abnormal enzymatic activity, altered gene expression, and damage to other cellular components, resulting in cell apoptosis (Xu et al., 2017). Multiple organ failure syndromes are caused by ongoing apoptosis and cellular physiological state deviation (Lin et al., 2011). Numerous research investigations have verified the adverse effect of heat stress on various physiological systems, including the immunological system, cardiovascular system, respiratory system, reproductive system and central nervous system (Paul et al., 2008; Xu et al., 2019; Shehata et al., 2020; Mishra et al., 2023).

Many researches have demonstrated the harmful effects of heat stress on laying hen performance, including decreased body weight, egg weight and egg production (Salem et al., 2022). It also impairs eggshell quality by inducing abrupt changes that raise ROS and lower production performance (Kilic and Simsek, 2013; Lara and Rostagno, 2013).

According to Zeweil et al. (2016) and Abdel-Moneim et al. (2022), feed additives, such as microalgae, have anti-cancer, anti-inflammatory, antibacterial, and antioxidant qualities that help lessen heat stress's negative impacts. Poultry producers have widely used synthetic antioxidants to lessen the detrimental impacts of stress (Ranjbarinasab et al., 2024). However, natural antioxidants derived from plants also have significant potential antioxidant effects in animals without deleterious effects on their health (Gulcin, 2012; Xu et al., 2018). *Chlorella* and *Spirulina* have also been used as normal antioxidants for poultry and plants (Sugiharto, 2020). According to Demisu and Benti (2018), *Spirulina platensis* is a cyanobacteria or blue-green microalgae belonging to the Cyanophyceae family. Because of its antibacterial qualities and favorable effects on the immune system and intestinal architecture, it is considered a prebiotic to improve production (Shanmugapriya et al., 2015).

In addition to satisfying consumer wants and preferences for natural products, normal feed additives in broilers support the productivity, general health and financial sustainability of broilers (Almeldin et al., 2024). Heat stress often results in decreased feed intake, stunted growth rates, elevated mortality rates, changed meat quality, financial losses, and negative effects on broiler chickens' immunity, respiratory distress, and physiological health (Ahmad et al., 2022). Because of their high concentrations of macro- and microelements and capacity to enhance feed efficiency, broilers' growth performance and meat quality (Michalak and Mahrose, 2020), microalgae are suggested as feed additives. This is mainly because of the properties of polysaccharides, which have been indicated to improve chicken health and productivity (Almeldin et al., 2024).

Metrics measuring performance are improved when poultry diets contain both macro- and microalgae. Studies highlight improving growth rates, carcass quality, feed conversion ratios and meat characteristics in broiler chickens. At the same time, supplementation in layer hens leads to higher egg production, higher-quality eggs and higher concentrations of good nutrients like omega-3 fatty acids. Algae also show potential in reducing the environmental impact of chicken farming (Abdel-Wareth et al., 2024). This review article focused on the most important effects of microalgae on poultry production and the methods used to reduce the harmful impacts of heat stress on broiler chickens.

Microalgae

Microalgae are a broad class of simple multicelled or single-celled microorganisms that grow quickly (Chaudhary, 2023). Using photosynthesis, microalgae produce biomass from sunlight and carbon dioxide, with oxygen and water vapor emerging as byproducts (Chisti, 2007). The microalgae may be grown in a broad range of habitats and are also stress-tolerant, allowing them to be grown in freshwater and marine environments (Anusree et al., 2023). Because microalgae are currently grown in large quantities in several nations worldwide, they are commercially available. It is estimated that there are currently 40,000 microalgae species (Chaudhary, 2023). According to Saadaoui et al. (2021), the microalga kinds that are frequently utilized are *Chlorella* sp., *Spirulina platensis*, *Dunaliella salina*, *Nannochloropsis granulata*, *Hematococcus pluvialis* and *Tetraselmis chui*. Protein comprises around 70% of microalgae, 20% of carbohydrates, 7% of lipids, fatty acids, minerals and vitamins (Brito et al., 2020; Mishra et al., 2023). Microalgae have a high energy content and additional nutritional quality, making it a viable substance for the animal business.

According to Camacho et al. (2019), almost 30% of the world's microalgae biomass production is now sold for use in poultry nutrition's applications. Microalgae can help birds' redox status by boosting the activity of antioxidant enzymes such as glutathione peroxidase, superoxide dismutase, and catalase (Mirzaie et al., 2018; Liu et al., 2021; Moustafa et al., 2021).

The intriguing makeup of microalgae includes lipids, carbohydrates, proteins, minerals, vitamins and bioactive substances like carotenoids. Numerous variables, including strain, species, growth conditions and biomass status (defatted algal meal or whole), influence the composition of macro and micronutrients (Valente et al., 2020).

Spirulina, *Chlorella* sp., and *Schizochytrium* sp. have been the most commonly utilized algae in animal production. Protein content in *Spirulina* is well-known to range from 60 to 70% of dry weight. Additionally, it contains a high concentration of fatty acids, primarily γ-linolenic acid, and is a rich source of antioxidants, containing vitamin E and β-carotene (Holman and Malau-Aduli, 2013). The latter may cause the meat's fatty acid concentration to rise (Altmann et al., 2019). On a dry weight basis, the range of difference for the contents of crude fat, crude carbs, and ash is 17.8–22.6%, 1.8–7.3%, and 6.5–9.5%, respectively (Madeira et al., 2017). According to Gutiérrez-Salmeán et al. (2015) and Madeira et al. (2017), *Chlorella* sp. is regarded as a significant source of cobalamin (vitamin B_{12}) and has a high protein concentration range from 50% to 60% of dry weight. Its contents of ash and carbs are comparable to those of *Spirulina*, but its levels of crude fat and n-3 polyunsaturated fatty acids are higher (12.6 and 9 points, respectively) (Madeira et al., 2017). The oils of *Schizochytrium* sp. are especially interesting since they contain a high concentration of docosahexaenoic acid (DHA). It was utilized in several experiments as a feed additive in the DHA-Gold extract form (Valente et al., 2020). It is distinguished by having a larger crude fat content range from 38.0% to 71.1% of dry weight despite having lower protein content (approximately 12.1%) than the other microalgae.

Spirulina, *Chlorella* sp., and *Schizochytrium* sp. are key microalgae in animal production, valued for high protein, fatty acids, and antioxidants. *Spirulina* boosts protein and antioxidant levels, *Chlorella* add vitamin B_{12} and polyunsaturated fats, and *Schizochytrium* contributes DHA-rich fat content. Limitations include nutrient variability across species and potential cost challenges for large-scale use.

Chemical composition of microalgae

Figure 1 shows the advantages and chemical makeup of microalgae. Algae and their byproducts can be used to produce rich biomass that can be used to replace plant-based meat products such as tempeh, tofu, lentils, almonds and chickpeas (Onwezen et al., 2021). This is an effective way to create new food alternatives. Different types of full- and defatted (lipid-extracted) microalgae yield moderate to high crude protein concentrations (14–61%) together with a well-balanced profile of essential amino acids (%), such as arginine (0.42–6.4), lysine (0.47–8.4), threonine (0.42–4.8), phenylalanine (0.36–5.0), methionine (0.33–2.3), histidine (0.20–2.0), tryptophan (0.13–2.1) and branched-chain amino acids including isoleucine (0.13–3.8), leucine (0.59–8.8), and valine (0.47–5.5) (Kalia et al., 2021). According to De Farias et al. (2019), people who follow a plant-based diet should prioritize certain necessary elements and/or foods. These include plant-based meals high in protein, vitamins (such as B_{12} and D), minerals (like calcium), and critical omega-3 fatty acids. Based on research on the bioaccessibility and digestion of algal biomass in various food matrices, recent studies published in the literature have suggested employing entire algae or algae extract to produce innovative cuisines.

According to Awad et al. (2023), dried *Spirulina*'s chemical composition contained approximately 60% of total protein and all vital amino acids, with a total fat concentration of 7%. It also contained a high concentration of vitamins, including fat-soluble vitamins A and E and water-soluble vitamins such as C, B_1, B_2, B_3, B_6, B_9, and B_{12}. According to Jubie et al. (2012), *Spirulina* also has a high concentration of minerals, such as sodium, calcium, phosphorus, iron, chromium, copper, selenium, magnesium, manganese, potassium and zinc.

Microalgae like *Spirulina* offer a rich nutritional profile with high protein content, essential amino acids, vitamins, and minerals, making them valuable as plant-based meat alternatives and for supporting nutrient needs in plant-based diets. Algae's balanced amino acid profile, alongside critical vitamins and minerals, enhances their potential in innovative food products. However, limitations exist due to variations in nutrient composition across different algae types, and potential challenges with digestibility and bioaccessibility in various food matrices, which may impact their effectiveness as nutrient sources in certain diets.

Chlorella vulgaris and *Arthrospira platensis* have high biological value and crude protein content (Becker, 2013). Microalgae types also produce high total phenolic vital content ranging from 510 to 2,200 mg gallic acid equivalents (GAE) per kilogram, as well as total vital flavonoids ranging from 66 to 550 mg per kilogram (El-Chaghaby et al., 2019). Also, microalgae include notable concentrations (%) of phosphorus (0.65–0.76), calcium (0.33–2.8), sodium (3.2–3.9), potassium (0.89–1.7), and trace elements (mg/kg) including copper (18–102), iron (1,390–11,100) and zinc (28–64) (Tibbetts et al., 2015; Kalia et al., 2021). Bioactive compounds of types of microalgae are found in Table 1.

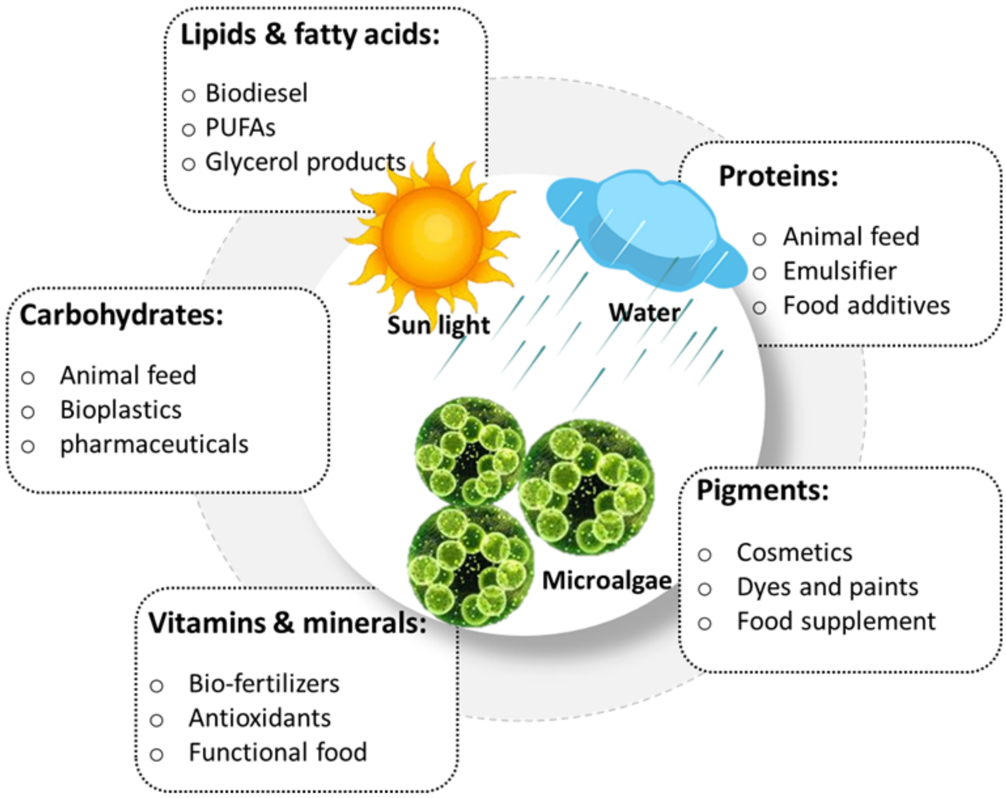

Figure 1. Chemical composition and advantages of microalgae

Table 1. Bioactive compound of types of microalgae

Microalgae	Bioactive compounds	References
Spirulina platensis	High protein (~70%), carbohydrates (~20%), lipids (~7%), vitamins, minerals and fatty acids.	Mishra et al., 2023; Brito et al., 2020
	Water-soluble vitamins (including C, B_6, B_1, B_3, B_2, B_9, and B_{12}). Fat-soluble vitamins (like E and A), and minerals (sodium, calcium, potassium, phosphorus, iron, copper, selenium, chromium, magnesium, manganese and zinc).	Jubie et al., 2012
	Protein is around 60% vital amino acids and total fat concentration is about 7%	Awad et al., 2023
	β-carotene, vitamin E and γ-linolenic acid	Holman and Malau-Aduli, 2013
	n-3 polyunsaturated fatty acids (9 points more) and crude fat about (12.6 points more).	Madeira et al., 2017
Schizochytrium sp.	Protein (about 12.1%), docosahexaenoic acid (DHA) and crude fat content ranging from 38.0 to 71.1%	Valente et al., 2020
Arthrospira platensis and *Chlorella vulgaris*	High biological value and high crude protein.	Becker, 2013
Chlorella vulgaris	Cobalamin (vitamin B_{12}) and protein (50–60%).	Madeira et al., 2017; Gutiérrez-Salmeán et al., 2015
	Beta-carotene.	Gille et al., 2016
	Fat 12.5%, proteins 61.6%, carbohydrates 13.7%, trace elements and vitamins (thiamine, B complex, C, E, D, and K).	Blas-Valdivia et al., 2011
Microalgae species	Total phenolics range from 510 to 2,200 mg. Gallic acid equivalent (GAE) per kilogram and vital flavonoids range from 66 to 550 mg per kilogram.	El-Chaghaby et al., 2019
	Calcium (0.33–2.8), sodium (3.2–3.9), phosphorus (0.65–0.76), potassium (0.89–1.7), and trace elements (mg/kg), including iron (1,390–11,100), zinc (28–64) and copper (18–102).	Tibbetts et al., 2015; Kalia et al., 2021

Mode of action of microalgae

B-carotene, phycocyanin, phycobiliproteins, zeaxanthin, and pigments are among the rich nutraceutical compounds in *Spirulina*, contributing to its nutritional enrichment. These compounds have promising biological activity as antioxidants, immunomodulators, anti-inflammatory, antibacterial, and antineoplastic agents (Agustini et al., 2015; Chaudhary et al., 2023). Microalgae possess antibacterial, antiviral, and health-promoting qualities. Abdel-Wareth et al. (2024) state that microalgae antioxidants may shield endogenous lipids from oxidation and peroxidation. Enzymes including glutathione (GSH), glutathione peroxidase (GPX), glutathione reductase (GR) and superoxide dismutase (SOD) are examples of endogenous antioxidants. The mode of action of microalgae is presented in Figure 2.

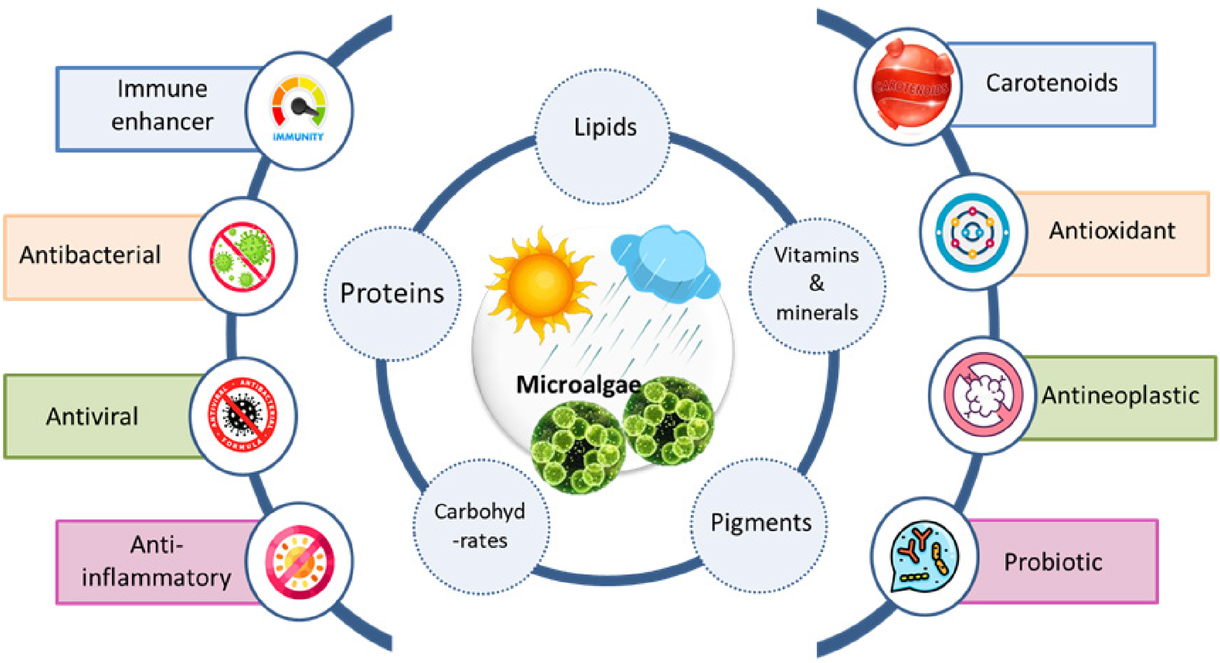

Figure 2. Mode of action of microalgae

Because of physiological and nutritional variables, broilers are more susceptible to lipid peroxidation, which increases peroxidative metabolites. Feeding bird's meals high in fat can cause oxidative stress, harming proteins, DNA, and bio-membrane lipids, among other tissue impairments (Delles et al., 2014). According to Lu et al. (2010), malondialdehyde (MDA) is a common lipid peroxidation consequence and a reliable oxidative stress marker.

Reactive oxygen species elimination and the availability of endogenous and exogenous antioxidants control the body's antioxidant level. In addition, birds fed the microalgae showed higher levels of SOD, and high total antioxidant capacity in their thigh and breast muscles as well as a higher ratio of polyunsaturated to saturated fatty acids, malondialdehyde, and polyunsaturated/saturated fatty acids due to the elevated SOD concentration in the microalgae (Long et al., 2018).

Spirulina platensis includes carotenoids, polysaccharides, phycocyanin and vital phenolic substances, which have been shown to have antibacterial, immunostimulatory, and antiviral properties (Dore et al., 2013). Adding microalgae (*Spirulina platensis*) to broiler diets significantly improved the standards of specific gut bacteria such as *Oscillospira*, *Lactobacillus*, *Ruminococcus*, *Oscillobacter*, *Colidextribacter* and *Flavonifractor*, which are known for improving volatile fatty acids. This inclusion contributes to the better formation of healthy gut microbiota in broiler chickens (Chaudhary et al., 2023). *Spirulina platensis* exhibits antiviral and antibacterial properties (Aladaileh et al., 2022). Algae vital compounds, like phycoerythrin, are widely used in biomedicine due to their anti-inflammatory and antibacterial properties (El-Shall et al., 2023). Probiotic concentrations of *Bifidobacterium longum*, *Streptococcus salivarius*, and *Lactobacillus acidophilus* in the gut of laying hens were considerably raised by feeding *Sarcodiotheca gaudichaudii* and *Chondrus crispus* at a 2% dietary inclusion level (Azeem et al., 2019).

Additionally, it has been shown that the compounds found in *Spirulina platensis*, including carotenoids, phycocyanin, polysaccharides, and phenolic chemicals, have hepatoprotective, immune-stimulatory, and anti-inflammatory effects (Cornish and Garbary, 2021). It has been discovered that broiler health and immunity are enhanced by *Spirulina* (Agustini et al., 2015). Broiler chicken diets supplemented with 5% *Spirulina* sp. increased immunological parameters, enhancing cellular and humoral immunity and the makeup of a healthy gut microbiota (Chaudhary et al., 2023). Compared to controls, broilers fed microalgae exhibited higher blood glucose, total cholesterol, albumin, urea, and creatinine concentrations, indicating improved nutritional and physiological properties (Long et al., 2018).

Another significant carotenoid that occurs naturally in algae is lutein (Yaakob et al., 2014). It is the second most prevalent carotenoid, typically found in algae and plants with dark green leaves and thylakoid membranes. It has strong antioxidant qualities (Cai et al., 2015). Lutein is the most prevalent carotenoid in *Chlorella* spp. cells among all others (Safafar et al., 2016), with the ability to accumulate up to 0.45% of the dry weight of the cell (Borowitzka, 2013). In certain cases, lutein may make up between 0.2% and 0.5% of the biomass of *Chlorella vulgaris*.

Beta-carotene is a primary carotenoid in *Chlorella vulgaris* (Gille et al., 2016). Supplementing culture media with salt can naturally increase the production of beta-carotene (Mojtaba et al., 2013). In cattle and aquaculture feeds, beta-carotene, which is produced by the microalgae and some plants, is utilized as a food coloring agent and increases pro-vitamin A (retinol) (Borowitzka, 2013; Yaakob et al., 2014). Because of its inherent antioxidant properties, astaxanthin – a carotenoid with 2 asymmetric carbons at the 3 and 3′ positions of the benzenoid rings on either end of the molecule – is referred to as "super vitamin E" (Yaakob et al., 2014). Its normal antioxidant activity is 10 times higher than ß-carotene and 500 times greater than α-tocopherol (Begum et al., 2016).

El-Kassas and Mohamed (2014) showed that lead (Pb), zinc (Zn), cadmium (Cd), chromium (Cr), and mercury (Hg) pollution in aquatic environments could be remediated using microalga species. As they have been shown to remove roughly 87.9% and 98.4% of total nitrogen and total phosphorous from polluted water, *Chlorella vulgaris* is good at utilizing the extra nutrients in aquatic environments, hence decreasing the eutrophication level (Sirakov et al., 2015; Singh et al., 2017). *Chlorella* species produce biomass protein by converting nutrients from wastewater. Furthermore, according to El-Kassas and Mohamed (2014), microalga cultivated in unfavorable settings detoxifies and changes aromatic amines from industrial effluents into simple organic amines and then algal biomass. *Chlorella vulgaris* efficiently bioabsorbs mercury, with less concomitant toxicity to the microalgal cell, even though mercury is considered the heavy metal with the highest toxicity index on microalgae (Peng et al., 2017).

Collectively, microalgae, particularly *Spirulina* and *Chlorella*, show great promise as nutritional supplements and environmental agents due to their rich content of proteins, essential amino acids, vitamins, antioxidants, and beneficial compounds like carotenoids and phycocyanin. These compounds offer various health benefits, such as antioxidant, anti-inflammatory, and immune-stimulatory effects, and can enhance gut microbiota in animals. Additionally, microalgae contribute to environmental sustainability by removing pollutants and excess nutrients from aquatic systems, thereby helping to manage water quality.

However, limitations include variability in nutrient composition among different species and environmental factors, which can affect their nutritional effectiveness and bioavailability. Moreover, large-scale application may face challenges due to potential high costs, and heavy metal bioaccumulation in polluted environments could pose risks, affecting both efficacy and safety as feed supplements.

Heat stress effects on poultry

In the poultry business, heat stress poses a major risk to the health and productivity of the birds. Extended exposure to elevated environmental temperatures can cause disruptions to fundamental biological functions, such as the redox system, which could hinder broiler productivity (Chaudhary, 2023). It has been observed that heat stress negatively impacts the digestion, carcass features, nutritional absorption, immunological response, immune organ development, and survival of broiler chickens (Lara and Rostagno, 2013; Zhang et al., 2015; Habibu et al., 2018; Hirakawa et al., 2020). The negative effects of heat stress are shown in Figure 3.

According to reports, broiler chickens exposed to syndrome heat stress at market age exhibit reduced growth performance, abnormalities in their serum metabolites, and unbalanced redox status (He et al., 2020). Additionally, broilers exposed to prolonged heat stress have been shown to have lower meat quality (Awad et al., 2020; Gonzalez-Rivas et al., 2020). The generally observed detrimental impacts of heat stress on broiler meat quality include decreased final pH and high lightness, cooking loss, and shear force (Gonzalez-Rivas et al., 2020). Heat stress eventually challenges the financial viability of chicken production in many nations, especially in the summer (Attia et al., 2011; Hajati et al., 2015).

Chaudhary (2023) discovered that while feed conversion ratio (FCR) increased in broilers, cyclic heat stress reduced average daily gain, final body weight, and average daily feed intake. According to a recent study by Almeldin et al. (2024), heat stress lowers the quantities of Fe in serum and tissue. This drop in Fe leads to a malfunction of the immune and antioxidant systems, which is detrimental to birds' health. This element is prevalent in the natural world and can be found in every ingredient used to make commercial poultry feeds. Mechanisms heavily dependent on Fe status are responsible for the absorption and transport of dietary Fe across the intestinal mucosa.

It could be concluded that heat stress is a significant challenge in poultry production, negatively impacting broiler health, productivity, and meat quality. Prolonged exposure to high temperatures disrupts biological systems, including digestion, nutrient absorption, immune function, and redox balance, which ultimately reduces growth performance, carcass quality, and survival rates. These effects threaten the economic sustainability of poultry farming, especially during hotter seasons.

However, limitations persist in fully mitigating these impacts, as factors such as environmental conditions and Fe deficiency, which weakens immune and antioxidant responses, continue to pose health risks for broilers. Comprehensive strategies for managing heat stress in poultry production are needed to address these complex physiological challenges.

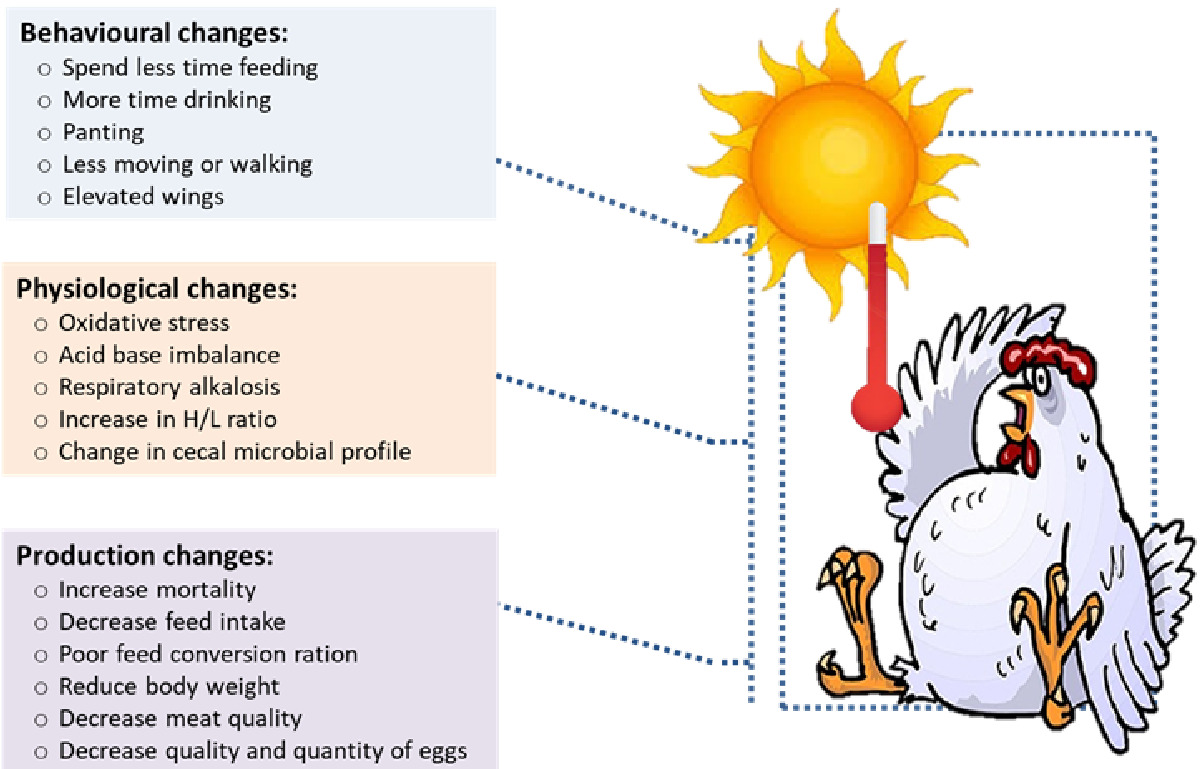

Figure 3. Negative effects of heat stress

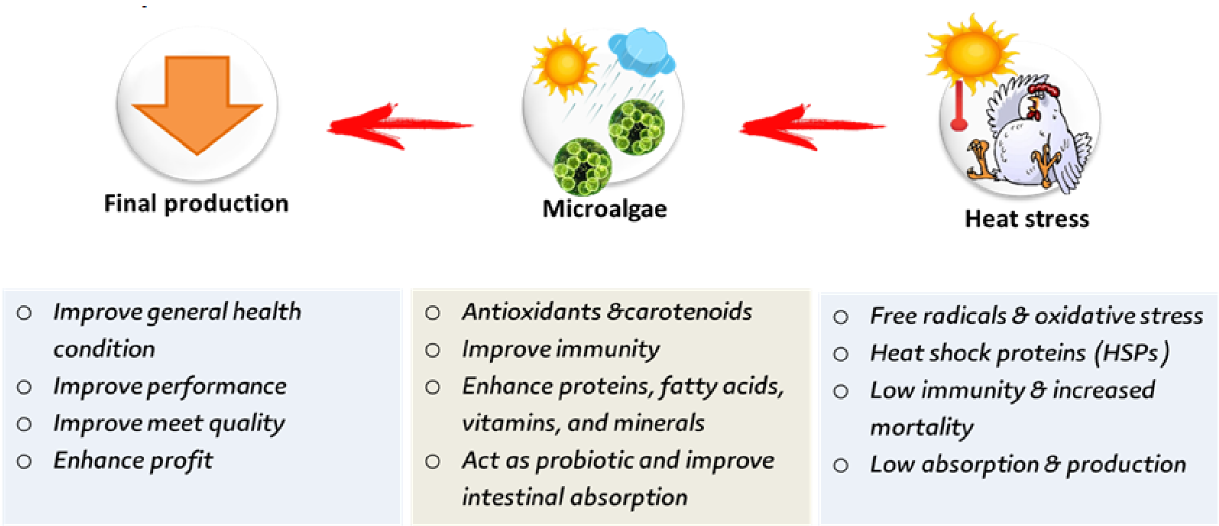

Figure 4. Effects of microalgae on birds during heat stress conditions

Beneficial effects of microalgae in heat stress

A vital source of animal-based protein for world consumption is broiler chickens. High temperatures, however, have a detrimental impact on the health and productivity of broilers, which causes the sector to suffer significant financial losses (Lara and Rostagno, 2013; Nawab et al., 2018; Humam et al., 2019). Thus, it is essential to use sustainable methods to decrease heat stress in broiler chickens. Microalgae supplements to the diet raised final body weight, average daily gain, and average daily feed intake while improving the feed conversion ratio. Furthermore, Chaudhary (2023) discovered that adding microalgae to the food enhanced the broiler heat-stressed animals' intestinal integrity, redox system and gut microbiome. This study's encouraging result raises the possibility that broiler supplements containing microalgae could help mitigate the negative impacts of heat stress. Because their natural antioxidant system cannot sufficiently remove cellular free radicals, broilers under heat stress are weaker than oxidative stress (Wasti et al., 2020). Effects of microalgae under heat stress are shown in Figure 4.

Chaudhary (2023) examined the expression of several genes linked to antioxidants in the ileum to comprehend how the redox system was enhanced by microalgae supplementation. Due to the microalgae's antioxidant qualities, heat-stressed broilers treated with the algae showed improved GPX3 expression. The broilers have become used to prolonged heat stress, as evidenced by the high expression of the GSTT1 gene in the under-heat stress group.

Physiological levels of free radicals, or ROS/RNS, are typically maintained. On the other hand, heat stress alters the redox dynamic and produces excessive free radicals, damaging nucleic acids, proteins and lipids through oxidative means (Arnaud et al., 2002). The combined activity of antioxidant genes, which contains catalase, superoxide dismutase and glutathione peroxidase, scavenges these free radicals. Because it catalyzes the conversion of superoxide to H_2O_2, which is then neutralized to H_2O and O_2 by glutathione peroxides and catalases, superoxide dismutase is regarded as the leading enzyme (Surai, 2016, 2018). Glutathione S-transferases, such as GSTT1, protect against H_2O-induced cellular damage by inhibiting the Jun N-terminal kinase (Sheehan et al., 2001). Thus, heat exposure induces oxidative stress that compromises intestinal integrity and nutritional absorption, which is why supplementing with microalgae improves intestinal epithelial damage. Heat shock proteins (HSPs) are generated in reaction to oxidative stress, which serves as molecular chaperones to shield cells from oxidative damage. Oxidative stress produces reactive oxygen species, which interact with biological proteins and reduce their functionality. According to Sikora and Grzesiuk (2007), HSPs are thus generated as a downstream mechanism to aid in protein structuring and inhibit protein aggregation. According to Fujimoto and Nakai (2010), heat shock proteins are biosynthesized more frequently when transcriptional factors such as heat shock factors (HSF1-4) attach to heat shock regulatory elements. Microalgae supplementation enhanced the synthesis of HSP70, HSP90, HSF1, and HSF3, as Chaudhary (2023) showed. HSF1 and HSF3 are important transcriptional regulators in producing significant heat shock proteins in avian species (Cedraz et al., 2017). According to Cedraz et al. (2017), HSF1 is thought to activate during medium thermal stress, while HSF3 is active at chronic thermal stress. HSF2 plays a little part in heat stress but is in charge of development and is active during neurogenesis, spermatogenesis, and embryogenesis (Pirkkala et al., 2001). As a result, adding microalgae to heat-stressed broilers increased the expression of heat-shock proteins, which is a hopeful outcome. A flock's immunological state is crucial to poultry production because it shields the birds from both endogenous and external diseases. Heat stress impairs immunity by interfering with immune organ development and decreasing birds' ability to fight off infections (Chegini et al., 2018; Hirakawa et al., 2020).

The TLR4 and NF-kB signaling pathways produce pro-inflammatory cytokines after pattern recognition receptors identify the infamous compounds (Tang et al., 2021). Birds' immune responses are largely stimulated by cytokines, which are immunological regulatory proteins released by a diverse range of cells. The body finds it more difficult to fight off infections under heat stress because it weakens the immune system and changes the expression of these immunological markers. On the other hand, a notable increase of the IL12 gene in heat-stressed broilers indicates that they have become accustomed to long-term heat stress. Interferon is produced and normal killer cells are stimulated by IL12 (Balu et al., 2011). Also, in a novel study, Chaudhary (2023) demonstrated that the birds treated with microalgae had higher mRNA expressions of immune genes, including TLR4, IL12, IL4 and NF-kB. These genes' elevated expressions are linked to improved immunity in birds given microalgae supplements because of the microalgae's immune-stimulating properties. Maintaining gut mucosal integrity is critical for limiting the paracellular diffusion of well-known antigens and facilitating effective nutrition absorption.

Heat stress syndrome is one of the numerous variables that can affect intestinal health by changing the length of the villi and lowering the small intestine's capacity for absorption (Burkholder et al., 2008). Chaudhary (2023) showed that in heat-stressed birds, ileal villi height was raised and crypt depth was reduced with microalgae supplementation. This means that the ratio of villi high to crypt depth, which is essential for effective nutrition absorption, was greatly raised by microalgae feeding. A bird grows more effectively when its nutrients are absorbed more effectively. The cecal unsteady fatty acids (acetate, butyrate and propionate) also affect the birds' performance. Bird immunity, barrier integrity, and gut development are all regulated by VFAs (Yang et al., 2020). According to Walugembe et al. (2015), VFAs regulate the proliferation of epithelial cells, control pH, encourage mineral absorption, and prevent the entry of harmful microbes into the gut. They also keep the environment in the gut appropriate. Most significantly, VFAs serve as a primary energy source for colonocytes and generate energy through gluconeogenesis and glycolysis (Jha et al., 2019).

Furthermore, VFA, particularly butyrate, reduces the amount of harmful bacteria that colonize the bowel (Jha and Mishra, 2021). In birds, plasma immunoglobulins may serve as indicators of immunological state. In the earlier investigation, plasma IgY, IgA and immunoglobulin levels were unaffected by supplementing with *Spirulina* in heat-stressed broilers (Elbaz et al., 2022). IgA, IgM, and IgY are the three main antibody classes unique to chickens among other bird species. The birds' immunological state and circulating antibody titers can be impacted by environmental status, like heat stress. More research is necessary to elucidate the basic mechanism of heat stress on the immune physiology of broilers, as there is a paucity of scientific information (Chaudhary, 2023).

According to Oakley and Kogut (2016), the gut microbiota is essential for immunological establishment, fermentation of polysaccharides, amino acid and VFA production, and gut development and maturation. Through reciprocal interactions, microbiota influences the operation of several organs, such as the gut-liver and gut-brain axes (Compare et al., 2012; Mullaney et al., 2022). Also, heat stress upsets the balance of the cecum microbiota, which results in comorbidity and impaired growth. Microalgae supplementation to the food enhanced the microbial wealth and variety in heat-stressed birds (Chaudhary, 2023). However, more research is needed to elucidate the underlying causes that can be connected to the impact of microalgal ingredients on cecal microbiota. The anatomical characteristics of the chicken gut, its shorter digestive tract and quicker digesta transit have a selection influence on microbial diversity, in contrast to other feeding animals (Pan and Yu, 2014). In a study by Shi et al. (2019), the *Oscillospira* population was reduced when broilers were exposed to heat stress. This conclusion is consistent with earlier research. On the other hand, the abundance of *Oscillospira* increased with the addition of microalgae. One of the key bacteria, *Ruminococcus*, ferments dietary fiber to produce butyrate, a volatile fatty acid essential for lowering inflammation and preserving the health of the gut epithelium (Lakshmanan et al., 2022).

Additionally, *Ruminococcus* is linked to the synthesis of neurometabolites, including N-acetyl aspartate, norepinephrine, and serotonin, which may have an impact on behavior and brain function (Mudd et al., 2017; Lukić et al., 2019). According to Chaudhary's (2023) research, the heat-stressed broilers exhibited a drop in the abundance of various bacterial species, such as *Turicibacter*, *Coprococcus*, *Blautia*, *Dorea*, and *Anaerotruncus*. In contrast, the microalgae-supplemented groups showed an increase in abundance. By altering lipid and bile acid metabolism, *Turicibacter* affects the body's fat composition (Lynch et al., 2022). Furthermore, research has demonstrated the connection between many bacterial genera, including *Anaerotruncus*, *Blautia*, *Dorea*, and *Coprococcus*, and the preservation of gut microbial equilibrium, as well as the production of vital vitamin B-complexes, VFAs, and host immunity (Nogal et al., 2021; Liu et al., 2021; Palmnäs-Bédard et al., 2022).

It is unclear, therefore, what function the majority of the bacteria in the broilers' ceca play. There may be other ramifications for the poultry industry if the type and impact of those bacteria on the gut health of the bird are recognized. The relationship between the microbiome and the host significantly impacts numerous biological processes. Also, gut dysbiosis can be detrimental and unfavorable to a bird's performance and overall health. Gut microbial wealth with beneficial bacteria can positively impact (Singh et al., 2021). Another study can determine the relationship between gut microbiota and several health indicators, even if the impact of bacteria on birds' health has not been adequately demonstrated. The results of the correlation analysis showed a strong link between the cecal microbiota and several genes. Ileal GPX3 expression had a favorable correlation.

In contrast, a negative correlation was found between *Lactobacillus* and sodium-dependent glucose transporter 1 (SGLT1). Through fermentation, immunological regulation, and intestinal homeostasis, these bacteria play a critical role in preserving gut health (Leal et al., 2023). *Ruminococcus* negatively correlated with the glucagon-like peptide 1 receptor (GLP1R) and peroxidoredoxin 1 (PRDX1). Many genes, including TLR4, CLDN1, CASP3, HSP70, HSF3, ZO2, and IL1ß, showed a negative correlation with *Romboutsia* and are thought to be involved in the control of cholesterol and lipid metabolism (Yin et al., 2023). *Lachno clostridium* has been linked through metagenomic research to some advantageous functions in intestinal health, including the synthesis of acetate (Nogal et al., 2021) and a connection to atherosclerosis in mice (Cai et al., 2022). The relationships between *Lachno clostridium* and ZO2, OCLN, NF-kB, IL4, CAT, and Cadherin were negative. According to Mikami et al. (2020) and Rodriguez-Castaño et al. (2020), *Flavonifractor* metabolizes flavonoids like quercetin and catechins and controls inflammation in obese mice. *Flavonifractor* exhibited a positive connection with SOD2 and NF-kB and a negative correlation with GLP2R. The bacteria that activate regulatory T-cells and reduce inflammation in animal models are called *Anaerotruncus*, and they have a negative correlation with the SGLT1 and SOD2 genes. Therefore, these bacteria might be crucial in immunological regulation, enhancing birds' abilities. A summary of the useful effects of microalgae in broilers under heat stress is in Table 2.

Selenium nanoparticle supplementation to *Spirulina* species enhanced antioxidant activities and growth performance in heat-stressed birds, according to Abdel-Moneim et al. (2022). The chicks were exposed to heat stress but still had access to additional dietary microalgae, which were boosted in their tissues and resulted in coordinated changes in their endogenous antioxidant defense and meat quality (Sun et al., 2018). Under conditions of chronic heat stress, supplementing broiler chickens with *Spirulina* significantly raises levels of SOD and GPX while lowering MDA levels (Agustini et al., 2015; Mirzaie et al., 2018). Additionally, it has been discovered that *Spirulina* helps birds stay healthy and immune and reduces oxidative stress brought on by heat stress (Mirzaie et al., 2018).

In summary, microalgae supplementation in broiler diets shows promise for alleviating heat stress impacts by enhancing antioxidant activity, gut health, immunity, and growth performance. The antioxidants, beneficial bacteria, and bioactive compounds in microalgae help strengthen broilers' resilience to heat-induced oxidative damage and gut microbiota imbalance, leading to better nutrient absorption and immune responses.

However, limitations include variability in microalgae composition, which may affect consistency in results, and gaps in understanding the exact mechanisms through which microalgae influence specific gut microbiota and gene expressions under heat stress. More research is needed to clarify these mechanisms and optimize supplementation for large-scale poultry production.

Table 2. Summary of useful effects of microalgae in broilers under heat stress

Dose/type	Useful effects	References
0.5, 1 or 1.5%. *Spirulina platensis*/Cobb 500	Decreased levels of blood cholesterol and low-density lipoprotein (LDL), and increased levels of high-density lipoprotein (HDL). This resulted in improved carcass dressing, breast, and leg percentages, decreased lipid peroxidation, and increased antioxidant enzyme activity.	Moustafa et al., 2021
3% of microalgae/Cobb 500	Increased the final body weight, tight-junction (CLDN2), immune-related (IL4), and ileal antioxidant (GPX3) gene expressions were elevated. There was an improvement in the ileal villus height to crypt depth ratio and increased microbial alpha and beta diversities. Increase in volatile fatty acid-producing bacteria (*Ocillospira, Ruminococcus*, *Lactobacillus*, *Flavonifractor*, *Oscillobacter*, and *Colidextribacter*).	Chaudhary et al., 2023
3 and 6% *Chlorella vulgaris*/ Ross 308	Decreased feed intake, in addition to the percentage of n3 polyunsaturated fatty acids (PUFA), the breast muscle's enhanced yellow and red indices.	Cabrol et al., 2024
1% *Spirulina platensis*/ Ross 308	Enhancing broiler meat's oxidative stability, quality, and carcass yield under heat stress conditions.	Ranjbarinasab et al., 2024
1.33 mg/kg astaxanthin/Cobb 500	Exhibit increased expression of genes related to cytoprotection and epithelial integrity, indicating that astaxanthin may improve how cells react to heat stress to reduce oxidative damage and increase cytoprotective potential.	Kuehu et al., 2024
1 g/kg microalgae/Ross 308	Improving the productivity of broilers, Fe retentions, carcass features, meat quality, and lowering ammonia excretions.	Almeldin et al., 2024

Conclusions

One of the world's main sources of protein is poultry meat. Oxidative stress can be brought on by free radicals produced by heat stress in the cell, especially ROS and reactive nitrogen species (RNS). Numerous studies have demonstrated the detrimental effects of heat stress on broiler reproductive, central neurological, respiratory, digestive, and immune systems. Numerous studies have demonstrated how heat stress reduces meat quality, growth performance, and carcass traits and increases mortality rates. Using photosynthesis, microalgae produce biomass from carbon dioxide and sunlight, with oxygen and water vapor emerging as byproducts. Microalgae may be grown in a broad range of habitats and are also stress-tolerant, allowing them to be grown in freshwater and marine environments. Three types of microalgae are frequently used: *Chlorella* sp., *Dunaliella salina*, and *Spirulina platensis*. Microalgae include a variety of beneficial substances, including protein, lipids, vitamins, and minerals. Microalgae offer numerous benefits, including boosting immunity and acting as an antioxidant, antibacterial, and antiviral. Many important carotenoids (beta-carotene, lutein, and astaxanthin) are found naturally in microalgae, reducing the negative impacts of heat stress. Microalgae have been widely used and have proven their efficiency in decreasing the impacts of heat stress in poultry. More studies are needed to clarify the possibility of using them in poultry drinking water.

Conflicts of interest

All authors declare that they have no conflicts of interest that could inappropriately influence this manuscript.

Author contribution

All authors contributed equally to writing this review article. All authors read and approved the final version of this manuscript.

Data availability statement

No data are available.

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