Review Article

MICROALGAE AS MULTIFUNCTIONAL FEED ADDITIVES IN POULTRY: ROLES IN NUTRITION, HEALTH AND PRODUCT QUALITY

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ABSTRACT

Microalgae have gained increasing attention as multifunctional feed ingredients in poultry nutrition due to their rich content of bioactive compounds, including pigments, polyunsaturated fatty acids, vitamins, minerals, polysaccharides, and secondary metabolites. This review summarizes experimental evidence on the functional properties of major microalgal species such as Spirulina (Arthrospira platensis), Chlorella spp., Haematococcuspluvialis, Nannochloropsis, Schizochytrium, and other marine microalgae in poultry diets. Emphasis is placed on their antioxidant, antimicrobial, anti-inflammatory, immunomodulatory, and gut healthpromoting effects. Microalgal supplementation enhances endogenous antioxidant defence systems, modulates cytokine responses, suppresses enteric pathogens, and improves intestinal morphology and microbiota composition. These functional effects translate into improved stress tolerance, immune competence, nutrient utilization, and overall bird health. In addition, microalgae positively influence poultry product quality by enhancing yolk pigmentation, enriching eggs and meat with omega-3 fatty acids, and improving oxidative stability and sensory attributes. Variability in responses across studies is largely associated with differences in algal species, inclusion level, processing form, duration of feeding, and physiological status of birds. Overall, microalgae represent promising natural feed additives for sustainable poultry production, although further research is needed to optimize their practical application at commercial scale.

Keywords: Microalgae, Poultry nutrition, Antioxidant, Immune modulation, Gut health, Egg and meat quality

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INTRODUCTION

Microalgae represent a diverse group of unicellular, photosynthetic microorganisms that include both eukaryotic microalgae and prokaryotic cyanobacteria. They are characterized by rapid growth rates, efficient nutrient utilization, and the capacity to synthesize a wide array of bioactive metabolites. In poultry nutrition, several species have attracted considerable attention, including *Spirulina*

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(*Arthrospira platensis*), *Chlorella vulgaris*, *Schizochytrium spp*., *Nannochloropsis spp*., *Haematococcuspluvialis*, *Dunaliellasalina*, and *Euglena gracilis*. These microalgae are rich sources of high-quality proteins and essential amino acids, long-chain polyunsaturated fatty acids (PUFAs) such as DHA and EPA, carotenoids (astaxanthin, lutein, β-carotene, fucoxanthin), phycobiliproteins including phycocyanin, structural polysaccharides such as β-glucans, vitamins, minerals, and diverse phenolic compounds (El-Ghany, 2020; Van Nerom *et al.*, 2024; Zhang *et al.*, 2025; Nuhu, 2013; Pugh *et al.*, 2001; Novoveská *et al.,* 2023).

Their incorporation into poultry diets has increased substantially due to their ability to supply natural pigments, potent antioxidants, omega-3 PUFAs, immunomodulatory polysaccharides and antimicrobial substances (Zhang *et al.*, 2025). Unlike conventional single-function feed additives, microalgae exert multiple physiological effects. These include scavenging reactive oxygen species (ROS), enhancing endogenous antioxidant defence systems, modulating inflammatory and immune signalling pathways, improving intestinal microbiota composition and gut architecture, and directly inhibiting pathogenic microorganisms (Van Nerom *et al.,* 2024). Such multifunctional activity enables concurrent improvements in bird health, stress resilience, growth performance, and product quality under environmental or biological challenges (El-Ghany, 2020; Zhang *et al.,* 2025).

Given their broad phytochemical profile and biological versatility, microalgae are increasingly recognized as promising multifunctional feed additives for sustainable poultry production. This review provides a comprehensive synthesis of the principal functional roles of microalgae in poultry nutrition, supported by experimental evidence from studies conducted in broilers and laying hens.The bioactive compounds present in microalgae and their biological actions at the cellular and molecular levels, tissue level, as well as their effects on production performance and product quality, are illustrated in Figure 1. The major findings from published literature on microalgae used in poultry nutrition including species, inclusion levels, duration of feeding, and their effects on production performance and functional traits are systematically summarized in Tables 1 and 2.

Antioxidant properties of microalgae in poultry

Microalgae are widely recognized for their strong antioxidant potential, which plays a central role in enhancing health, productivity, and stress resilience in poultry. Species such as *Spirulina* (*Arthrospira platensis*), *Chlorella vulgaris*, *Haematococcuspluvialis*, *Nannochloropsis*, and DHA-rich marine microalgae provide a concentrated source of natural antioxidants that promote cellular protection and physiological stability (El-Ghany, 2020; Van Nerom *et al.*, 2024; Zhang *et al.*, 2025).

Their antioxidant activity operates through both direct radical scavenging and stimulation of endogenous defence systems. Microalgae are rich in carotenoids (astaxanthin, lutein, β-carotene, fucoxanthin, zeaxanthin), phycobiliproteins, chlorophyll, polyphenols, vitamins (A, C, E, B-complex) and essential minerals. These compounds function as non-enzymatic antioxidants, neutralizing reactive oxygen species (ROS) and reducing lipid peroxidation. Carotenoids, in particular, protect cellular membranes from oxidative damage, while pigments such as phycocyanin contribute additional ROS-quenching capacity.

Beyond direct scavenging effects, microalgae enhance endogenous antioxidant enzymes. Feeding trials in broilers and layers consistently report increased activity of superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx), alongside reduced malondialdehyde (MDA), a marker of oxidative stress. Such responses are especially evident under heat stress and other environmental challenges (Mirzaie *et al.*, 2018; Park *et al.*, 2018; Abdel-Moneim *et al.,* 2022; El-Bahr *et al.,* 2020). Supplementation with *Spirulina, Chlorella*, *Haematococcus*, and *Nannochloropsis* has also been shown to elevate glutathione levels and total antioxidant capacity, while DHA-rich microalgae improve hepatic antioxidant status (Long *et al.,* 2018). While effects of Chlorella may vary with dosage and duration, higher inclusion levels (e.g., 2%) improve total antioxidant capacity in layers (Panaite *et al.*, 2023), consistent with its carotenoid- and vitamin-rich profile (El-Ghany, 2020).

Oxidative stress in poultrytriggered by heat stress, mycotoxins, or pathogen exposureleads to ROS accumulation, cellular injury, and compromised performance. Microalgae mitigate these effects by enhancing antioxidant gene expression, protecting lymphoid organs against toxin-induced damage, and supporting immune cell function (Raju *et al.*, 2005; Chaudhary *et al.,* 2023).

Importantly, antioxidant benefits extend to product quality. Microalgae improve oxidative stability of meat and eggs by preserving polyunsaturated fatty acids and enhancing carotenoid deposition, thereby reducing lipid oxidation and improving shelf life (Dal Bosco *et al.*, 2014; Englmaierová *et al.,* 2013; Rizzi *et al.*, 2009). Additionally, modulation of gut microbiota toward beneficial lactic acid–producing bacteria may indirectly reduce oxidative burden, contributing to improved metabolic efficiency and systemic resilience.

Antimicrobial properties of microalgae in poultry

Microalgae possess pronounced antimicrobial and gut-modulating properties that contribute substantially to intestinal health, pathogen control, and microbial balance in poultry. Their bioactive constituentsincluding polyunsaturated fatty acids (PUFAs), phenolics, carotenoids, polysaccharides, alkaloids, and antimicrobial peptidesexert direct antibacterial effects while simultaneously supporting beneficial microbial communities and strengthening gut integrity (El-Ghany, 2020; Van Nerom *et al.*, 2024; Zhang *et al.*, 2025).

Direct antimicrobial activity has been widely documented, particularly for *Spirulina platensis*. Crude extracts inhibit several major poultry pathogens, including *Klebsiella pneumoniae*, *Shigella shigae*, *Pseudomonas aeruginosa*, *Escherichia coli*, *Proteus vulgaris*, *Salmonella typhi*, and *Staphylococcus aureus* (Mala *et al.*, 2009). Comparable inhibitory effects against *S. aureus*, *E. coli*, *S. typhi*, and *Enterococcus faecalis* were reported by Kaushik and Chauhan (2008) and El-Baz *et al.* (2013). In vivo studies further confirm these findings; *Spirulina* improved pathogen clearance in chicks experimentally infected with *E. coli* and *S. aureus* (Nuhu, 2013). These effects are attributed to bioactive molecules such as γ-linolenic acid, lauric and palmitoleic acids, alkaloids, and lipopolysaccharides, which disrupt bacterial membranes and interfere with cellular metabolism (El-Sheekh *et al.*, 2014). Marine microalgae also produce phenolics, terpenoids, antimicrobial peptides, and fatty acid derivatives capable of inhibiting pathogens such as *Listeria* and *Salmonella* through membrane destabilization and metabolic disruption (Ferrazzano *et al.*, 2020; Rojas *et al.*, 2020; Balakrishnan *et al.*, 2021; Stirk and van Staden, 2022).

In practical feeding trials, microalgae reduce pathogenic bacterial loads within the gastrointestinal tract. Dietary *Arthrospira platensis* at 0.02% significantly decreased E. coli counts in broilers (Khalilnia *et al.*, 2023). Supplementation with astaxanthin-rich *Haematococcus pluvialis* lowered caecal *Clostridium perfringens* populations and, in some cases, *Campylobacter* counts (Waldenstedt *et al.,* 2003). However, antimicrobial responses are species-specific; for example, *Tetraselmischuii* at 2% did not reduce *Salmonella infantis* following experimental infection (Corrales-Martinez *et al.*, 2022), highlighting variability in efficacy.

Beyond direct inhibition, microalgae promote competitive exclusion by enhancing beneficial bacterial populations. *Spirulina* consistently increases *Lactobacillus* counts in broilers, quails, and layers (Mariey *et al.*, 2012; Shanmugapriya *et al.*, 2015; Yusuf *et al.,* 2016). Similarly, *Chlorella* improves *Lactobacillus* abundance and bacterial diversity in laying hens and ducks (Janczyk *et al.*, 2009; Oh *et al.*, 2015), while *Spirulina* supplementation enhances cecal *Lactobacilli* in broilers (Park *et al.*, 2018). Fathi *et al.* (2018) further reported reduced total intestinal bacteria and *E. coli* counts alongside increased *Lactobacillus* populations. Under heat stress, microalgae also stimulate short-chain fatty acid (SCFA)-producing genera such as *Ruminococcus*, *Oscillospira*, *Flavonifractor*, and *Colidextribacter* (Chaudhary *et al.*, 2023). SCFAs lower gut pH, inhibit pathogen colonization, and enhance mucosal immunity (Liu *et al.*, 2021).

Collectively, these antimicrobial and microbiota-modulating effects are reinforced by prebiotic-like actions. Red seaweeds such as *Chondruscrispus* and *Sarcodiothecagaudichaudii* improve gut microbiota and productivity in layers (Kulshreshtha *et al.*, 2014). Microalgal polysaccharides, carotenoids, and PUFAs strengthen gut barrier integrity, promote villus development, and reduce enteric inflammation (Choo *et al.*, 2020; Ávila-Román *et al.*, 2021; Talero *et al.*, 2015; Nabil-Adam *et al.*, 2023). Moreover, species such as *Spirulina*, *Chlorella*, and *Dunaliella* enhance digestive enzyme activity and immune responsiveness, further supporting gastrointestinal stability (Alghamdi *et al.*, 2024).

Anti-inflammatory properties of microalgae in poultry

Microalgae contain a diverse array of bioactive compounds that confer significant anti-inflammatory benefits in poultry, thereby enhancing immunity, disease resistance, and resilience to environmental and metabolic stressors. Species such as *Spirulina* (*Arthrospira platensis*), *Chlorella*, *Schizochytrium*, *Nannochloropsis*, and several marine microalgae are particularly recognized for these properties. Their anti-inflammatory actions arise from the synergistic effects of polyunsaturated fatty acids (PUFAs), carotenoids, phenolics, vitamins, flavonoids, pigments, and structural polysaccharides (El-Ghany, 2020; Van Nerom *et al.*, 2024; Zhang *et al.*, 2025).

A central mechanism involves the modulation of lipid-mediated inflammatory pathways. Microalgae are rich in DHA, EPA, and ALA—fatty acids that poultry cannot synthesize efficientlywhich regulate the arachidonic acid cascade and reduce the production of pro-inflammatory eicosanoids such as prostaglandins and leukotrienes (Van Nerom *et al.*, 2024; Zhang *et al.*, 2025). Concurrently, carotenoids (β-carotene, fucoxanthin, lutein, astaxanthin), polyphenols, and phycocyanin exert strong antioxidant effects, limiting oxidative stress that otherwise triggers inflammatory signalling (El-Ghany, 2020; Van Nerom *et al.*, 2024; Zhang *et al.*, 2025).

Microalgal structural polysaccharides, including β-glucans from *Euglena* and *Chlorella*, further regulate inflammatory responses by modulating cytokine production and enhancing immune coordination (Van Nerom *et al.,* 2024). Polysaccharides in *Chlorella* also stimulate immunoglobulin synthesis, leukocyte proliferation, and lymphoid tissue development, indirectly contributing to controlled inflammatory responses (El-Ghany, 2020).

At the molecular level, several metabolites directly influence cytokine expression. *Spirulina* supplementation elevates interferons and antibody titres during immune challenges, thereby moderating excessive inflammatory reactions (El-Ghany, 2020). In heat-stressed broilers, dietary *Spirulina* increased IL-4 while decreasing IL-12 expression, reflecting a shift toward an anti-inflammatory cytokine profile (Van Nerom *et al.*, 2024). Microalgae also suppress key pro-inflammatory mediators such as TNF-α, IL-1β, and IL-6 (Zhang *et al.,* 2025). Moreover, inflammatory signalling pathways including NF-κB and COX-2 are downregulated by polyphenols and glycoglycerolipids, limiting transcription of inflammatory genes and attenuating both acute and chronic inflammatory responses (Zhang *et al.,* 2025).

Protective effects are particularly evident under stress conditions. *Spirulina* mitigates aflatoxin-induced inflammation by reducing lymphoid organ damage and enhancing thymus, spleen, and bursa development (El-Ghany, 2020). These effects are linked to improved antioxidant status and enhanced phagocytic activity. Microalgae also strengthen gut mucosal integrity; improvements in villus height, crypt structure, and goblet cell populations have been reported with *Spirulina, Chlorella,* and *Porphyridium* supplementation (Van Nerom *et al.,* 2024). Enhanced barrier integrity reduces microbial translocation and associated inflammatory signalling (Zhang *et al*., 2025).

Because oxidative stress and inflammation are closely interconnected, the antioxidant properties of microalgae reinforce their anti-inflammatory actions. Increased SOD, CAT, and GPx activity, coupled with reduced MDA levels, collectively stabilize tissues and moderate cytokine release (El-Ghany, 2020; Van Nerom *et al.,* 2024). Overall, microalgae regulate inflammation through coordinated lipid, antioxidant, cytokine, and gut-mediated mechanisms.

Immunomodulatory properties of microalgae in poultry

Microalgae such as *Spirulina* (*Arthrospira platensis*), *Chlorella vulgaris*, *Euglena gracilis*, *Dunaliella*, and several marine microalgal species exert pronounced immunomodulatory effects in poultry. Their rich composition of high-quality proteins, essential fatty acids, β-glucans, vitamins, minerals, carotenoids, pigments, and polysaccharides enables them to influence both innate and adaptive immunity, thereby enhancing disease resistance and improving resilience under stress conditions (El-Ghany, 2020; Van Nerom *et al*., 2024; Zhang *et al.,* 2025).

Evidence of immune stimulation was first demonstrated in early experimental studies. *Spirulina* supplementation enhanced macrophage phagocytic activity, stimulated lymphocyte proliferation, and promoted the development of primary and secondary lymphoid organs, including the thymus, spleen, and bursa of Fabricius (Qureshi *et al*., 1996; Raju *et al*., 2005). Broilers receiving *Spirulina* exhibited elevated white blood cell counts and increased phagocytic capacity, indicating strengthened innate immunity (Al-Batshan *et al*., 2001). These responses are partly attributed to its zinc-rich composition, which supports cellular immune functions (Abdel-Daim *et al*., 2013; Abou-Gabal *et al.*, 2015). Similarly, β-glucans present in *Chlorella* and *Euglena* are well-established immunostimulants that activate macrophages and B-cells and enhance cytokine synthesis (Pugh *et al.,* 2001). In broilers challenged with *Eimeria*, dietary *Euglena gracilis* increased intestinal macrophage infiltration, further confirming its role in reinforcing innate immune responses (Levine *et al.,* 2018).

Beyond innate immunity, microalgae consistently enhance humoral immune responses. Supplementation with *Spirulina* has been shown to increase antibody titres against Newcastle disease virus, avian influenza virus, and sheep red blood cells (Zeweil *et al.,* 2016; Mobarez *et al.,* 2018). *Chlorella* supplementation improves lymphocyte counts, circulating immunoglobulin concentrations, and lymphoid tissue development, along with enhanced phagocytic activity (Kang *et al.*, 2013; Moradikor and Mohamadi, 2015). Additional studies have confirmed increased immunoglobulin synthesis following microalgal inclusion in diets (Pugh *et al.*, 2001; Abdelnour *et al.*, 2019). However, immunological responses are influenced by bird age, strain, environmental stressors, and dietary inclusion levels; some investigations reported no significant changes in IgA or IgY levels in heat-stressed broilers or layers fed *Nannochloropsis* (Mens *et al.*, 2022; Chaudhary *et al*., 2023).

Microalgae also regulate immune homeostasis through modulation of cytokine profiles and inflammatory signalling pathways. In heat-stressed broilers, dietary inclusion of 3% *Spirulina* increased IL-4 expression while reducing IL-12, suggesting a shift toward a Th2-biased, anti-inflammatory immune response (Chaudhary *et al*., 2023). Carotenoids such as astaxanthin and lutein further modulate immune signalling and protect immune cells from oxidative damage, thereby enhancing functional competence (Novoveská *et al.,* 2023). Moreover, microalgal bioactive compounds influence regulatory pathways such as NF-κB and COX-2, contributing to improved cytokine balance and mitigation of inflammation-associated immune suppression (Talero *et al*., 2015; Nabil-Adam *et al.,* 2023).

Importantly, microalgae demonstrate protective effects under stress and disease conditions. *Spirulina* alleviates mycotoxin-induced immunosuppression by improving lymphoid organ weights and enhancing T-cell activity (Raju *et al.*, 2005). It also increases leukocyte counts and has been suggested as a supportive immunostimulant during avian influenza (H5N1) exposure. Species such as *Dunaliellasalina* and *Spirulina* enhance immune responses during heat stress, partly through antioxidant–immunomodulatory synergy that elevates SOD, GPx, and CAT activity (Chaudhary *et al.*, 2023; Alghamdi *et al.*, 2024).

Finally, gut-mediated mechanisms play a critical role in immunomodulation. Microalgae increase beneficial microbial populations, particularly *Lactobacillus,* alongside improvements in villus height and intestinal integrity, thereby strengthening mucosal immunity and reducing pathogen load (Chang *et al.,* 2021). Enhanced barrier function and nutrient absorption further support systemic immune competence (Choo *et al*., 2020). Collectively, these coordinated effects position microalgae as multifunctional immunomodulators in poultry nutrition.

Effects pf microalgae on intestinal histology of poultry

Dietary supplementation with microalgae consistently exerts beneficial effects on intestinal histomorphology in poultry, leading to improved villus architecture, enhanced absorptive surface area, and strengthened mucosal integrity. These structural improvements are closely linked to the antioxidant, antimicrobial, immunomodulatory, and microbiota-modulating properties of species such as *Spirulina* (*Arthrospira platensis*), *Chlorella vulgaris*, *Haematococcuspluvialis*, *Porphyridiumcruentum*, *Tetraselmischuii*, and *Dunaliellasalina* (El-Ghany, 2020; Van Nerom *et al.*, 2024; Zhang *et al.*, 2025).

One of the most consistently reported outcomes is an increase in villus height (VH), a key indicator of enhanced nutrient absorption. Spirulina supplementation promotes villus elongation partly through stimulation of beneficial gut microbiota, particularly *Lactobacillus* spp., which supports epithelial regeneration and mucosal health (Mariey *et al.*, 2012; Shanmugapriya *et al.*, 2015; Yusuf *et al.*, 2016). Concurrent reductions in pathogenic bacteria such as *Escherichia coli* and *Clostridium perfringens* further decrease mucosal inflammation, indirectly facilitating increased VH and reduced crypt hyperplasia (Fathi *et al.*, 2018). Comparable improvements have been reported with *Chlorella* supplementation; enhanced microbial balance in the crop and ceca of ducks and laying hens was associated with improved villus morphology and increased mucosal thickness (Janczyk *et al.*, 2009; Oh *et al.*, 2015). Likewise, astaxanthin-rich *Haematococcuspluvialis* reduced *C. perfringens* colonization, resulting in diminished intestinal tissue damage and improved villus structure (Waldenstedt *et al.*, 2003).

Beyond absolute villus height, microalgae frequently increase the villus height–crypt depth ratio (VH:CrD), reflecting improved intestinal maturity and reduced epithelial turnover. Both high (3–6%) and low (0.02–0.03%) inclusion levels of *Spirulina* enhanced VH and VH:CrD while reducing crypt depth in broilers, indicating more efficient mucosal renewal and absorptive function (Sefcová *et al.,* 2021; Khalilnia *et al.*, 2023). Other species, including *Porphyridium cruentum, Tetraselmischuii*, and *Tisochrysis lutea*, significantly increased duodenal and ileal VH as well as goblet cell numbers (Sefcová *et al.*, 2021). Similarly, *Dunaliell asalina* supplementation produced dose-dependent improvements in VH and VH:CrD in laying hens (Fernandes *et al.*, 2020). However, responses are not uniform; *Nannochloropsislimnetica* showed minimal histological changes in hens (Mens *et al.,* 2022), and low-level *Chlorella* inclusion (<1%) often failed to influence VH or crypt depth (Lee *et al.*, 2023).

Microalgae also enhance goblet cell density, thereby increasing mucin production and strengthening the intestinal barrier. *Spirulina* and *Porphyridium cruentum* have demonstrated notable effects in augmenting goblet cell populations (Sefcová *et al.,* 2021). Improvements in tunica muscularis thickness, although inconsistent, may contribute to better peristalsis and mucosal support. Extracts enriched with mesobiliverdin IXα further promote epithelial integrity by stimulating *Lactobacillus* proliferation and villus development (Chang *et al.*, 2021).

Under environmental stress, particularly heat stress, intestinal integrity is compromised. Microalgae mitigate these adverse effects by enhancing VH:CrD, improving overall histomorphology, and upregulating tight-junction and antioxidant genes (Chaudhary *et al.*, 2023). For instance, 3% *Spirulina* improved ileal VH:CrD in heat-stressed broilers, highlighting its protective role.

Collectively, through direct epithelial support and indirect microbiota-mediated mechanisms, microalgae promote healthier villi, stabilize crypt architecture, and enhance nutrient absorption, thereby improving overall intestinal resilience in poultry (El-Ghany, 2020).

Effects of microalgae on egg quality

Microalgae are increasingly utilized as functional feed ingredients to enhance the nutritional, sensory, and functional quality of eggs. Their richness in carotenoids, polyunsaturated fatty acids (PUFAs), vitamins, minerals, and other antioxidant compounds enables targeted improvements in yolk composition and stability (El-Ghany, 2020; Van Nerom *et al.*, 2024; Zhang *et al.*, 2025). One of the most visible and commercially important effects is enhanced yolk pigmentation. Carotenoid-rich species such as *Spirulina* intensify yolk color, producing deeper yellow to orange hues in layers and quails (Mariey *et al.*, 2012; Shanmugapriya *et al.*, 2015). *Chlorella vulgaris* increases yolk concentrations of lutein and zeaxanthin, resulting not only in richer pigmentation but also improved oxidative stability (Englmaierová *et al.*, 2013). Similarly, marine microalgae such as *Haematococcus pluvialis* (astaxanthin source) and *Phaeodactylum* contribute to red–orange pigmentation, further enhancing consumer appeal (Panaite *et al.*, 2023; Van Nerom *et al.*, 2024).

Beyond color, omega-3-rich microalgae substantially improve yolk fatty acid profiles. Supplementation with *Schizochytrium*, *Nannochloropsis*, or *Isochrysis* enhances deposition of DHA, EPA, and ALA in the yolk, thereby reducing the n-6:n-3 ratio and increasing the functional value of eggs (Rizzi *et al.*, 2009; Emam *et al.*, 2024). DHA-rich algal sources improve yolk lipid composition without compromising sensory attributes (Long *et al.*, 2018; Zhang *et al.*, 2025). In addition, *Spirulina* and *Chlorella* supplementation enhances yolk antioxidant capacity, improves protein digestibility, and enriches overall nutrient composition (Panaite *et al.*, 2023). Natural antioxidants present in microalgae reduce lipid peroxidation, thereby improving shelf-life and maintaining egg quality during storage (Zhang *et al.*, 2025). Collectively, these effects support the production of value-added functional eggs with enhanced nutritional and market value.

Effects of microalgae on meat quality

Microalgae also exert significant benefits on poultry meat quality by improving fatty acid composition, oxidative stability, pigmentation, and overall biochemical properties. Inclusion of *Spirulina*, *Chlorella,* and DHA-rich microalgae in broiler diets increases n-3 and n-6 PUFA content in breast and thigh muscles, enhancing the nutritional profile of meat (Dal Bosco *et al*., 2014; Bonos *et al*., 2016; Long *et al*., 2018). Improved serum and tissue fatty acid profiles translate into healthier meat products with greater consumer appeal (Zhang *et al*., 2025).

Antioxidant-rich microalgae reduce lipid oxidation and improve meat stability during storage. Species such as *Spirulina* and *Haematococcuspluvialis* lower oxidative deterioration through their high carotenoid, vitamin E, and phycocyanin contents (Waldenstedt *et al*., 2003; El-Ghany, 2020; Van Nerom *et al*., 2024). Dietary *Spirulina* enhances endogenous antioxidant enzyme activity (SOD, GPx, CAT), further stabilizing muscle tissues and maintaining freshness (Park *et al*., 2018). Microalgae also influence meat color and sensory attributes; Spirulina imparts a desirable darker tone due to pigment deposition (Bonos *et al*., 2016), while astaxanthin-rich sources enhance red pigmentation and reduce drip loss, improving texture and visual appeal (Waldenstedt *et al*., 2003; Abdel-Wareth *et al*., 2024).

In addition, microalgae indirectly improve carcass characteristics by enhancing nutrient utilization, gut health, and immune competence. Improved feed efficiency and muscle deposition contribute to better carcass yield (Fathi *et al*., 2018; Yusuf *et al*., 2016), while reduced *Clostridium perfringens* contamination enhances meat safety (Waldenstedt *et al*., 2003; Khalilnia *et al*., 2023). Improvements in amino acid profiles, reduced cholesterol levels, and enhanced muscle biochemistry further support tenderness, juiciness, and overall meat quality (An *et al*., 2016; El-Bahr *et al.,* 2020; Zhang *et al*., 2025).

Recommended dietary inclusion ranges of microalgae in poultry diets

Although variability exists in biomass composition, processing methods, bird genotype, and production systems, tentative inclusion ranges can be proposed for broilers and layers based on available literature evidence. In broilers, *Spirulina* (*Arthrospira platensis*) is most frequently used at 1.0–2.0%, a range consistently associated with improvements in growth performance, antioxidant status, immune responses, and intestinal morphology. *Chlorella vulgaris* generally produces favourable outcomes at 0.5–2.0%, with approximately 1% often sufficient to enhance immune function and microbial balance without compromising feed efficiency. DHA-rich marine microalgae such as *Schizochytrium* and *Nannochloropsis* are typically incorporated at 0.5–2.0% to enrich meat fatty acid profiles while maintaining productive performance.

In laying hens, *Spirulina* and *Chlorella* are commonly included at 0.5–2.0%, contributing to improved yolk pigmentation, enhanced antioxidant capacity, and better overall egg quality traits. For targeted omega-3 enrichment, marine microalgae are generally added at 1–3%, resulting in dose-dependent increases in yolk DHA deposition. These suggested ranges are indicative and should be optimized according to specific production objectives, environmental conditions, and economic feasibility.

General considerations and limitations

Consistent functional benefits of microalgae are evident across studies; however, heterogeneity in reported responses is substantial. Sources of variability include algal species and strain, biomass quality and processing (fresh, dried, or extracted), inclusion rate and duration, bird species and strain, rearing environment and stressors, and interactions with other diet components (Van Nerom *et al.*, 2024). Several practical constraints remain: large-scale algal production and stabilization, economic feasibility of inclusion at functional doses, potential sensory changes at high inclusion levels, and regulatory acceptance for specific algal products (El-Ghany, 2020, Van Nerom *et al.*, 2024). Additionally, many studies differ in experimental design and outcome measures, complicating meta-analysis and direct comparison (El-Ghany, 2020, Abdel-Wareth *et al.*, 2024).

Future research directions and knowledge gaps

Although numerous studies have demonstrated the beneficial effects of microalgae in poultry nutrition, several important knowledge gaps and methodological limitations remain (El-Ghany, 2020; Van Nerom *et al.*, 2024; Zhang *et al.*, 2025). A critical review of the literature reveals substantial heterogeneity among studies with respect to algal species and strain, cultivation conditions, biomass processing methods (fresh, dried, extracted, or fermented), inclusion levels, duration of supplementation, and growth phase of birds at feeding (Novoveská *et al.*, 2023; Van Nerom *et al.*, 2024). In addition, many studies lack comprehensive compositional characterization of the microalgal biomass, which limits reproducibility and hinders meaningful comparison across experiments (Zhang *et al.*, 2025; Novoveská *et al.*, 2023). Standardized and uniform reporting of nutrient composition and bioactive profiles is therefore essential.

Most published investigations are short-term trials conducted under controlled experimental settings (El-Ghany, 2020; Van Nerom *et al.*, 2024). Long-term studies evaluating lifetime productivity, reproductive performance, carcass yield, egg quality stability, and economic returns under commercial rearing conditions are comparatively scarce (Zhang *et al.*, 2025). Well-designed large-scale dose–response trials under practical farm environments are needed to determine optimal inclusion levels and assess field applicability (Van Nerom *et al.,* 2024).

Mechanistic understanding also warrants further clarification. Although improvements in antioxidant status, immune modulation, gut morphology, and microbiota balance are well documented (El-Ghany, 2020; Zhang *et al.,* 2025), deeper investigation of molecular pathways including Nrf2, NF-κB, tight-junction proteins, and microbiota–host signallingwould strengthen causal interpretation (Talero *et al.*, 2015; Nabil-Adam *et al.*, 2023). Integration of microbiome, transcriptomic, and metabolomic approaches could provide more comprehensive insights (Van Nerom *et al.*, 2024).

Furthermore, challenges related to large-scale cultivation, biomass stabilization, enhancement of nutrient bioavailability, and regulatory approval must be addressed (Novoveská *et al.,* 2023; Van Nerom *et al.*, 2024). Future research should therefore prioritize methodological standardization, mechanistic validation, commercial-scale evaluation, and techno-economic feasibility to facilitate sustainable and evidence-based application of microalgae in poultry nutrition (Zhang *et al.*, 2025).

CONCLUSION

Microalgae constitute a promising group of multifunctional feed additives in poultry nutrition, providing nutritional and health-promoting benefits beyond conventional feed ingredients. Experimental evidence demonstrates that microalgal species such as *Spirulina, Chlorella*, *Haematococcus*, *Nannochloropsis*, and *Schizochytrium* enhance antioxidant defenses, modulate immune and inflammatory responses, suppress enteric pathogens, and improve intestinal morphology and microbial balance. These functional effects contribute to improved stress tolerance, gut health, immune competence, and productive performance in poultry. In addition, microalgae enhance egg and meat quality by improving yolk pigmentation, enriching products with omega-3 fatty acids, and increasing oxidative stability and shelf life. Despite these advantages, variability in responses remains due to differences in algal species, processing methods, inclusion levels, bird genotype, and environmental conditions. Future research should focus on optimizing application strategies, economic feasibility, and validation under commercial production systems to fully realize the potential of microalgae in sustainable poultry production.

Table.1. Summary of the effects of dietary microalgae supplementation on production performance and functional traits in broilers

Type of microalgae	Dose	Duration	Observed effects	Reference
Dunaliella salina + Spirulina (1:1)	0.5–2.0 g/kg (optimal 1.0–1.5 g/kg)	7–42 d age	↑ BWG; ↑ antioxidant enzymes; ↑ immunity; ↑ *Lactobacillus*; ↑ FCR; ↓ cholesterol; ↓ pathogenic bacteria	Alghamdi *et al.,* 2024
Spirulina platensis	5 or 10 g/kg	0–42 d age	↔ BWG; ↔ FCR; ↔ TBARS; ↑ thigh PUFA (EPA, DPA, DHA); ↑ functional fatty acid enrichment without performance compromise	Bonos *et al.*, 2016
Spirulina extract & MBV-enriched extract	0.05% and 0.1%	0–30 d age	↔ Growth; ↑ villus height, ↑ *Lactobacillus salivarius*; ↓ IL-6; improved gut microbiota; ↔biochemical changes	Chang *et al.*, 2021

Spirulina platensis	3%	0–35 d (heat stress d22–35)	↑ BW; ↑ ADG;↑ FCR; ↑ GPX3; ↑ HSP70/90; ↑ villus height & VH:CD; ↑ microbial diversity; ↑heat tolerance	Chaudhary *et al*., 2023
Chlorella vulgaris, Spirulina platensis, Amphora coffeaformis	1 g/kg	4–36 d age	↑ BW (CV, AC); ↑ EPA, DHA (SP, AC); ↑ essential AA; ↑ SOD; ↓ MDA, ↓PC; ↓ APC & cooking loss; ↔FCR	El-Bahr *et al*., 2020
Spirulina platensis	0.3–0.9 g/kg	7–38 d age	↑ BW, ↑ PI, ↑ immune organs; ↑ WBC & lymphocytes; ↑ *Lactobacillus*; ↓ FCR, ↓ *E. coli*, ↓ cholesterol, ↓ triglycerides; optimal at 0.7 g/kg	Fathi *et al*., 2018
Chlorella vulgaris	1%	0–28 d age	↑ BWG; ↑ IgA;↑IgM;↑IgG; ↑ WBC;↑ lymphocytes; ↑ *Lactobacillus*; ↔FCR; ↔E. coli;↔Salmonella	Kang *et al*., 2013
Euglena gracilis (~55% β-1,3-glucan)	50–200 g/ton	0–28 d (Eimeria challenge d14)	↓ lesion scores; ↑ intestinal macrophages;↑ immune cells; ↑ FCR; ↔oocyst shedding	Levine *et al*., 2018
Schizochytrium limacinum	1% or 2%	0–42 d age	↑ ADG, ↑ FCR; ↓ abdominal fat;↓ TC; ↑ EPA & DHA deposition; ↓ n-6/n-3 ratio; ↑ SOD, T-AOC; ↓ MDA	Long *et al*., 2018
Spirulina platensis	0.5–2%	17–45 d age (heat stress d38–44)	↓ corticosterone; ↓ H/L ratio; ↓ cholesterol; ↓ TG; ↓ MDA; ↑ SOD; ↑ GPx; ↑ antibody titre; ↔performance	Mirzaie *et al*., 2018
Spirulina (Arthrospira) platensis (freeze-dried)	0.25–1.0%	0–35 d age	↑ BWG;↑ FCR; ↑ EPEI; ↑ SOD;↑GPx; ↑ digestibility; ↑ *Lactobacillus*; ↓ NH_3 emission; ↓ drip loss; ↔meat colour	Park *et al*., 2018
Haematococcus pluvialis	7–179 mg astaxanthin/kg	0–35 d (C. jejuni challenge d10)	↔BW;↔FI;↔FCR; ↓ *Clostridium perfringens*; ↔Campylobacter; ↑ tissue astaxanthin;↑carotenoids (dose-dependent)	Waldenstedt *et al.,* 2003

Abbreviations:BW = body weight; BWG = body weight gain; ADG = average daily gain; FI = feed intake; FCR = feed conversion ratio; PI = performance index; EPEI = European production efficiency index; DM = dry matter; AA = amino acids; PUFA = polyunsaturated fatty acids; EPA = eicosapentaenoic acid; DPA = docosapentaenoic acid; DHA = docosahexaenoic acid; TC = total cholesterol; TG = triglycerides; WBC = white blood cells; IgA = immunoglobulin A; IgM = immunoglobulin M; IgG = immunoglobulin G; SOD = superoxide dismutase; GPx = glutathione peroxidase; T-AOC = total antioxidant capacity; MDA = malondialdehyde; PC = protein carbonyl; TBARS = thiobarbituric acid reactive substances; H/L ratio = heterophil to lymphocyte ratio; VH = villus height; CD = crypt depth; MHC-II = major histocompatibility complex class II; APC = aerobic plate count; AGP = antibiotic growth promoter; NH_3 = ammonia.
Symbols: ↑ = increased; ↓ = decreased; ↔ = no significant change compared to control.

Table.2. Summary of the effects of dietary microalgae supplementation on production performance and functional traits in layers

Type of microalgae	Dose	Duration	Observed effects
Nannochloropsis oculata	0.5–1.0% of diet (optimal 1.0%)	34–47 wk age (13 wk; summer heat stress)	↑ Egg number; ↑ weight, mass;↑shell thickness; ↑ TAC;↑T3; ↑ P4; ↑ FCR;↓cholesterol;↓ALT;↓AST;↓corticosterone;↓mortality; FI ↓; ↔LBW
Spray-dried Chlorella sp.	12.5 g/kg diet	25–39 wk age (12 wk)	↑ Egg weight; ↑ shell weight & thickness; ↑ yolk colour;↑lutein & zeaxanthin; ↑ oxidative stability; ↑ FCR; ↔production rate
Dunaliella salina (marine biomass)	0.25–1.0% of diet	40–52 wk age (84 d)	↑ Egg weight& mass;↑yolk weight;↑carotenoids; ↑ villus height; ↓ TBARS; ↔FI; ↑ hepatic carotenoid deposition
Chlorella vulgaris (spray-dried; bullet-milled)	5 g/kg diet	23 wk age (9 d trial)	↑ Cecal bacterial diversity; ↑ crop Lactobacillus diversity; ↓ L. ingluviei; ↔processing effect; ↑gut health benefit
Chondrus crispus & Sarcodiotheca gaudichaudii	0.5–2% of diet (optimal 1–2%)	67–71 wk age (30 d)	↑ Egg production; yolk weight; ↑ FCR; ↑ villus height;↑SCFA;↑Bifidobacterium; ↓ C. perfringens; ↔FI
Nannochloropsis limnetica (dried biomass)	1–3% of diet	25–29 wk age (28 d)	↑ Rate of lay (2–3%);↑FI; ↑ yolk EPA & DHA (dose-dependent); ↓ plasma haptoglobin; ↔egg traits;↔nutrient retention
Chlorella sp. (drinking water)	0–400 ppm (optimal 400 ppm)	65 wk age (9 wk; heat stress)	↑ Egg weight;↑SRBC antibody titer (IgM, IgG); ↑production; ↔FCR; ↑humoral immunity under heat stress
Chlorella vulgaris or Spirulina platensis	2% of diet (SBM replacement)	38–46 wk age (8 wk)	↑ Yolk redness; ↑ β-carotene;↑SOD;↑CAT;↑GSH; ↑ egg weight (SP); ↑ n-3 FA (CV); ↔cholesterol
DHA-rich microalgae (vs linseed/ fish oil)	Dietary n-3 source (level not specified)	Laying period trial	↑ Yolk DHA; ↓ n-6 FA; ↑ egg Se; ↑ egg weight vs control; no fishy off-flavor
Spirulina platensis	0.1–0.3% (1–3 kg/ton)	38–46 wk age (8 wk)	↑ Egg production; ↑ egg mass&weight; ↑ shell thickness; ↑yolk colour; ↓ serum & yolk cholesterol, ↑ALT; ↑AST; ↔Haugh unit

Abbreviations: BW = Body weight; BWG = Body weight gain; FI = Feed intake; FCR = Feed conversion ratio; LBW = Live body weight; PI = Production index; EPEI = European production efficiency index; TAC = Total antioxidant capacity; T-AOC = Total antioxidant capacity; SOD = Superoxide dismutase; CAT = Catalase; GPx = Glutathione peroxidase; MDA = Malondialdehyde; PC = Protein carbonyl; TBARS = Thiobarbituric acid reactive substances; TC = Total cholesterol; TG = Triglycerides; ALT = Alanine aminotransferase; AST = Aspartate aminotransferase; T3 = Triiodothyronine; P4 = Progesterone; EPA = Eicosapentaenoic acid; DHA = Docosahexaenoic acid; PUFA = Polyunsaturated fatty acids; SCFA = Short-chain fatty acids; SRBC = Sheep red blood cells; H/L ratio = Heterophil to lymphocyte ratio; APC = Aerobic plate count.

Symbols: ↑ = Increased; ↓ = Decreased; ↔ = No significant change;

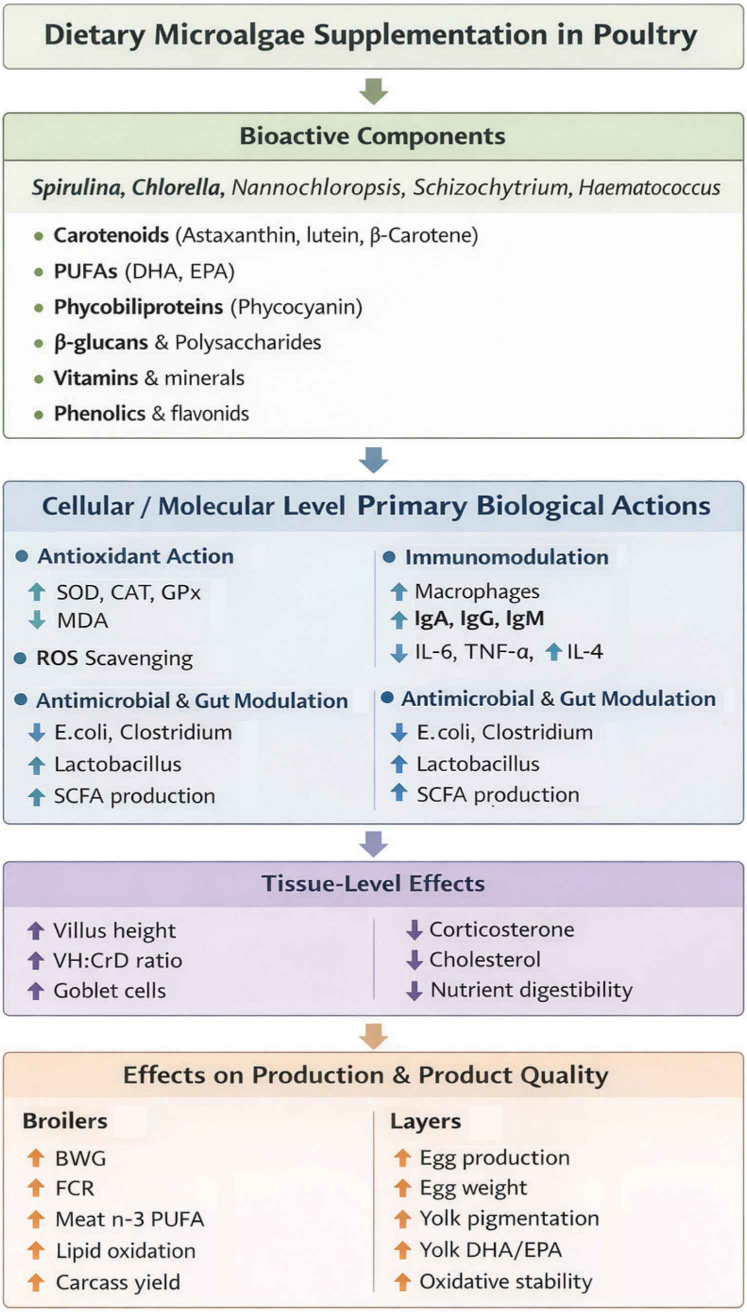

Fig.1. Integrated mode of action of microalgae and its implications for poultry health and productivity

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