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# Algae and Algae-Derived Bioactive Compounds in Aquaculture: Applications in Fish Health, Welfare, Nutrition, Gut Function, and Disease Resistance

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***Abstract:*** The rapid expansion of aquaculture has increased the need for sustainable nutritional strategies that support fish growth, health, welfare, and resilience to environmental and infectious stressors. In this context, algae and algae-derived bioactive compounds have attracted considerable attention because of their diverse nutritional and functional properties. Microalgae and macroalgae provide proteins, omega-3 polyunsaturated fatty acids, carotenoids, polysaccharides, polyphenols, vitamins, minerals, peptides, and other bioactive compounds that may influence antioxidant defense, immune responses, intestinal function, gut microbiota, stress tolerance, and disease resistance. Recent studies indicate that dietary algae can improve growth performance, feed utilization, physiological condition, and resistance to stress and disease in several cultured fish species. However, their effects depend on algal species and strain, chemical composition, processing, fish species, inclusion level, feeding duration, and environmental conditions. This review summarizes current knowledge on algae and algae-derived bioactive compounds in aquaculture, with particular emphasis on fish nutrition, health, welfare, intestinal function, antioxidant defense, stress tolerance, and disease resistance. The potential and limitations of major compounds, including fucoidan, laminarin, astaxanthin, omega-3 fatty acids, phycobiliproteins, polyphenols, and bioactive peptides, are also discussed. Overall, algae represent multifunctional and promising resources for developing sustainable nutritional strategies and improving fish health and resilience in modern aquaculture.

***Keywords:*** *Microalgae, Macroalgae, Nutrition, Disease, Antioxidant Defense.*

## I. INTRODUCTİON

Aquaculture has become a major component of the global aquatic food system, driven by increasing demand for animal protein, declining wild fish stocks, and advances in farming and hatchery technologies. According to the Food and Agriculture Organization, global aquaculture production reached a record level in 2022, and aquaculture surpassed capture fisheries in the production of aquatic animals for the first time (FAO, 2024). However, the rapid intensification of aquaculture has also increased the need to improve the health, welfare, sustainability, and efficiency of farmed fish. Farmed fish are frequently exposed to stressors such as high stocking density, handling, transportation, temperature fluctuations, poor water quality, hypoxia, nutritional deficiencies, and pathogen exposure. Persistent or repeated stress can impair physiological balance, antioxidant defenses, intestinal function, metabolism, and immune responses, increasing disease susceptibility and negatively affecting growth and survival. Therefore, modern aquaculture increasingly focuses on preventive strategies that improve fish resilience rather than relying mainly on treatments after disease outbreaks. Nutrition plays a central role in this approach. Aquafeeds provide not only essential nutrients for growth but also bioactive compounds that can support digestion, antioxidant capacity, intestinal health, metabolism, stress tolerance, and host–microbiota interactions. As a result, functional feed ingredients such as probiotics, prebiotics, phytochemicals, organic acids, peptides, vitamins, minerals, and marine-derived compounds have received increasing attention (Siddik et al., 2023). Among these resources, algae have considerable potential because they combine nutritional value with a wide range of bioactive compounds. Microalgae can provide proteins, essential fatty acids, long-chain polyunsaturated fatty acids, carotenoids, polysaccharides, vitamins, minerals, and antioxidant compounds. Macroalgae, or seaweeds, including brown, green, and red algae, are particularly rich in polysaccharides such as fucoidan, laminarin, alginate, ulvan, agar, and carrageenan, as well as polyphenols, pigments, proteins, minerals, and other bioactive molecules. These compounds may contribute to fish health by supporting antioxidant defense, intestinal function, microbial balance, stress tolerance, immune responses, and resistance to disease. However, their effects should not be considered simply as "immune stimulation." Fish health depends on the interaction of nutrition, metabolism, immunity, oxidative status, intestinal microbiota, stress physiology, and environmental conditions. Algae are therefore better viewed as multifunctional dietary resources that can support physiological homeostasis and resilience. This review summarizes current knowledge on the use of algae and algae-derived bioactive compounds in aquaculture, with particular emphasis on fish nutrition, health, welfare, intestinal function, antioxidant defense, stress tolerance, immune competence, and disease resistance. The potential limitations related to species specificity, dosage, bioavailability, processing, safety, and commercial application are also discussed (Siddik et al., 2024; Ma and Hu, 2024).

## II. ALGAL DİVERSİTY AND THEİR POTENTİAL İN AQUACULTURE

Algae represent a highly diverse group of aquatic organisms and include both microalgae and macroalgae (seaweeds). They have considerable potential in aquaculture because they combine high nutritional value with a wide range of biologically active compounds. Depending on their species and biochemical composition, algae can provide proteins, essential amino acids, omega-3 long-chain polyunsaturated fatty acids (LC-PUFAs), carotenoids, polysaccharides, polyphenols, vitamins, minerals, peptides, and other metabolites. These compounds may contribute to fish growth, metabolism, antioxidant defense, intestinal function, stress tolerance, and disease resistance. Therefore, algae can be considered not only as feed ingredients but also as multifunctional resources for improving fish health and supporting sustainable aquaculture (Mohan et al., 2019). Microalgae include genera such as

*Chlorella, Nannochloropsis, Tetraselmis, Scenedesmus, Chlamydomonas,* and *Haematococcus*, while Arthrospira (commonly known as *Spirulina*) is a cyanobacterium frequently included in aquaculture research within the broader microalgal group. Macroalgae are generally classified into green, red, and brown seaweeds and include genera such as *Ulva*, *Gracilaria, Kappaphycus*, *Laminaria, Saccharina, Ascophyllum,* and *Sargassum*. The chemical composition of these organisms varies substantially according to species, strain, geographical origin, season, cultivation conditions, harvest stage, and processing method. Consequently, the biological effects of algae cannot be generalized across all species or products. Microalgae are increasingly investigated as alternative or complementary sources of protein and lipids in aquafeeds. Many species contain substantial amounts of protein and essential amino acids, while others are particularly valuable for their lipid and fatty acid profiles. *Chlorella, Arthrospira,* and *Scenedesmus* are generally recognized as protein-rich biomass sources, whereas *Nannochloropsis* is particularly attractive because of its EPA content. In contrast, *Schizochytrium* is widely investigated as a DHA-rich lipid source. These long-chain omega-3 fatty acids are important for membrane structure, cellular signaling, metabolism, reproduction, and stress adaptation (Eladl et al., 2024).

The nutritional value of microalgae, however, depends not only on their crude nutrient content but also on digestibility and nutrient accessibility. Some species possess resistant cell walls that can limit the availability of intracellular proteins and lipids. Processing techniques such as mechanical disruption, enzymatic hydrolysis, and fermentation may therefore improve nutrient accessibility and utilization. In addition, the potential of microalgae to complement plant-based ingredients is particularly relevant because they can contribute essential amino acids, fatty acids, micronutrients, and bioactive compounds that may compensate for some limitations of terrestrial plant proteins (Ma and Hu, 2024). Beyond their nutritional value, algae are important sources of diverse bioactive compounds. Carotenoids, phycobiliproteins, polysaccharides, polyphenols, peptides, and omega-3 fatty acids have received particular attention because of their potential biological effects. Carotenoids such as astaxanthin, β-carotene, lutein, zeaxanthin, and canthaxanthin can contribute to antioxidant protection and pigmentation. Astaxanthin is especially important in aquaculture because of its role in pigmentation and its antioxidant properties. However, the effectiveness of algal pigments depends on their concentration, chemical form, stability during feed processing, and bioavailability (Siddhnath et al., 2024; Mirzapour-Kouhdasht et al., 2024). Phycobiliproteins, including phycocyanin and phycoerythrin, are another important group of algal compounds. Phycocyanin, particularly from Arthrospira, has attracted attention because of its antioxidant and other biological activities. Its stability can be affected by processing and storage, making extraction and stabilization technologies important for maintaining its functional properties (Yu et al., 2024; Ashaolu, 2024). Macroalgae are particularly rich in structurally diverse polysaccharides. Brown seaweeds contain fucoidan, laminarin, and alginate; green seaweeds contain ulvan; and red seaweeds are important sources of carrageenan and agar. These compounds may influence intestinal function, microbial communities, oxidative balance, and host defense. Their biological activity depends strongly on molecular characteristics such as molecular weight, sulfation, monosaccharide composition, and extraction method. Thus, different algal sources or extraction procedures may produce substantially different physiological responses (Mohan et al., 2019). The intestine is a major target of algal bioactive compounds because it integrates digestion, nutrient absorption, barrier function, microbial ecology, and immune surveillance. Some algal polysaccharides are poorly digested and can reach the lower gastrointestinal tract, where they may interact with intestinal microorganisms. Their potential prebiotic effects may promote favorable microbial communities and support intestinal barrier function and nutrient utilization. Studies with seaweed-derived ingredients have reported changes in digestive enzyme activity and gut microbiota, suggesting that algae may influence gastrointestinal health beyond their direct nutritional contribution. Algal antioxidants may also help maintain physiological redox balance. Compounds such as carotenoids, polyphenols, phycobiliproteins, and certain peptides can contribute to antioxidant defense and may reduce oxidative damage associated with intensive farming conditions. However, antioxidant activity demonstrated in vitro should not automatically be interpreted as a physiological benefit in fish. Absorption, metabolism, dosage, and interactions with endogenous antioxidant systems must be considered when evaluating the actual effects of these compounds (Siddik et al., 2023).

Algae may also influence immune and inflammatory processes. Dietary algal products have been associated with changes in hematological and immune parameters, including lysozyme activity, phagocytosis, complement activity, cytokine expression, and other indicators of host defense. For example, Laurencia caspica extract has been reported to influence immune-related gene expression and improve resistance to Aeromonas hydrophila in rainbow trout. Nevertheless, these effects are highly dependent on the algal species, compound composition, dietary dose, exposure period, and fish species. Overall, algae should be considered multifunctional biological resources rather than single-purpose feed additives. Microalgae can provide valuable proteins, amino acids, omega-3 fatty acids, pigments, vitamins, and minerals, while macroalgae are particularly rich in polysaccharides, polyphenols, and minerals. These components may collectively support fish growth, intestinal function, antioxidant protection, physiological resilience, and disease resistance. However, their successful application requires appropriate species selection, optimized processing, controlled inclusion levels, and a better understanding of bioavailability and mechanisms of action. Future research integrating nutritional trials, molecular analyses, microbiome studies, and economic assessments will be essential for translating the biochemical diversity of algae into reliable and sustainable applications in modern aquaculture (Siddik et al., 2023).

## III. MAJOR BİOACTİVE COMPOUNDS DERİVED FROM ALGAE

The biological potential of algae in aquaculture is largely associated with their ability to synthesize and accumulate a wide diversity of bioactive compounds. Unlike conventional feed ingredients, which primarily provide nutrients such as proteins, lipids and carbohydrates, algae can simultaneously supply nutritionally valuable molecules and compounds capable of influencing physiological and metabolic processes in fish. The composition and concentration of these compounds vary considerably among algal taxa and are affected by environmental conditions, cultivation systems, geographical origin, season, harvesting stage and processing methods. Consequently, the biological effects of an algal ingredient depend not only on the amount incorporated into the diet but also on its species-specific biochemical profile and the preservation and bioavailability of its active constituents (Siddik et al., 2024; Eladl et al., 2024; Mirzapour-Kouhdasht et al., 2024). Recent studies have identified polysaccharides, carotenoids and other pigments, polyphenols, proteins and bioactive peptides, polyunsaturated fatty acids, phycobiliproteins, vitamins, minerals and other secondary metabolites as the major groups responsible for the functional properties of algae in animal nutrition and aquaculture (Siddhnath et al., 2024; Ma and Hu, 2024).

### *A. Polysaccharides*

Algal polysaccharides are important bioactive compounds, particularly in macroalgae. Brown, green, and red seaweeds contain different polysaccharides, including fucoidan, laminarin, ulvan, carrageenan, and agar. These compounds may support fish health by influencing intestinal function, antioxidant capacity, gut microbiota, and host defense (Mohan et al., 2019; Bakky et al., 2022). Among them, fucoidan, laminarin, and ulvan have received considerable attention. Fucoidan may improve antioxidant and intestinal responses, while laminarin, a β-glucan, may influence innate defense and microbial balance. Ulvan from green seaweeds has also shown potential effects on antioxidant status and intestinal health. However, their biological activity depends strongly on molecular structure, algal source, extraction method, dose, and fish species (Abdel-Latif et al., 2022). An important feature of these polysaccharides is their potential prebiotic effect. Because many are poorly digested in the upper gastrointestinal tract, they can reach the intestine and interact with microorganisms, potentially promoting beneficial bacteria and supporting intestinal barrier function and nutrient utilization. Nevertheless, responses vary according to the algal product, dietary level, and existing gut microbiota (Mota et al., 2023). Overall, algal polysaccharides represent promising multifunctional compounds for improving gut health, antioxidant protection, microbial balance, and physiological resilience in farmed fish.

### *B. Carotenoids and Other Pigments*

Carotenoids are important bioactive compounds produced by microalgae and include astaxanthin, β-carotene, lutein, zeaxanthin, and canthaxanthin. In aquaculture, these pigments are valuable not only for improving fish coloration but also for their antioxidant and protective functions. Astaxanthin is particularly important in fish nutrition because it contributes to pigmentation and may help protect cells against oxidative stress caused by intensive farming conditions such as handling, temperature fluctuations, hypoxia, and pathogen exposure (Siddik et al., 2024). Microalgae such as *Chlorella, Dunaliella,* and *Haematococcus* are promising natural sources of carotenoids. β-carotene may also contribute to vitamin A metabolism, while lutein and other carotenoids can support antioxidant defense. However, their effectiveness depends on algal species, cellular accessibility, processing, and bioavailability. Algae also contain phycobiliproteins, particularly phycocyanin and phycoerythrin. Phycocyanin from *Arthrospira (Spirulina)* has received considerable attention because of its antioxidant and functional properties. Cultivation conditions, extraction methods, and stabilization processes strongly influence its quality and biological activity (Mao et al., 2024; Yu et al., 2024). Overall, algal pigments represent promising functional ingredients that may simultaneously contribute to pigmentation, antioxidant protection, and physiological health in cultured fish.

### *C. Polyphenols and Phlorotannins*

Polyphenols constitute another important class of algal secondary metabolites. Seaweeds, particularly brown algae, contain distinctive polyphenolic compounds known as phlorotannins, which are polymers of phloroglucinol. These compounds can exhibit antioxidant, antimicrobial and anti-inflammatory properties and are therefore of considerable interest in the context of fish health. Their concentration can vary substantially according to algal species, environmental conditions, season and extraction procedure. From an aquaculture perspective, the antioxidant activity of algal polyphenols is particularly relevant. Fish continuously generate reactive oxygen species through normal metabolic activity, and this production can increase markedly during environmental or biological stress. If the production of reactive oxygen species exceeds the capacity of endogenous antioxidant systems, oxidative damage may occur to lipids, proteins and nucleic acids. Dietary compounds with antioxidant properties may help maintain the balance between oxidant production and antioxidant defenses. Seaweed-derived polyphenols may therefore complement endogenous antioxidant enzymes such as superoxide dismutase, catalase and glutathione peroxidase. However, the biological activity of polyphenols should not be interpreted solely on the basis of chemical antioxidant assays. The ability of a compound to neutralize free radicals in vitro does not necessarily indicate that the compound will exert the same effect following ingestion. Absorption, metabolism, transformation by the intestinal microbiota and interactions with dietary components all influence physiological activity. Consequently, future aquaculture studies should increasingly combine chemical characterization with measurements of oxidative biomarkers, tissue responses and molecular mechanisms in vivo (Andriopoulos et al., 2022).

### *D. Proteins, Bioactive Peptides and Amino Acids*

Algae are also valuable sources of proteins and peptides. Depending on species and cultivation conditions, microalgae can contain substantial amounts of protein with a relatively favorable amino acid composition. Species such as *Chlorella, Arthrospira, Nannochloropsis* and *Tetraselmis* have therefore been investigated extensively as alternative protein sources for aquafeeds. The contribution of algal proteins to fish nutrition is important in the context of reducing dependence on fishmeal and other conventional protein sources. However, the biological value of algal protein depends on digestibility, amino acid profile, cell-wall characteristics and processing method (Siddik et al., 2024). In addition to intact proteins, enzymatic hydrolysis of algal proteins can generate peptides with biological activities that differ from those of the parent proteins. Algal-derived peptides have been reported to exhibit antioxidant, antimicrobial and other physiological activities. Such peptides may potentially interact with oxidative and inflammatory pathways or contribute directly to antimicrobial defense. The increasing application of enzymatic hydrolysis, fermentation and other processing technologies has consequently created opportunities for producing more concentrated functional ingredients from algal biomass. The distinction between nutritional protein and bioactive peptide fractions is important in aquaculture research. A fish may exhibit improved growth simply because an algal ingredient supplies digestible amino acids, whereas an observed improvement in oxidative or immune parameters may arise from peptides or other non-protein compounds. Controlled experiments using protein isolates, hydrolysates and purified fractions can therefore help determine whether a biological response results from improved nutrition or from specific bioactive molecules. Recent reviews of algae-derived compounds emphasize peptides as one of the major functional compound classes with potential antioxidant, anti-inflammatory and other biological activities (Mirzapour-Kouhdasht et al., 2024).

### *E. Polyunsaturated Fatty Acids*

Lipids represent another major functional component of microalgae. Many microalgal species are rich in polyunsaturated fatty acids (PUFAs), including α-linolenic acid, linoleic acid and, importantly, the long-chain omega-3 fatty acids eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These fatty acids have essential physiological roles in membrane structure, neural development, vision, reproduction and cellular signaling. Their role in regulating inflammatory processes is also highly relevant to fish health. Microalgae are particularly attractive because they provide a more direct biological source of long-chain omega-3 fatty acids than terrestrial plant oils. Species such as Nannochloropsis are recognized as valuable EPA sources, whereas certain microalgae and thraustochytrid organisms are particularly rich in DHA. The incorporation of algal oils into aquafeeds may therefore contribute not only to the nutritional quality of the diet but also to maintaining appropriate tissue fatty-acid profiles when marine-derived oils are reduced. The relationship between dietary PUFAs and fish health is complex. Omega-3 fatty acids influence the composition and fluidity of cellular membranes and serve as precursors for signaling molecules involved in inflammatory and immune processes. Therefore, dietary manipulation of algal lipids may influence how fish respond to environmental and infectious challenges. Recent reviews of microalgae in aquafeeds identify long-chain PUFAs among the major health-promoting compounds responsible for their value in aquaculture (Radwan et al., 2026).

### *F. Vitamins and Minerals*

Although vitamins and minerals are not always classified as secondary bioactive metabolites, their contribution to the functional properties of algae should not be overlooked. Microalgae can supply vitamins such as vitamin E, vitamin C-related compounds, B-group vitamins and provitamin A carotenoids, while seaweeds can provide substantial quantities of minerals and trace elements. These micronutrients participate in antioxidant defense, energy metabolism, immune function, tissue development and enzymatic reactions. Vitamin E is particularly relevant to oxidative stability because it protects cellular membranes from lipid peroxidation. Selenium, zinc, iron, copper and manganese are also essential for the activity of various antioxidant and metabolic enzymes. However, mineral concentrations in seaweeds can vary considerably and may occasionally be associated with excessive accumulation of undesirable elements depending on the cultivation environment. Thus, the use of algae as a micronutrient source requires appropriate quality control and compositional monitoring. Reviews of microalgae in aquafeeds emphasize that vitamins and minerals contribute substantially to their nutritional and functional value, although their specific effects depend on species and dietary context (Siddik et al., 2024).

### *G. Sterols, Terpenoids and Other Secondary Metabolites*

In addition to the major compound classes discussed above, algae synthesize numerous lower-abundance secondary metabolites, including sterols, terpenoids, halogenated compounds and other specialized metabolites. These molecules are often species-specific and may contribute to antimicrobial, antioxidant or anti-inflammatory activities. Brown, red and green seaweeds differ markedly in their secondary-metabolite profiles, which partly explains why biological responses can vary considerably among algal species (Eladl et al., 2024). Some of these compounds may have considerable potential as functional feed ingredients, but they remain less extensively characterized in aquaculture than polysaccharides, carotenoids and PUFAs. Furthermore, the presence of biologically active secondary metabolites does not automatically indicate nutritional safety. Certain algal species can accumulate undesirable compounds or environmental contaminants, and therefore species identification, cultivation conditions and quality control are critical considerations before commercial application. The development of algae-derived functional feed additives should consequently consider both beneficial and potentially adverse bioactive constituents (Mirzapour-Kouhdasht et al., 2024).

### *H. Synergistic Effects of Algal Bioactive Compounds*

One of the most important considerations when evaluating algae in aquaculture is that their biological activity rarely originates from a single compound. Whole algal biomass represents a complex mixture of proteins, lipids, polysaccharides, pigments, minerals, vitamins and secondary metabolites. These components may interact synergistically and produce physiological effects that are not reproduced by an isolated molecule. For example, an algal meal may simultaneously provide EPA, carotenoids, proteins and polysaccharides, thereby influencing membrane composition, antioxidant status, intestinal microbiota and nutrient metabolism. This multifunctionality is one of the principal advantages of algae over many conventional single-compound feed additives. At the same time, it creates difficulties in identifying the exact mechanisms responsible for observed responses. A dietary treatment that improves fish health may produce this effect through several interconnected pathways, including improved nutrient supply, reduced oxidative stress, altered intestinal microbiota and modulation of host signaling pathways. Recent reviews emphasize that seaweed-derived metabolites can affect growth, antioxidant responses, disease resistance, stress physiology and gut microbial communities simultaneously (Radwan et al., 2026). The concept of synergism is particularly relevant when considering the use of whole algae versus purified extracts. Whole biomass may be less concentrated in a particular bioactive compound but may provide a broader spectrum of biological activities. In contrast, an extract may allow a more predictable dose of a target compound but may lose interactions with other constituents present in the original biomass. The optimal approach will therefore depend on the intended application, target fish species, dietary formulation and desired physiological response.

### *I. Bioavailability, Processing and Standardization*

The biological effectiveness of algal compounds depends not only on their concentration but also on their bioavailability and stability. Cell-wall structure, molecular properties, processing, and storage can influence the absorption and utilization of proteins, lipids, pigments, polyphenols, and other bioactive compounds. Technologies such as cell disruption, enzymatic hydrolysis, fermentation, extraction, and encapsulation can improve their accessibility and stability (Mirzapour-Kouhdasht et al., 2024). Standardization is also essential because algal products can vary considerably in their chemical composition. Detailed characterization of proteins, fatty acids, carotenoids, polysaccharides, and phenolic compounds is therefore necessary to improve reproducibility and determine appropriate dietary doses. Overall, algae provide diverse bioactive compounds that can support antioxidant defense, intestinal health, metabolism, and physiological resilience. However, their effects depend on algal species, processing, dosage, exposure duration, and fish species, highlighting the need for standardized products and mechanistic research (Radwan et al., 2026).

## IV. MİCROALGAE AS NUTRİTİONAL AND FUNCTİONAL FEED INGREDİENTS

Microalgae are promising aquafeed ingredients because they provide both essential nutrients and bioactive compounds. They can supply proteins, amino acids, lipids, omega-3 LC-PUFAs, carbohydrates, pigments, vitamins, and minerals, supporting fish growth, metabolism, health, and product quality (Ma and Hu, 2024). Their nutritional composition varies considerably with species, strain, and cultivation conditions. For example, Arthrospira and Chlorella are rich in protein, Nannochloropsis provides EPA, while Schizochytrium is a valuable source of DHA. Therefore, microalgae should be selected according to the specific nutritional or functional purpose rather than treated as a single feed ingredient (Siddik et al., 2024).

### *A. Microalgal Protein as an Alternative Protein Source*

Microalgae are promising alternative protein sources for aquafeeds because of their relatively high protein content and diverse essential amino acid profiles. Species such as *Arthrospira*, *Chlorella*, *Nannochloropsis*, and *Tetraselmis* have been investigated as partial replacements for fishmeal (Radwan et al., 2026; Ma and Hu, 2024). However, their nutritional value depends not only on protein content but also on amino acid composition, digestibility, cell-wall structure, and processing methods. Cell disruption and other processing techniques can improve nutrient accessibility and utilization (Agboola et al., 2019). Fishmeal replacement levels vary considerably among species and depend on both the algal product and dietary formulation. Therefore, microalgae are best considered as complementary ingredients that can improve the nutritional quality of aquafeeds rather than as universal substitutes for fishmeal.

### *B. Microalgal Lipids and Long-Chain Polyunsaturated Fatty Acids*

Lipids constitute another major nutritional advantage of microalgae. Depending on species and cultivation conditions, microalgae can accumulate considerable quantities of lipids, including neutral lipids, phospholipids and polyunsaturated fatty acids. Of particular importance for aquaculture are the omega-3 LC-PUFAs eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These fatty acids are essential components of cellular membranes and play important roles in growth, development, neural function, vision, reproduction and regulation of inflammatory processes. The dependence of aquaculture on fish oil as a source of EPA and DHA has generated considerable interest in algal-derived lipids. Microalgae occupy a fundamental position at the base of aquatic food webs and are natural sources of the LC-PUFAs that subsequently accumulate in zooplankton and fish. The use of microalgal biomass or extracted algal oils can therefore provide a more direct route for introducing these fatty acids into aquafeeds while reducing dependence on finite marine resources. Species such as Nannochloropsis are particularly valuable sources of EPA, whereas DHA-rich algal oils can be obtained from several heterotrophic microalgal and thraustochytrid organisms (Radwan et al., 2026). The significance of algal lipids extends beyond their nutritional contribution. The fatty acid composition of the diet directly affects the fatty acid composition of fish tissues and cellular membranes. Changes in membrane fatty acids can influence membrane fluidity, receptor function and the synthesis of lipid mediators involved in inflammatory and stress responses. Consequently, dietary microalgae may influence fish physiology through both direct nutrient supply and modification of cellular lipid metabolism. This characteristic is particularly relevant when plant oils are used to reduce fish-oil inclusion, because many terrestrial plant oils contain high levels of C18 fatty acids but relatively low levels of EPA and DHA. Algal oils may therefore help maintain the desired omega-3 fatty acid profile of aquafeeds and edible fish tissues (Ma and Hu, 2024).

### *C. Carbohydrates, Polysaccharides and Dietary Fiber*

Although microalgae are generally discussed primarily as protein and lipid sources, their carbohydrate fraction can also have important nutritional and functional consequences. Microalgal carbohydrates include storage compounds as well as structural polysaccharides and extracellular polymeric substances. The digestibility of these carbohydrates varies considerably according to their chemical structure and the digestive capacity of the target species. Some algal polysaccharides may reach the lower gastrointestinal tract relatively intact and interact with the intestinal microbial community. This property provides a potential link between microalgal carbohydrates and gut health. Rather than serving exclusively as energy sources, specific polysaccharides may act as fermentable substrates or functional molecules capable of influencing microbial composition and host–microbe interactions. This is particularly relevant in intensive aquaculture, where maintenance of intestinal integrity and microbial balance is increasingly recognized as a key component of fish health. Microalgae-derived β-glucans represent one of the most interesting examples of this functional potential. β-glucans can interact with innate immune recognition pathways and have been investigated extensively as dietary components capable of influencing host defense. In the context of microalgae, their contribution may occur alongside carotenoids, proteins, vitamins and other bioactive molecules, making whole-cell biomass potentially different from purified β-glucan preparations. Recent reviews have specifically identified β-glucans among the major microalgal biomolecules with potential applications as functional aquafeed additives (Ma and Hu, 2024).

### *D. Microalgae as Sources of Antioxidant Compounds*

One of the most important functional properties of microalgae is their high content of antioxidant compounds. Intensive aquaculture exposes fish to multiple stressors, including high stocking densities, handling, transportation, temperature fluctuations, hypoxia, suboptimal water quality and infectious agents. These conditions can increase the generation of reactive oxygen species and disrupt the normal balance between oxidant production and antioxidant defense. Microalgae contain several compounds that may contribute to antioxidant protection, particularly carotenoids, chlorophyll-related pigments, phycobiliproteins, polyphenols, tocopherols and other secondary metabolites. Astaxanthin, β-carotene, lutein and zeaxanthin are among the most extensively studied carotenoids. Their antioxidant activity can help limit lipid peroxidation and oxidative damage, while some carotenoids may additionally influence cellular signaling and other physiological processes. Consequently, the inclusion of carotenoid-rich microalgal biomass or extracts may have effects that extend beyond simple pigmentation. The antioxidant properties of microalgae are particularly relevant because oxidative stress is closely interconnected with immune function, inflammation and disease susceptibility. Excessive oxidative stress can impair cellular membranes, proteins and nucleic acids and can alter the activity of immune cells. By contributing antioxidant compounds to the diet, microalgae may support the endogenous antioxidant system of fish and potentially improve physiological resilience during periods of stress. Experimental and review literature has reported associations between microalgal dietary inclusion and changes in antioxidant-related parameters in aquatic animals, although the magnitude of the response depends on species, dose and the biochemical composition of the algal preparation (Siddik et al., 2024).

### *E. Effects on Growth Performance and Feed Utilization*

The nutritional and functional properties of microalgae can ultimately influence growth performance and feed utilization. When appropriately formulated and processed, microalgal ingredients may provide amino acids, fatty acids, vitamins and minerals that support tissue synthesis and metabolic activity. In addition, functional compounds may indirectly affect growth by improving intestinal condition, reducing oxidative stress or supporting physiological homeostasis. However, positive growth responses should not be assumed solely because an ingredient is rich in bioactive compounds. Excessive inclusion of some microalgae can reduce feed intake or nutrient digestibility because of high ash content, cell-wall components, unusual polysaccharides, nucleic acids, pigments or other factors. Consequently, the optimal dietary inclusion level is determined by the balance between nutritional benefits and potential limitations. The literature on fishmeal replacement demonstrates this principle clearly: moderate inclusion levels can be beneficial or neutral, whereas excessive substitution may reduce growth and feed efficiency (2024). This dose-dependent response is especially important when whole microalgal biomass is used. A relatively low inclusion level may provide sufficient amounts of functional compounds while contributing only modestly to the total indigestible fraction of the diet. At higher inclusion levels, however, the same biomass may introduce nutritional constraints that offset its health-promoting properties. Therefore, the objective should not necessarily be to maximize microalgal inclusion but to determine the biologically and economically optimal inclusion level for each fish species and production system (Hachimi et al., 2026).

### *F. Microalgae and Fish Health*

Microalgae are increasingly recognized as multifunctional feed ingredients because their bioactive compounds can simultaneously influence antioxidant defense, intestinal health, inflammatory responses, and host protection. Carotenoids, polysaccharides, β-glucans, vitamins, EPA, and DHA may interact with different physiological pathways, and experimental studies have reported improvements in antioxidant activity, hematological and immune parameters, and resistance to some pathogens. However, these effects vary according to algal species, processing method, dietary dose, feeding period, fish species, and environmental conditions. Therefore, microalgae should be considered a supportive nutritional strategy rather than a replacement for good husbandry and disease management (Siddik et al., 2024; Ma and Hu, 2024). The gastrointestinal tract is one of the main targets of algal bioactive compounds. Microalgal proteins and lipids support intestinal tissues, while polysaccharides and other compounds may influence the gut microbiota, epithelial integrity, nutrient utilization, and resistance to opportunistic pathogens. EPA and DHA can regulate membrane and inflammatory pathways, whereas carotenoids and polyphenols may contribute to antioxidant protection. These combined effects may explain the broader benefits observed with whole microalgal biomass. However, changes in gut microbial composition do not necessarily indicate improved fish health. Future studies should therefore combine microbiome analyses with intestinal morphology, barrier-function markers, metabolomics, and growth and health parameters to better understand the mechanisms involved (Mahfuj et al., 2026).

### *G. Whole Biomass versus Algal Extracts*

Microalgae can be used in aquafeeds as whole biomass, extracts, oils, or purified compounds. Whole biomass provides a wide range of nutrients and bioactive compounds and may benefit from their combined effects. However, resistant cell walls and the relatively low concentration of individual compounds can limit their utilization. In contrast, extracts and concentrated products allow specific compounds such as carotenoids, omega-3 fatty acids, and phycobiliproteins to be supplied at lower inclusion levels and with greater formulation precision, although their production is more costly and may alter the properties of the target compounds (Ma and Hu, 2024; Siddik et al., 2024). Processing is therefore a key factor determining the nutritional and functional value of microalgae. Harvesting, drying, cell disruption, enzymatic treatment, and fermentation can improve nutrient accessibility and bioavailability, whereas excessive heat or inappropriate processing may degrade sensitive lipids and pigments. High production costs, variable digestibility, and differences in algal composition remain important limitations. Consequently, species selection, optimized processing, standardization, and appropriate inclusion levels are essential for the successful application of microalgae. Overall, properly processed microalgal products have strong potential as multifunctional feed ingredients supporting fish growth, health, antioxidant defense, intestinal function, and physiological resilience (Naya et al., 2026).

## CONCLUSİON

Algae have strong potential to support sustainable and health-oriented aquaculture because they provide both essential nutrients and diverse bioactive compounds. Microalgae and macroalgae can contribute proteins, omega-3 fatty acids, pigments, polysaccharides, vitamins, minerals, and polyphenols, which may support growth, antioxidant defense, intestinal health, stress tolerance, and disease resistance. However, the effects of algal products vary considerably according to species, cultivation conditions, processing, dose, and fish species. Future research should therefore focus on standardization, bioavailability, dose optimization, safety, and understanding the mechanisms of action of specific algal compounds. Reducing production and processing costs will also be essential for commercial application. An important future approach is the integration of algae into circular aquaculture systems, where nutrients from aquaculture effluents can be recovered and converted into algal biomass. This could simultaneously support wastewater treatment, biomass production, and resource recycling. Overall, rather than completely replacing conventional feed ingredients, the most practical strategy is likely to use whole algae or specific algal fractions according to their nutritional and functional properties. With further advances in biotechnology, feed technology, environmental assessment, and economic analysis, algae-derived ingredients could become valuable components of more resilient, efficient, and environmentally sustainable aquaculture systems.

### *References*

[1] Andriopoulos, V., Gkioni, M. D., Koutra, E., Mastropetros, S. G., Lamari, F. N., Hatziantoniou, S., & Kornaros, M. (2022). Total Phenolic Content, Biomass Composition, and Antioxidant Activity of Selected Marine Microalgal

Species with Potential as Aquaculture Feed. Antioxidants, 11(7), 1320. https://doi.org/10.3390/antiox11071320

[2] Ashaolu, T. J. (2024). The powerful phycobiliproteins-phycocyanin and phycoerythrin: Pleiotropic applications and biofunctional uses. *Algal Research, 82*, 103636. https://doi.org/10.1016/j.algal.2024.103636.

[3] Abdel-Latif, H. M. R., Dawood, M. A. O., Alagawany, M., Faggio, C., Nowosad, J., & Kucharczyk, D. (2022). Health benefits and potential applications of fucoidan (FCD) extracted from brown seaweeds in aquaculture: An updated review. Fish & shellfish immunology, 122, 115-130.

[4] Agboola, J. O., Teuling, E., Wierenga, P. A., Gruppen, H., & Schrama, J. W. (2019). Cell wall disruption: An effective strategy to improve the nutritive quality of microalgae in African catfish (Clarias gariepinus). Aquaculture Nutrition, 25, 783-797. https://doi.org/10.1111/anu.12896

[5] Ahmad, M. T., Shariff, M., Yusoff, F. M., Goh, Y. M., & Banerjee, S. (2020). Applications of microalga Chlorella vulgaris in aquaculture. Reviews in Aquaculture, 12, 328-346. https://doi.org/10.1111/raq.12320.

[6] Ahmad, A., Hassan, S. W., & Banat, F. (2022). An overview of microalgae biomass as a sustainable aquaculture feed ingredient: Food security and circular economy. Bioengineered, 13, 9521-9547. https://doi.org/10.1080/21655979.2022.2061148.

[7] Bakky, M. A. H., Tran, N. T., Zhang, Y., & Li, S. (2022). Utilization of marine macroalgae-derived sulphated polysaccharides as dynamic nutraceutical components in the feed of aquatic animals: A review. Aquaculture Research, 53, 5787-5808. https://doi.org/10.1111/are.16078.

[8] Eladl, S. N., Elnabawy, A. M., & Eltanahy, E. G. (2024). Recent biotechnological applications of value-added bioactive compounds from microalgae and seaweeds. Botanical studies, 65(1), 28. https://doi.org/10.1186/s40529-024-00434-y.

[9] FAO. (2024). *The State of World Fisheries and Aquaculture 2024: Blue Transformation in Action*. Food and Agriculture Organization of the United Nations.

[10] Hachimi Alaoui M, Elmoujtahid A, Bamaarouf M, El Arroussi H. Exploring the Potential of Microalgae as Feed Ingredients for Sustainable Aquaculture: A Review of Nutritional and Environmental Benefits. Aquac Nutr. 2026 Jan 27;2026:5217142. doi: 10.1155/anu/5217142.

[11] Ma, M., & Hu, Q. (2024). Microalgae as feed sources and feed additives for sustainable aquaculture: Prospects and challenges. *Reviews in Aquaculture, 16*, 818-835. https://doi.org/10.1111/raq.12869.

[12] Mao, M., Han, G., Zhao, Y., Xu, X., & Zhao, Y. (2024). A review of phycocyanin: Production, extraction, stability and food applications. International journal of biological macromolecules, 280(Pt 3), 135860. Advance online publication. https://doi.org/10.1016/j.ijbiomac.2024.135860.

[13] Mahfuj, S., Ferdous, T., Babon, A. I., Sarker, P. C., Ahsanul Haque, M., Al-Emran, M., Zahangir, M. M., & Shahjahan, M. (2026). Probiotics and Spirulina platensis enhance growth, antioxidant response and immunity in rohu (Labeo rohita) under thermal stress. Fish & shellfish immunology, 168, 111008. https://doi.org/10.1016/j.fsi.2025.111008.

[14] Mirzapour-Kouhdasht, A., Garcia-Vaquero, M., & Huang, J. Y. (2024). Algae-derived compounds: Bioactivity, allergenicity and technologies enhancing their values. *Bioresource technology*, *406*, 130963. https://doi.org/10.1016/j.biortech.2024.130963

[15] Mohan, K., Ravichandran, S., Muralisankar, T., et al. (2019). Application of marine-derived polysaccharides as immunostimulants in aquaculture: A review of current knowledge and further perspectives. Fish & Shellfish Immunology, 86, 1177-1193. https://doi.org/10.1016/j.fsi.2018.12.072.

[16] Mota, C. S. C., Pinto, O., Sá, T., Ferreira, M., Delerue-Matos, C., Cabrita, A. R. J., Almeida, A., Abreu, H., Silva, J., Fonseca, A. J. M., Valente, L. M. P., & Maia, M. R. G. (2023). A commercial blend of macroalgae and microalgae promotes digestibility, growth performance, and muscle nutritional value of European seabass (Dicentrarchus labrax L.) juveniles. Frontiers in nutrition, 10, 1165343. https://doi.org/10.3389/fnut.2023.1165343.

[17] Naya-Català, F., Domingo-Bretón, R., Ma, Q., Holhorea, P. G., Belenguer, Á., Moroni, F., Calduch-Giner, J., Silkina, A., Van Mullem, D., Halim, R., & Pérez-Sánchez, J. (2026). From Brewery Waste to Sustainable Aquafeed: Harnessing Nannochloropsis Microalgae for Fishmeal-Free Gilthead Sea Bream Diets. Aquaculture nutrition, 2026, 1003936. https://doi.org/10.1155/anu/1003936.

[18] Radwan, M., Fares, M., Al Malki, J. S., Mohammadein, A., & Moussa, M. A. (2026). Elucidating the Effect of Dietary Laminarin on Striped Catfish (Pangasianodon hypophthalmus) Growth Performance, Histological Features, Immune-Antioxidant-Related Genes, and Resistance to Aeromonas hydrophila Infection. Probiotics and antimicrobial proteins, 18(1), 858–875. https://doi.org/10.1007/s12602-025-10566-7.

[19] Siddhnath, Surasani, V. K. R., Singh, A., Singh, S. M., et al. (2024). Bioactive compounds from micro-algae and its application in foods: A review. Discover Food, 4, 27. https://doi.org/10.1007/s44187-024-00096-6.

[20] Siddik, M. A. B., Francis, P., Rohani, M. F., Azam, M. S., Mock, T. S., & Francis, D. S. (2023). Seaweed and Seaweed-Based Functional Metabolites as Potential Modulators of Growth, Immune and Antioxidant Responses, and Gut Microbiota in Fish. Antioxidants *(Basel, Switzerland)*, *12*(12), 2066. https://doi.org/10.3390/antiox12122066.

[21] Siddik, M. A. B., Sørensen, M., Islam, S. M. M., Saha, N., Rahman, M. A., & Francis, D. S. (2024). Expanded utilisation of microalgae in global aquafeeds. Reviews in Aquaculture*, 16*, 6-33. https://doi.org/10.1111/raq.12818.

[22] Theobald, E. J., Irving, A. D., & Capper, A. (2024). Selection of marine macroalgae for nutrient biofilter and bioproduct trials in the coastal waters of Queensland, Australia. Aquaculture International, 32, 9631-9669.

[23] Yu, Z., Zhao, W., Sun, H., Mou, H., Liu, J., Yu, H., Dai, L., Kong, Q., & Yang, S. (2024). Phycocyanin from microalgae: A comprehensive review covering microalgal culture, phycocyanin sources and stability. Food research international (Ottawa, Ont.), 186, 114362. https://doi.org/10.1016/j.foodres.2024.114362.