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Utilizing Algae as a Sustainable Protein Source to Improve Growth and Immunity in Broiler Chickens

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Abstract

Algae are gaining attention as a sustainable and nutrient-dense alternative in poultry feed, offering a range of benefits for both animal health and the environment. This review highlights the potential of macroalgae and microalgae as novel nutritional resources for poultry, particularly as alternative protein sources. Rich in protein, essential amino acids, omega-3 fatty acids, vitamins, minerals, and antioxidants, algae present a viable option to replace traditional ingredients such as soybean meal in poultry diets. Microalgae such as *Spirulina* and *Chlorella* contain 50–70% protein by dry weight, exceeding the protein content of conventional feeds like soybean meal. Various studies have indicated that certain microalgae species are highly nutritious, with proteins making up nearly half of their dry weight. These microorganisms are notable for their high levels of essential fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), nutrients that are often scarce in standard poultry feeds. Microalgae also contain beneficial carotenoids like beta-carotene, which contribute to their overall nutritional benefits. These components play a crucial role in promoting muscle development, strengthening immune responses, and supporting the general health of poultry. In addition, compounds like phycocyanin and astaxanthin found in algae possess antioxidant properties that help alleviate oxidative stress and enhance immune system performance. Including microalgae in poultry diets has also been linked to better disease resistance, which may lower the dependence on antibiotics. Furthermore, broiler chickens fed with algae-supplemented diets have demonstrated improved growth rates, more efficient feed conversion, and better carcass characteristics. More studies are necessary to gain a comprehensive understanding of how algae function in poultry nutrition and their long-term effects. As a natural alternative to antibiotics,

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algae show potential to promote growth in poultry, aligning with the increasing global emphasis on antibiotic-free and sustainable farming practices. Additionally, their inclusion in poultry feed may enhance the nutritional profile of poultry meat and eggs, catering to the rising consumer interest in healthier and eco-conscious food products.

Algae definition:

Algae are generally described as eukaryotic organisms that carry out photosynthesis using chlorophyll as their main pigment. Unlike higher plants, they do not possess a protective layer of sterile cells around their reproductive structures **(Lee, 2008).** However, there are exceptions within this group—for example, species like *Prototheca*, which belong to the green algal group Chlorophyta but lack chlorophyll and do not photosynthesize. While cyanobacteria are often labeled as "blue-green algae," they are actually prokaryotic organisms and are typically not included in the formal definition of algae by most scientific classifications **(Allaby, 1992; Nabors, 2004).** Algae exhibit significant variation in form and function. They can range from tiny single-celled organisms to large, complex seaweeds.

These organisms appear in different colors as green, red, brown, and golden depending on their pigment composition and habitat **(Madeira *et al*., 2017).** Ecologically, they play a vital role by contributing to oxygen production and serving as a food source at the base of aquatic food chains. Most microalgae are autotrophs, using sunlight and carbon dioxide for energy and growth. However, some species can grow heterotrophically by utilizing organic carbon sources. This metabolic flexibility makes them especially suitable for cultivation in controlled environments like bioreactors, where they are used for biomass and biocompound production. Algae can thrive in a variety of ecosystems, from coastal waters to dry inland regions. Due to their wide-ranging characteristics, classifying algae is a complex and evolving field.

They are typically divided into major groups based on color and pigment types—namely green algae (*Chlorophyceae*), brown algae (*Phaeophyceae*), and red algae (*Rhodophyceae*). Each group varies in composition depending on factors such as species, habitat conditions, and methods of harvesting. The term “algae” broadly includes both large multicellular forms like seaweeds and smaller unicellular varieties. These organisms are structurally simple and usually aquatic, lacking organs like roots, stems, or leaves. Despite this simplicity, they are ecologically and economically important. Their rapid growth and adaptability make them useful for a range of applications, including renewable energy (biofuels), environmental cleanup (wastewater treatment), and health-related industries (pharmaceuticals).

Introduction

According to projections by the United Nations (2022), the global population is expected to rise to 8.5 billion by 2030 and reach 9.7 billion by 2050. This population increase is likely to intensify demand for food, particularly animal-based products. Estimates suggest that global meat consumption will grow by 14% by 2030 compared to the average consumption between 2018 and 2020 **(OECD/FAO, 2021; Nasir *et al*., 2022).** Similarly, egg consumption worldwide is projected to rise by 39% from 2012 to 2050 **(FAO, 2018).** Meeting this growing demand will place additional stress on key feed resources such as maize and soybean meals, which are the primary components of traditional poultry diets. Therefore, exploring sustainable and environmentally friendly alternatives to conventional feed ingredients is becoming increasingly important.

Alternative protein sources such as insect meals, single-cell proteins, and agro-industrial by-products offer promising solutions. Insect-based proteins, like black soldier fly larvae and mealworms, provide high nutritional value with a lower environmental footprint. Similarly, single-cell proteins from fungi, yeast, and bacteria present a sustainable alternative to conventional feed ingredients. Additionally, by-products such as distillers' dried grains, rice bran, and cassava meal can help reduce dependence on traditional feed sources.

Meeting the growing global demand for food while balancing the needs of the food, feed, and biofuel industries requires extensive arable land. However, expanding agricultural areas can lead to significant environmental challenges, including deforestation and the overuse of chemical agents such as pesticides, fertilizers, and herbicides (**Kusmayadi *et al*., 2021**; **Madeira *et al*., 2017**). Increasing crop production on newly cultivated lands is particularly difficult because much of the Earth's surface consists of arid and semi-arid regions, making many countries unable to meet their internal demand for feed ingredients. As a result, they must rely on costly imports, which contradict key United Nations Sustainable Development Goals (SDGs), such as eradicating poverty (SDG 1), achieving zero hunger and sustainable agriculture (SDG 2), and combating climate change (SDG 13) (**United Nations**, **2022**).

Given the growing need for sustainable and efficient feed alternatives, it is crucial to identify ingredients that provide essential nutrients, are easy to produce, and reduce the strain on conventional agriculture. Microalgae present a promising solution to these challenges, as they can be cultivated locally and possess a rich nutritional profile, including proteins, lipids, carotenoids, minerals, and vitamins **(Bleakley & Hayes, 2017; Kalia & Lei, 2022; Kusmayadi *et al*., 2021; López-V *et al*., 2017).**

A key advantage of incorporating microalgae into animal feed is their exceptional solar-to-chemical energy conversion efficiency. They exhibit a remarkable ability to fix carbon dioxide (CO_2), surpassing most terrestrial plants **(Dineshbabu *et al*., 2019**). Furthermore, microalgae require minimal nutrients for optimal growth and can thrive in diverse environments such as rivers, lakes, and even extreme conditions like thermal waters, deserts, and cold regions. Their rapid growth is sustained by just sunlight, water, and essential inorganic compounds (nitrogen, phosphorus, and potassium). Additionally, they can be cultivated in small spaces using open or closed systems, making them a viable option for compact and scalable production **(Dineshbabu *et al*., 2019; Grossmann *et al*., 2020; Liu *et al*., 2021; Rizwan *et al*., 2018; Sathasivam *et al*., 2019).**

Algae also possess anti-inflammatory and antioxidant properties, which contribute to their health benefits in poultry (**Zhang *et al*., 2014**; **Calder, 2017 and Eggersdorfer *et al*., 2018)**. They are considered potential prebiotics, capable of enhancing digestive function, improving nutrient absorption, and reducing the adverse effects of antibiotics on gut microbiota. Additionally, algae may help mitigate the risks associated with antimicrobial agents (**Sako *et al*., 1999**). Studies have demonstrated that incorporating DHA-rich microalgae at 1–2% in broiler diets improve carcass traits, antioxidant status, and lipid metabolism, as indicated by reduced serum cholesterol and triglyceride levels (**Gatrell *et al*., 2017 and Long *et al*., 2018**).

This review aims to thoroughly examine the use of algae and their by-products in poultry nutrition, emphasizing their diverse functional benefits. Special attention is given to their antioxidant and antimicrobial activities, as well as their influence on bird health, growth efficiency, and meat quality. By identifying and addressing current research gaps, this review aspires to enhance our understanding of how algae can support more sustainable and productive poultry farming practices.

Chemical and nutritional composition of algae:

Microalgae are drawing increasing interest globally as a nutrient-rich and sustainable food source. Their use is expanding beyond traditional dietary roles to include broader health-promoting applications. With an estimated 100,000 species existing in nature, microalgae are valued for their rich composition of proteins, carbohydrates, fats, vitamins, minerals, and carotenoids. The nutritional makeup of these organisms can vary widely depending on environmental and biological conditions such as species type, temperature, pH levels, nutrient concentrations, and light exposure **(Madeira *et al*., 2017; Batista *et al*., 2013; Dineshbabu *et al*., 2019; Janssen *et al*., 2022).** Generally, proteins, fats, and carbohydrates are the most abundant macronutrients found in microalgal biomass (see Table 1).

Table (1). Nutritional composition of common algae:

Species	Nutrients (% on dry matter)				References
	Crude protein	Lipid	Carbohydrate	Ash	
Botryococcus braunii	39.1-39.9	24.9-34.4	18.5-30.6	5.4-7.2	Tibbetts *et al.* (2015)
Chlorella vulgaris	42 - 58	5 – 40	12-55	--	Safi *et al.* (2014)
Isochrysis galbana	39.6	23.9	13.3	14.5	Batista *et al.* (2013)
Nannochloropsis oculata	17.9-30.8	17.8-33.7	23.3-29.3	--	Paes *et al.* (2016)
Spirulina maxima	44.9	3.6	16.6	30.9	Batista *et al.* (2013)
Spirulina platensis	46-63	4-9	8-14	--	Becker (2007)

Microalgae have emerged as a potential alternative to traditional feed sources in animal nutrition. Nonetheless, one of the key obstacles to their effective use, particularly in monogastric species, is their limited digestibility **(Austic *et al.*, 2013; Skrede *et al.*, 2011; Madeira *et al.*, 2017).** This issue stems largely from their tough cell walls, which are composed of high levels of fibrous materials, polysaccharides, and phenolic compounds. These components can bind to amino acids, leading to the formation of insoluble complexes that hinder the absorption of essential nutrients **(Safi *et al.*, 2014; Bernaerts *et al.*, 2018; Saadaoui *et al.*, 2021; Nagarajan *et al.*, 2021).**

Cyanobacteria, such as *Spirulina* spp., tend to have higher digestibility compared to green algae like *Chlorella* spp., which have more rigid cell walls (**Cerri *et al*.**, **2021**). To improve digestibility, several techniques can be applied, including physical, chemical, and enzymatic methods to disrupt the cell walls. Physical approaches like ball milling, high-pressure homogenization, and ultrasound have been shown to help break down the tough cell walls, making nutrients more accessible. Chemical techniques often involve the use of enzymes to break down the polysaccharides and proteins, enhancing nutrient availability. In addition, fermentation has proven effective in reducing anti-nutritional factors in microalgae, further improving their digestibility. Studies suggest that fermenting *Chlorella* spp. can increase nutrient absorption and improve growth performance in animals like pigs **(Demarco *et al.*; 2022).**

Protein content of algae:

Microalgae, particularly red algae, are renowned for their high protein content, while green and brown algae typically have moderate to low levels of protein **(Becker, 2007; Safi *et al.*, 2014 and Tibbetts *et al.*, 2015).** Notably, some microalgae species, such as *Chlorella vulgaris*, *Spirulina maxima*, and *Spirulina platensis*, can contain up to 50% of their biomass in the form of proteins **(Grossmann *et al.*, 2020 and Safi *et al.*, 2014),** which can exceed the protein content found in soybean and sunflower meals **(Batal *et al.*, 2016; Janssen *et al.*, 2022 and Shukla & Cheryan, 2001).**

Incorporating microalgae into poultry diets is a beneficial option due to their protein concentration, which ranges from 26% to 63% (**Becker**, **2007**). Since poultry typically requires a protein level of around 24% for optimal growth and egg production **(Abbas *et al.*, 2022; Fernandes *et al.*, 2024 and Mishra *et al.*, 2023),** substituting soybean meal with microalgae does not lead to protein deficiency, even at higher inclusion levels. Moreover, the proteins in microalgae are of high quality, containing essential amino acids vital for animal health and development **(Brown *et al.*, 1997; Dineshbabu *et al.*, 2019 and Grossmann *et al.*, 2020).** This is especially important since soybean meal, a common protein source in poultry feed, is considered an incomplete protein due to its lack of certain essential amino acids, thus reducing its biological value (**ra**nges from 0.3% to 3.5% (see Table 2). These levels surpass those found in soybean meal, which contains 2.4–3% lysine and 0.54–0.7% methionine (**Batal, Dale, & Farms**,

2016). For instance, *C. vulgaris* and *S. platensis*, which have been extensively studied, contain approximately 8.4% and 4.8% lysine, respectively, and methionine levels of 2.2% and 2.5%, respectively. These concentrations are notably higher than those found in soybean meals, which is significant because it allows for reduced use of synthetic amino acids in poultry diets. **del-Wareth *et al*., 2024; Bleakley & Hayes, 2017).**

Microalgae are particularly rich in essential amino acids, including lysine and methionine. Lysine concentrations range from 2.3% to 8.5% from total protein, while methionine content ranged 0.3 to 3.5% (**Batal *et al*., 2016).**

Lipids content of algae:

Lipids are included in poultry diets to boost energy density, offering several benefits. These include reducing feed dust, preventing particle separation in mash diets, improving palatability, and providing essential fatty acids. In particular, the addition of microalgae to poultry diets can significantly enhance the energy supply **(Safi *et al*., 2014; Tibbetts *et al*., 2015).** Microalgae, depending on species and cultivation methods, have been found to produce lipids in substantial quantities, up to 47.8% **(Tibbetts *et al*., 2015).** Most of these lipids are saturated fatty acids (SFA), while polyunsaturated fatty acids (PUFA) and monounsaturated fatty acids (MUFA) are present in moderate to lower amounts **(Lim *et al*., 2012; Ötleş and Pire, 2001; Nascimento *et al*., 2013; Safi *et al*., 2014).** The SFA in microalgae include myristic acid, palmitic acid, and stearic acid, with concentrations as high as 19.2%, 46%, and 7.4%, respectively. Additionally, notable MUFAs include palmitoleic acid, elaidic acid, and Cis-11-eicosenoic acid.

Polyunsaturated fatty acids (PUFAs) from microalgae, particularly docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), play a crucial role in animal nutrition. These fatty acids possess antioxidant properties, enhance the energy content of feed, and contribute to overall animal health **(Gohara-Beirigo *et al*., 2022 and Muñoz *et al*., 2021).** Additionally, PUFAs can be transferred to eggs and meat, improving their nutritional value. Incorporating microalgae into poultry diets is especially beneficial since poultry lacks the ability to efficiently convert alpha-linolenic acid (ALA) into EPA and DHA. Furthermore, commonly used feed ingredients, such as soybean meals, require genetic modification to produce these essential fatty acids (**Ursin**, **2003**).

Beyond DHA and EPA, microalgae also synthesize other valuable PUFAs, including alpha-linolenic acid (ALA), gamma-linolenic acid (GLA), linoleic acid (LA), and arachidonic acid (ARA). These fatty acids support immunity and other physiological functions in poultry **(Banskota *et al*., 2019).** Notably, GLA is rarely found in conventional poultry feed ingredients and could serve as an alternative to flaxseed in poultry diets (**Saadaoui *et al*., 2021**).

Carbohydrates content of algae:

Microalgae-derived carbohydrates play a dual role as both structural components and primary energy reserves, constituting 5–40% of their dry weight. These carbohydrates, stored intracellularly, are critical for carbon and energy provision in poultry feed. Enhancing biomass productivity through strain selection—prioritizing fast- (**Debnath *et al*., 2021**). However, this poses a challenge: elevated carbohydrate levels, particularly structural polysaccharides, may reduce nutrient digestibility in monogastric poultry due to their inability to break down rigid cell walls.

Microalgae polysaccharides are categorized into structural (cellulose, hemicellulose) and storage (starch, glycogen) forms. Cellulose and hemicellulose, prevalent in green algae, reinforce cell walls but act as anti-nutritional factors in poultry feed, mimicking indigestible dietary fiber. Starch, a more digestible polymer, serves as the primary energy reserve in species like *Chlamydomonas*, while glycogen occurs in limited taxa. The recalcitrance of structural polysaccharides underscores the need for processing methods (e.g., enzymatic pretreatment) to improve nutrient bioavailability **(Cezare-Gomes *et al*., 2019; Nagarajan *et al*., 2021).**

Glucose dominates the monosaccharide pool (1.0–78.99%), followed by galactose (1.5–54.1%), which together account for the bulk of soluble sugars in species such as *Dunaliella* and *Tetraselmis* **(Safi *et al*.,**

2014 aand Wang *et al*., 2022). Minor sugars like arabinose, xylose, and ribose are species-specific and often negligible, highlighting variability in microalgal carbohydrate profiles.

Mineral and vitamins contents of alagae:

Microalgae serve as a rich source of various vitamins that can supplement animal feeds, particularly vitamins B1, B2, B6, C, and E. Thiamine (vitamin B1) is well-documented in numerous microalgae species, with concentrations ranging from 1.38 to 21.8 mg/kg, surpassing those found in soybean meals (1.7 to 6.9 mg/kg) (**Batal *et al*., 2016**). This vitamin plays a crucial role in body growth and appetite regulation (**Hunton, 2016**).

Riboflavin (vitamin B2) is also abundantly present in microalgae, with levels reaching up to 40.6 mg/kg (**Pratt and Johnson, 1965**). This vitamin is essential for preventing leg paralysis and promoting growth in poultry (**Hunton, 2016**). Given that poultry requires between 2.5 and 3.5 mg/kg of riboflavin in their diet, incorporating microalgae can help meet these nutritional needs.

There are approximately 200 carotenoids that can be extracted from microalgae **(Banskota *et al*., 2019),** some of which are found in concentrations higher than those in soybean meals (**Gohara-Beirigo *et al*., 2022**). This makes microalgae a promising and more sustainable alternative to synthetic pigments and vitamins in poultry diets, offering higher bioavailability **(Surai *et al*., 2003**). Among carotenoids, xanthophylls—characterized by the presence of hydroxyl groups—are of particular interest in poultry nutrition.

Microalgae offers a highly valuable dietary resource for meeting the mineral needs of poultry, providing substantial amounts of calcium, phosphorus, sodium, and other essential minerals. These nutrients help maintain the proper balance required for poultry health and productivity.

Calcium is found in nearly all microalgae species, with concentrations reaching up to 8.2%, significantly higher than common poultry feed ingredients like soybean meal, which contains only 0.2–0.31% calcium **(Batal *et al*., 2016**). Calcium is crucial for egg production, with laying hens requiring higher levels (around 4%) for proper eggshell formation. Additionally, calcium plays key roles in blood clotting, muscle contraction, and the function of enzymes involved in the breakdown of polysaccharides, phospholipids, and proteins (**Bernaerts *et al*., 2018**). Phosphorus concentrations in microalgae can reach up to 1.5%, significantly higher than the 0.59%–0.72% found in soybean meal (**Batal *et al*., 2016**). This makes microalgae a valuable addition to poultry diets, as its organic phosphorus content can reduce the need for phytase supplementation.

Antioxidants activity of algae:

Algae, particularly microalgae, are valuable sources of natural antioxidants like carotenoids and tocopherols, which play a key role in combating oxidative stress by neutralizing free radicals. These antioxidant compounds contribute significantly to overall poultry health and help in disease prevention. Microalgae also offer a range of bioactive effects, including antibacterial and antiviral properties. Their antioxidant activity is especially crucial in safeguarding cellular lipids from oxidative damage and lipid peroxidation. Maintaining antioxidant balance in the body involves both the removal of reactive oxygen species (ROS) and the equilibrium between internally produced and externally supplied antioxidants **(Long *et al*., 2011).**

The body's natural defense system includes key antioxidant enzymes such as superoxide dismutase (SOD), glutathione (GSH), glutathione peroxidase (GPX), and glutathione reductase (GR). In broiler chickens, factors related to diet and metabolism make them especially prone to oxidative damage, particularly lipid peroxidation. Diets high in fat can heighten oxidative stress in poultry, potentially leading to cellular damage, including DNA mutations, membrane lipid degradation, protein breakdown, and tissue injury **(Delles *et al*., 2014).** Malondialdehyde (MDA), a major end product of lipid peroxidation, is commonly used as an indicator of oxidative stress levels **(Lu *et al*., 2010).**

Algae enhance the antioxidant defense system in poultry by scavenging ROS and reducing oxidative stress. The presence of carotenoids, tocopherols, and other bioactive compounds help protect cell membranes from lipid peroxidation, promoting overall health and resilience. Additionally, microalgae improve the activity of endogenous antioxidant enzymes, lowering MDA levels and mitigating oxidative damage. Their antibacterial and antiviral properties further support immune function, reducing the risk of infections. These combined benefits highlight the potential of microalgae as a natural feed additive to enhance poultry health and performance.

Incorporating algae into animal feed enhances the body's antioxidant defenses and supports gut health through antimicrobial actions. In the liver, this supplementation boosts the activity of crucial antioxidant components, including glutathione (GSH), glutathione peroxidase (GPX), glutathione reductase (GR), catalase (CAT), and superoxide dismutase (SOD). At the same time, it lowers oxidative stress indicators such as malondialdehyde (MDA) and reactive oxygen species (ROS). Similar improvements are seen in muscle tissues, where algae increase levels of omega-3 fatty acids—eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA)—and enhance antioxidant enzymes like SOD, GPX, and glutathione S-transferase (GST), while also reducing MDA and ROS. In the circulatory system, algae supplementation leads to elevated GPX, CAT, and SOD levels, alongside decreased concentrations of MDA and ROS, reflecting improved systemic antioxidant status. Additionally, algae exhibit antimicrobial properties within the gut, potentially contributing to a healthier microbial balance and reduced pathogenic bacteria.

Algae supplementation has been shown to enhance the composition of gut microbiota by encouraging the growth of beneficial bacteria and limiting harmful species. In muscle tissues, the breakdown of reactive oxygen species (ROS) is largely facilitated by the upregulation of key antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPX). While SOD and CAT work directly to neutralize free radicals, GPX plays a crucial role in regenerating oxidized antioxidants, maintaining cellular redox balance.

According to **Sun *et al.* (2018),** administering high doses of astaxanthin from microalgae notably boosts the activity of key antioxidant enzymes—such as GSH, GPX, GR, and GST—in the liver and muscle tissues (breast and thigh) of broiler chickens by 21 days of age. Moreover, the microalgae's high DHA content contributes to increased levels of EPA, DHA, SOD, and overall antioxidant capacity in the supplemented birds. These birds also exhibit enhanced polyunsaturated fatty acid profiles and elevated MDA levels in muscle tissues compared to unsupplemented controls **(Long *et al.*, 2001).**

Spirulina contains various bioactive antioxidants that help reestablish oxidative balance, as noted by **Kalia Lie (2022).** Research on broiler chickens subjected to extended periods of heat stress indicates that spirulina supplementation elevates the activity of key antioxidant enzymes such as superoxide dismutase (SOD) and glutathione peroxidase (GPX), while concurrently lowering malondialdehyde (MDA) levels—an indicator of lipid peroxidation **(Agustini *et al.*, 2015; Mirzaie *et al.*, 2018).** Furthermore, floridoside, a carbohydrate reserve compound found in red algae, has been clinically recognized for its strong antioxidant capabilities **(Abdel-Moneim *et al.*, 2022).**

Algae-derived non-starch polysaccharides, such as beta-glucans, are increasingly recognized for their positive effects on health. Research by **Agustini *et al.* (referenced in Mirzaie *et al.*, 2018)** highlighted that dried *Spirulina* contains a range of health-promoting compounds, including phenolics, flavonoids, saponins, triterpenoids, and steroids, which contribute to its strong antioxidant potential. In particular, *Spirulina platensis* is well-regarded for its ability to combat oxidative stress **(Aladaileh *et al.*, 2022).** Brown algae also offer numerous antioxidant compounds that can inhibit enzymes like hyaluronidase, potentially protecting nerve cells and supporting bone health by lowering matrix metalloproteinase activity. Additionally, algae-derived molecules such as phycoerythrin are gaining interest in biomedical fields due to their antioxidant properties **(El -Shall *et al.*, 2023).** Incorporating microalgae like *Haematococcus pluvialis* and *Spirulina platensis* into the diet has been shown to enhance antioxidant defenses in muscle tissue, improving free radical neutralization and boosting the activity of antioxidant enzymes.

Antibacterial activity of algae:

Algae have gained attention as a valuable source of prebiotic substances that can encourage the growth of beneficial microorganisms in the poultry gut. These compounds contribute to better gut health and improve the efficiency of nutrient absorption. In addition to their prebiotic qualities, algae also contain antibacterial agents that help reinforce the gut's natural defenses against harmful microbes. The intestinal microbiota—a diverse and dynamic population of microorganisms—plays a vital role in digestion, immune regulation, and controlling inflammation. Although algae are typically associated with aquatic environments, recent studies highlight their potential to support gastrointestinal health in animals **(Park *et al*., 2018; Mullenix *et al*., 2021).**

Algae contain a variety of bioactive compounds such as polysaccharides, pigments, lectins, amino acids, and phenolic substances—that exhibit antibacterial activity. These compounds can suppress or eliminate harmful bacteria without causing harm to nearby tissues. The immune system protects the body by blocking bacterial infections and counteracting their negative effects. Algal compounds play a role in strengthening gut immunity, making it more effective at resisting harmful microbes and promoting overall health.

Research conducted in vitro has revealed that both macroalgae and microalgae exhibit significant antimicrobial effects against a variety of pathogenic bacteria and fungi present in freshwater environments **(Aladaileh *et al*., 2022).** These algae produce numerous secondary metabolites with strong inhibitory activity against harmful microorganisms. Building on these findings, several in vivo investigations have examined the potential of algae as a feed additive in poultry production. One well-studied species, *Spirulina platensis*, is rich in biologically active compounds such as phycocyanin, carotenoids, polysaccharides, and phenolic substances, which have been linked to immune enhancement as well as antibacterial and antiviral functions **(Azeem *et al*., 2019).** Incorporating *Spirulina* into broiler diets has been reported to increase populations of beneficial gut microbes, including *Ruminococcus*, *Oscillospira*, *Lactobacillus*, *Oscillobacter*, *Flavonifractor*, and *Colidextribacter*, all of which are known to produce health-promoting volatile fatty acids. This dietary inclusion supports the establishment of a balanced intestinal microbiota. Furthermore, algae supplementation has been associated with enhanced gut health and immune function, particularly during the initial week after exposure to *Eimeria*. These benefits appear to be more evident under pathogen stress, suggesting algae's potential role in long-term disease resistance and gut barrier maintenance **(Frazzini *et al*., 2022).**

Research indicates that incorporating *Chondrus crispus* and *Sarcodiotheca gaudichaudii* into poultry diets at a 2% inclusion rate can notably enhance gut microbiota, particularly by increasing levels of beneficial bacteria such as *Bifidobacterium longum*, *Lactobacillus acidophilus*, and *Streptococcus salivarius* in laying hens. Algal bioactives are also recognized for their antioxidant potential and their role in modulating harmful bacteria, including strains like *Escherichia coli* O138. Furthermore, fucoidan extracted from species like *Turbinaria ornata* and *Sargassum polycystum* has shown significant antibacterial properties against a range of pathogens, including *Vibrio harveyi*, *Staphylococcus* spp., *E. coli*, and *Aeromonas hydrophila* (**Fries-Craft *et al*., 2021; Frazzini *et al*., 2022).**

Role of algae as immune stimulates:

Various species of algae have been found to possess properties that modulate the immune system in poultry. When included in chicken diets, algae can enhance gut health by improving immune responses and maintaining intestinal integrity. This occurs through increased mucin secretion by goblet cells and the reinforcement of tight junctions between enterocytes, which together strengthen the gut barrier. Algae also boost the activity of intestinal alkaline phosphatase (IAP), an enzyme involved in neutralizing lipopolysaccharides (LPS), thereby helping to reduce inflammation triggered by these bacterial toxins **(Aladaileh *et al*., 2022).**

Supplementing with algae has been shown to influence immune cell function, steering them toward a more anti-inflammatory state. Dendritic cells, for example, reduce their output of inflammatory cytokines such as IL-6, IL-12, and IL-1β, while increasing anti-inflammatory mediators like IL-10 and TGF-β. This altered cytokine environment encourages T cells to secrete IL-10 and IL-4, both of which contribute to dampening inflammatory responses. Likewise, macrophages produce lower levels of inflammatory markers including TNF-α, IL-1, IL-6, and IL-2, signaling a shift toward resolving inflammation. Algae also appear to stimulate B cell activity, boosting IgA production—important for protecting mucosal surfaces—and helping to regulate IgG and IgM levels **(Aladaileh *et al.*, 2022; Park *et al.*, 2018; Mullenix *et al.*, 2021).**

Algae are a valuable source of various bioactive substances, including polysaccharides, carotenoids, phycocyanin, and phenolic compounds, all of which are associated with health -promoting properties such as boosting the immune system, reducing inflammation, and protecting liver function. One of the most studied microalgae, *Spirulina platensis*, has shown beneficial effects on the health and immunity of broiler chickens. Dietary supplementation with *Spirulina* at a 5% inclusion level has been reported to enhance both innate and adaptive immune responses, support the development of beneficial gut microbes, and improve overall poultry well-being **(Sako *et al.*, 1999).**

Microalgae are not only known for their ability to modulate the immune system but also for their high antioxidant content, which plays a vital role in defending the body against oxidative stress. These antioxidants help neutralize reactive oxygen species (ROS), thereby contributing to the maintenance of oxidative balance and supporting immune health in poultry **(Omar *et al.*, 2022; El-Shall *et al.*, 2023).** As a result, incorporating algae particularly *Spirulina platensis*—into poultry feed can offer several advantages, including stronger immune responses, better gut health, and improved resistance to infections.

Effect of algae on broiler chicken performance:

Spirulina and Chlorella spp. have been used in broiler chicken trials at various inclusion levels, but research on other bird species like ducks, quails, and ostriches is limited. The r0esults regarding the effects of microalgae in bird diets are inconsistent, with most studies focusing on performance and meat quality. These conflicting results are likely due to differences in inclusion levels, the nutritional composition of the microalgae, and the breed of the birds (Table 2).

The research on the inclusion of Spirulina platensis (S. platensis) and Chlorella vulgaris (C. vulgaris) in broiler chicken diets shows varying results depending on the inclusion levels and the specific outcomes being measured. Generally, low doses of S. platensis (up to 0.07%) do not negatively impact key performance metrics like live weight, feed intake, or feed conversion ratio (FCR). In fact, some studies have shown improved performance, such as higher weight gain and better FCR with certain levels of Spirulina. For example, **Hanafy** (**2022**) observed higher weight gain in broilers fed 0.07% Spirulina. At 1% inclusion, **Shanmugapriya *et al*.** (**2015**) found improved body weight and feed conversion, while other studies reported no major performance changes at levels around 0.5% (**Kaoud**, **2012**).

S. platensis supplementation may enhance gut health, as shown by increased villus length and better nutrient absorption in several studies (**Ansari *et al*., 2018; Khalilnia *et al*., 2023**). This is likely due to its high protein content and the ability to promote beneficial gut bacteria. The effects on meat quality were mixed. Some studies (e.g., **Bonos *et al*., 2016; Moujahed *et al*., 2011**) found no significant effects on meat tenderness, flavor, or overall acceptability. However, the addition of Spirulina increased levels of polyunsaturated fatty acids (EPA, DHA), improving the fatty acid profile of the meat. Like Spirulina, C. vulgaris supplementation influences the fatty acid profile of meat, increasing the content of polyunsaturated fatty acids like EPA and DHA **(El-Bahr *et al*., 2020; Varzaru *et al*., 2024).** C. vulgaris also affected meat color, especially at higher inclusion levels, like the effects seen with Spirulina **(Toyomizu *et al*., 2001).**

Table (2). Overview of Algal Supplementation Effects on Broiler Chicken Performance and Meat Characteristics

Algae	Inclusion level	Initial age of chicks	Experimental period	Main effect	References
Chlorella Vulgaris	10%	21 days	2 weeks	No effect of body weight Increased while improved meat quality	**Alfaia *et al.* (2021)**
Chlorella Vulgaris	0.1, 0.5, 2 and 4%	Quail 13 weeks	13 weeks	Improved protein profile in the meat	**Anjalai *et al.* (2018)**
Chlorella Vulgaris	3 – 6%	1 day old	6 weeks	Decreased feed intake and body weight and increased PUFA in the meat	**Cabrol *et al.* (2024)**
Chlorella Vulgaris	0.1 and 0.2%	1 day pekin ducks	6 weeks	Improved performance and meat quality	**Oh *et al.* (2015)**
Chlorella Vulgaris	1 and 2%	14 days	14 weeks	Improved meat quality	**Varzaru *et al.* (2024)**
Aurantiochytrium limacinum	0.5, 2.5 and 5%	1 day old	6 weeks	Growth performance not affected while improved meat quality	**Moran et al. (2018)**
Spirulina Platensis	0.03, 0.05, 0.07 and 0.09%	7 days old	38 days	Inclusion of 0.7 or 0.9% improved growth. 1% decreased abdominal fat	**Fathi (2018)**
Spirulina Platensis	6, 11, 16 and 21%	1 day old	3 weeks	Performance not affected up to 16%	**Evans *et al.* (2015)**
Spirulina Platensis	17 and 21%	1 day old	5 weeks	Had no effect on growth performance	**Neumann *et al.* (2018)**
Spirulina Platensis	15%	1 day old	2 weeks	Reduced performance	**Pestana *et al.* (2020)**
Spirulina Platensis	0.25, 0.5, 0.75 and 1%	1 day old	5 weeks	Improved growth performance and enzyme activity	**Park *et al.* (2018)**
Spirulina Platensis	0.1%	7 days old	6 weeks	Improved growth performance	**Kaoud (2012)**

Several studies have focused on incorporating various microalgae species into poultry diets, highlighting their potential benefits for meat quality, growth, and health. For instance, **Mooney *et al*. (1998)** found that supplementing broiler diets with Schizochytrium spp. at moderate (2.8%) and high (5.5%) levels significantly increased the n-3 polyunsaturated fatty acid (PUFA) content in breast muscle. Similarly, **Moran *et al*. (2018)** demonstrated that feeding broilers diets with 0.5%, 2.5%, and 5% Aurantiochytrium limacinum did not affect growth but significantly boosted the DHA content of the meat. **Liu *et al*. (2020)** conducted a study on Aurantiochytrium spp. in laying hens, supplementing their diet with levels of 0.5%, 1.0%, 1.5%, and 2.0% over 15 weeks. They observed a dose-dependent increase in long-chain n-3 PUFA, particularly DHA, in both breast and thigh muscles, resulting in more favorable n-6/n-3 ratios, which could potentially benefit human health. No effects on meat tenderness, color, antioxidant enzyme activity, or meat oxidation were reported.

A range of studies has explored the impact of various microalgae species in poultry nutrition. For instance, **Tao *et al.* (2018)** incorporated 10% *Nannochloropsis oceanica* into broiler diets, reporting enhanced antioxidant defenses and reduced lipid peroxidation in both liver and muscle tissues. In a separate investigation, **Austic *et al.* (2013)** replaced portions of soybean and corn meal with defatted diatomaceous biomass (DFA). However, inclusion levels of up to 7.5% DFA negatively affected chick growth performance. **Šefcová *et al.*** (2021) evaluated the effects of small amounts (0.2%) of several microalgae species—

Tisochrysis lutea, *Tetraselmis chuii*, and *Porphyridium cruentum*—on broilers. Their results demonstrated improvements in body weight and intestinal villus morphology, potentially enhancing nutrient uptake. Additionally, diets containing *T. chuii* helped minimize weight loss during meat thawing. **El-Bahr *et al.* (2020)** studied the addition of *Acanthophora coffeaeformis* to broiler feed and observed increased weight gain, enhanced breast muscle composition in terms of fatty and amino acids, and a reduction in both microbial load and oxidative stress indicators.

Several studies have evaluated the use of enzymes to improve the digestibility of microalgae in broiler feed, though results have been inconsistent. In the study by **Pestana *et al.* (2020),** broilers were fed a diet containing 15% *Spirulina spp.* along with small amounts of Rovabio® Excel AP (0.005%) and lysozyme (0.01%). Despite these additions, no improvements in growth performance or feed conversion ratio (FCR) were observed; in fact, birds in the control group performed better overall. **Alfaia *et al.* (2021)** incorporated 10% *Chlorella vulgaris* into broiler diets and supplemented them with either Rovabio® or a combination of four carbohydrate-active enzymes (CAZymes). Although growth rates were unaffected, changes in plasma metabolites were noted, including an increase in cholesterol and very-low-density lipoprotein (VLDL) levels, suggesting alterations in lipid metabolism. Similarly, **Mishra *et al.* (2023)** included 3% *Arthrospira platensis* and xylanase in broiler diets, but reported no meaningful differences in FCR, carcass characteristics, or organ weights. In another study, **Costa *et al.* (2024)** examined the effects of adding 15% *Spirulina spp.* (both extruded and unextruded) with a concentrated enzyme blend. While the unprocessed version led to reduced body weight and weight gain, the extruded form produced outcomes comparable to the control. In summary, although enzyme supplementation may influence certain metabolic parameters, it does not consistently enhance growth performance in broilers fed microalgae. Processing techniques such as extrusion may have a more significant impact on nutrient utilization than enzymes alone.

Microalgae can play distinct roles in broiler chicken diets depending on the inclusion level. When added in larger amounts, they can serve as substitutes for traditional protein-rich feed components. In contrast, smaller quantities offer functional health benefits **(Tavernari *et al.*, 2018).** These benefits, both nutritional and physiological, contribute to improved overall performance and health in broilers. For instance, *Arthrospira* (commonly referred to as *Spirulina*) has been reported to support immune function, enhance resistance to pathogens, and elevate T-cell activity **(Fries-Craft *et al.*, 2021).** Supplementing broiler feed with various doses of *Arthrospira platensis* has also been associated with positive changes in intestinal structure, such as increased villus height, deeper crypts, and a higher villus-to-crypt ratio, which are markers of enhanced gut health **(El-Hady *et al.*, 2022).** While the exact biological mechanisms are not fully understood, Figure 1 presents potential pathways through which microalgae may support gut function and promote growth in broiler chickens.

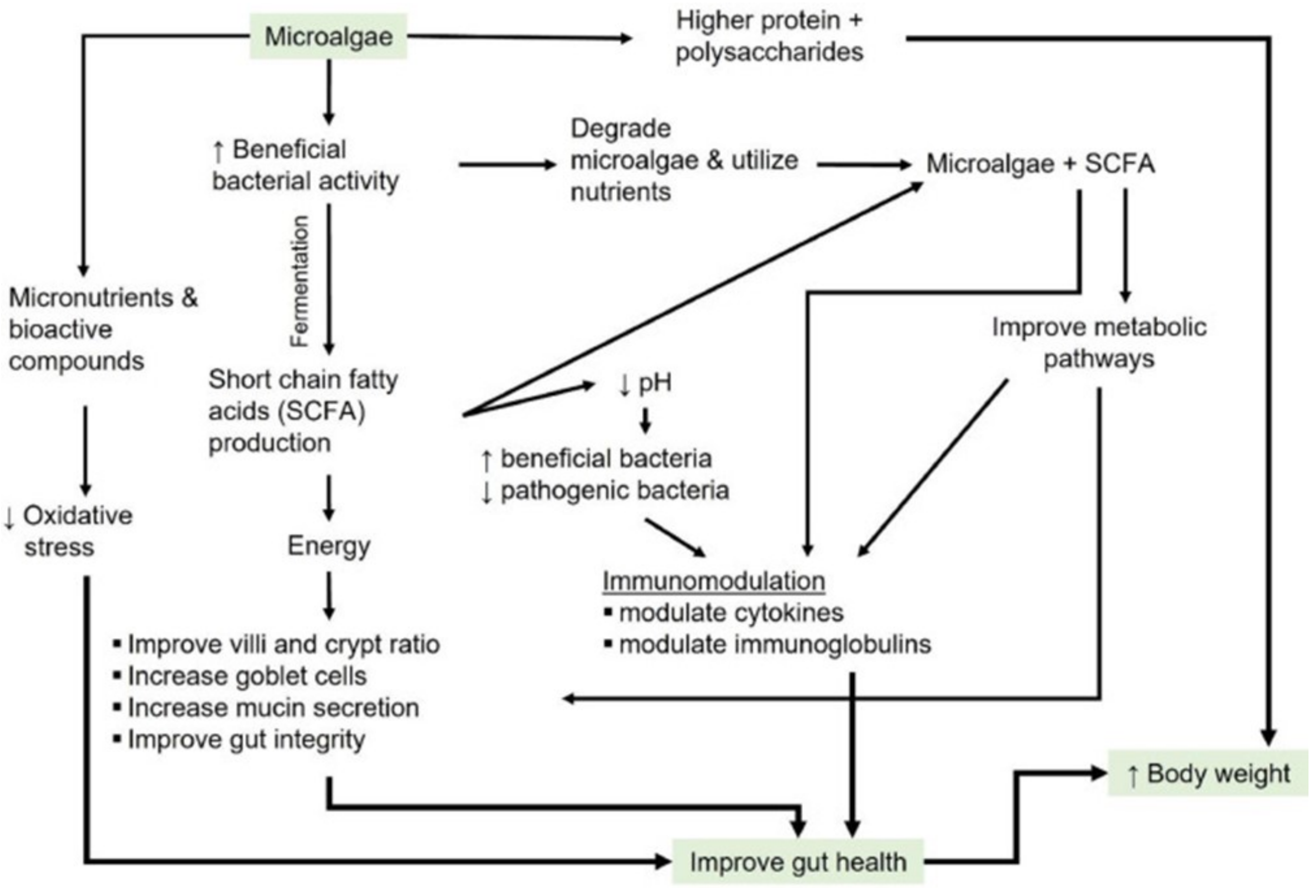

Figure (1). Potential mechanisms by which microalgae enhance gut health and promote growth in broiler chickens

The evidence on the optimal inclusion levels of Spirulina and Chlorella spp. in broiler diets remains inconclusive. Lower inclusion levels of microalgae seem to have minimal effects on performance and meat quality, likely because experimental diets are like control diets, apart from differences in carotenoid composition. Some benefits of microalgae, such as reduced mortality and improved overall health, have been noted in layer diets. Species like Spirulina can function as probiotics, promoting beneficial gut bacteria, improving nutrient absorption, and enhancing immune function **(Patel *et al*., 2021**). Additionally, microalgae compounds like carotenoids offer antioxidant effects, which may protect intestinal cells and reduce inflammation.

Several factors complicate the comparison of findings across studies. For instance, sample sizes vary, which can affect the statistical significance of results. Larger sample sizes tend to produce more reliable findings. Furthermore, some studies fail to provide detailed information on the production, processing, and preservation conditions of the microalgae used, which are critical for understanding their nutritional profiles and impacts on animal health. Most studies only report basic data like crude protein and dry matter content, while missing more detailed information on minerals, fatty acids, carotenoids, and vitamins. Beak conditioning of poultry, a common practice in commercial farming, also influences feed consumption, but its impact is rarely addressed in the studies reviewed, which limits the interpretation of negative outcomes. Moreover, some microalgae species, such as *Dunaliella salina*, may cause issues like diarrhea in poultry if salt concentrations are too high (**Tammam *et al*., 2011**). Proper analysis of salt content and careful formulation are necessary before trial initiation to prevent such issues.

Conclusion

Incorporating microalgae into poultry feed is emerging as a valuable alternative to traditional protein sources, offering several potential benefits for animal health and product quality. Research indicates that microalgae can improve the nutritional profile of poultry meat by increasing levels of omega-3 fatty acids and antioxidants. Moreover, these algae may help balance the gut microbiota by encouraging the growth of beneficial microbes, which supports better digestion and nutrient uptake. Microalgae also exhibit properties that stimulate growth naturally and may serve as a substitute for antibiotics, making them a strong candidate for more sustainable and health-conscious poultry production. Despite these advantages, issues such as limited digestibility and variable nutrient content remain. More research is required to identify the most effective inclusion rates and processing strategies to maximize nutrient bioavailability. For microalgae to become a dependable and cost-efficient component of poultry diets, standardized methods for their cultivation must be established. This involves optimizing environmental conditions, nutrient inputs, and post-harvest processing. Addressing these technical aspects will be key to fully integrating microalgae into mainstream animal nutrition.

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