

Feature Review

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## Towards Sustainable Aquaculture: A Review on The Use of Microalgae as Functional Feed Ingredients

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**Abstract** Population growth is intensifying the demand for sustainable protein sources, positioning aquaculture as a strategic sector for global food security. However, the industry faces nutritional, economic, and environmental challenges, particularly due to the high cost and ecological impact of fishmeal (FM) and fish oil (FO), which are widely used in commercial feeds. These inputs are rich in essential fatty acids, such as docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), whose production relies on intensive harvesting of marine species, thereby compromising the sustainability of the supply chain. In this context, microalgae have emerged as promising alternatives due to their high nutritional and functional value, including proteins, long-chain polyunsaturated fatty acids (LC-PUFAs), antioxidants, and bioactive compounds. This review compiles scientific evidence demonstrating that the inclusion of microalgae in fish and shrimp diets can maintain or enhance lipid composition, immunocompetence, pathogen resistance, antioxidant activity, and gut health in cultured organisms. Species such as *Schizochytrium* sp., *Nannochloropsis* sp., *Chlorella* sp., and *Spirulina* sp. have shown promising results. Although further studies are needed to determine optimal inclusion levels and potential synergies among species, current data support the potential of microalgae to contribute to a more efficient and sustainable aquaculture.

**Keywords** Fishmeal; Fish oil; Antioxidants; Bioactive compounds

## 1 Introduction

The development and growth of the human population have driven a continuous search for alternatives to meet the increasing demand for resources, especially food (Gil et al., 2024). In this context, expanding the production of proteins for human consumption in a safe and sustainable way represents a significant challenge for various sectors, including aquaculture.

Aquaculture is an activity focused on the production of aquatic organisms such as fish, crustaceans, mollusks, and algae. This practice plays a strategic role in global food security, since, according to data from the Food and Agriculture Organization of the United Nations (FAO, 2024), aquaculture production has reached 223.2 million tons. Of this total, 185.4 million tons corresponded to the production of aquatic animals, while 37.8 million tons referred to algae production. Furthermore, approximately 89% of aquatic animal production was intended for human consumption.

Despite the significant figures achieved by aquaculture, challenges still persist regarding the nutrition of farmed organisms, especially fish and shrimp (Evrendilek, 2024). These issues go beyond technical aspects such as diets formulation, balanced and nutritionally adequate feed, and also encompass economic and environmental concerns, including high production costs and the sustainability of the production system. In this context, it is worth noting that feed accounts for a large portion of the total production costs (Baki and Yücel, 2017) making it one of the main obstacles to the economic viability of aquaculture, especially for small and medium-sized producers.

The high cost of aquaculture feed is largely associated with the use of ingredients such as fishmeal (FM) and fish oil (FO), which are valued for their high concentration of polyunsaturated fatty acids (PUFAs), especially docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) (Zhang et al. 2024) which play essential roles in

the growth and reproduction processes of aquatic organisms (Thiruvassagam et al., 2024). However, the intensive use of these inputs raises important concerns related to the sustainability of their production. According to FAO (2024), approximately 19% of fish aquaculture production is directed toward the manufacture of these ingredients, which raises significant environmental concerns, as this practice is closely linked to overfishing (Satyakumar et al., 2024) of species such as anchoveta (*Engraulis ringens*), the main raw material used. This fishing pressure has led to a progressive reduction in natural stocks of the species, compromising the long-term sustainability of the production chain.

Given the concerns regarding the sustainability of FM and FO production, initiatives have emerged aimed at replacing these ingredients in aquaculture diets. However, such replacement presents a considerable challenge, as alternative ingredients must not only be safe for farmed organisms but also possess a nutritional composition compatible with that of traditional inputs, particularly regarding the PUFA profile, with emphasis on long-chain polyunsaturated fatty acids (LC-PUFAs), such as DHA and EPA (Zhang et al., 2024). A deficiency of these compounds in the diet can significantly impair the zootechnical performance of fish and shrimp, affecting their growth, reducing their immunocompetence, and decreasing their final nutritional value, which may negatively impact their commercial acceptance.

In this context, microalgae have emerged as a promising alternative due to their high nutritional and functional value. These microorganisms are important sources of essential amino acids, carbohydrates, carotenoids, polysaccharides, and long-chain polyunsaturated fatty acids (LC-PUFAs) (Bergmann et al., 2024), in addition to containing bioactive compounds with antioxidant potential, such as flavonoids, alkaloids, glycosides,  $\beta$ -carotene, and phenolic compounds (Salem et al., 2022). Given this multifunctional potential, the present work aims to compile updated scientific evidence on the feasibility of using microalgae as partial or total replacements for fishmeal and fish oil in diets formulated for fish and shrimp, with a focus on nutritional and immunological aspects.

## 2 Effects of Microalgae Inclusion on The Nutritional Quality of Fish and Shrimp

The wide diversity of microalgae species, combined with their high nutritional value, has sparked growing interest in research aimed at developing sustainable solutions. These investigations primarily seek to mitigate the environmental impacts associated with conventional aquaculture practices, particularly the intensive production and use of fishmeal (FM) and fish oil (FO) in commercial feed formulations.

In this context, Sarker et al. (2020) investigated the total replacement of FO and the gradual replacement of FM using whole cells of *Schizochytrium* sp. and defatted biomass of *Nannochloropsis oculata* in the feeding of Nile tilapia (*Oreochromis niloticus*) over a period of 183 days. The authors observed that the fillets of fish fed with the total replacement diet (100NS) of FM and FO had a significantly higher lipid content (1.8%) compared to the control diet (commercial feed with FM and FO). Regarding amino acid composition, methionine and histidine levels were lower in the 33% replacement diet (33NS) and numerically higher in the 66% replacement diet (66NS), when compared to both the control and 100NS diets. Additionally, the levels of polyunsaturated fatty acids (PUFAs) were significantly higher in the microalgae-based diets, regardless of the replacement level, especially docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA). DHA deposition in the fillet was highest in the 100NS diet (5.15 mg/g), contrasting with the lowest value observed in the control diet (2.47 mg/g).

Supporting the potential of microalgae as alternative nutrient sources in aquafeeds, Karapanagiotidis et al. (2022) evaluated the replacement of FM with *Chlorella vulgaris* and FO with a blend of *Schizochytrium* sp. and *Microchloropsis gaditana* (SM) in the diet of *Sparus aurata* over 12 weeks. The results indicated that fish fed with 100% FO replacement (SM100) showed increased levels of muscle PUFAs, including linoleic acid (18 : 2n-6),  $\gamma$ -linolenic acid (18 : 3n-6), arachidonic acid (20 : 4n-6), adrenic acid (22 : 4n-6), and docosapentaenoic acid (DPA, 22 : 5n-6). On the other hand, SM diets with 50% and 100% replacement led to lower concentrations of n-3 PUFAs such as stearidonic acid (18 : 4n-3), eicosatetraenoic acid (ETA, 20 : 4n-3), and DPA (22 : 5n-3), compared to the control group.

Complementary results were presented by Seong et al. (2021), who evaluated the lipid profile of *Pagrus major* fed for 75 days with FO-free diets containing meals of *Nannochloropsis* sp. (NAN:  $22.8 \pm 1.0\%$ ) and *Schizochytrium* sp. (SCH:  $25.0 \pm 0.0\%$ ). Both treatments resulted in higher n-6 PUFA levels in the whole fish body compared to the control diet. However, the n-3 PUFA levels were lower in these groups. In contrast, supplementation with combinations of *Nannochloropsis* sp., *Schizochytrium* sp., and *Chlorella* sp. (NSC), or only *Nannochloropsis* sp. and *Schizochytrium* sp. (NS), led to increases in total n-3 PUFA contents ( $13.3 \pm 2.6\%$  and  $13.1 \pm 0.6\%$ , respectively) and long-chain n-3 PUFA (LC-PUFA n-3) levels of  $9.4 \pm 1.5\%$  and  $10.1 \pm 0.6\%$ , respectively.

The feasibility of similar replacements was also explored in shrimp feeding by Pakravan et al. (2017), who analyzed the effects of replacing FM with *Spirulina platensis* at different levels in the diet of *Litopenaeus vannamei* over eight weeks. Shrimp receiving 100% FM replacement with *S. platensis* showed higher whole-body concentrations of fatty acids such as linoleic acid ( $16.10 \pm 0.08\%$ ) and  $\alpha$ -linolenic acid ( $2.40 \pm 0.05\%$ ). Meanwhile, arachidonic acid ( $4.24 \pm 0.03\%$ ), DHA ( $10.70 \pm 0.23\%$ ), and EPA ( $9.86 \pm 0.02\%$ ) levels were higher in the group with 25% FM replacement, suggesting that intermediate replacement levels may favor the accumulation of nutritionally relevant fatty acids.

Additional studies with *L. vannamei* reinforce these findings. Allen et al. (2019) reported that diets containing high levels of fermented *Schizochytrium* sp. meal led to reduced EPA levels in the muscle compared to the control diet ( $4.94 \pm 0.04\%$ ). On the other hand, FO-free diets with 62% and 75% of *Schizochytrium* sp. meal resulted in higher DHA levels ( $5.58 \pm 0.19\%$  and  $5.46 \pm 0.15\%$ , respectively). Additionally, Li et al. (2022) demonstrated that total replacement of FM with *Chlorella sorokiniana* (C-100) negatively affected the amino acid profile of shrimp, reducing total amino acid content ( $877.9 \pm 13.1$  g/kg), essential amino acids ( $425.7 \pm 11.4$  g/kg), tyrosine ( $35.9 \pm 0.5$  g/kg), and proline ( $54.8 \pm 4.2$  g/kg). Moreover, methionine levels decreased in all microalgae-included groups, while lysine levels dropped in the 80% and 100% replacement groups ( $66.4 \pm 3.3$  g/kg and  $64.1 \pm 0.7$  g/kg, respectively) (Figure 1).

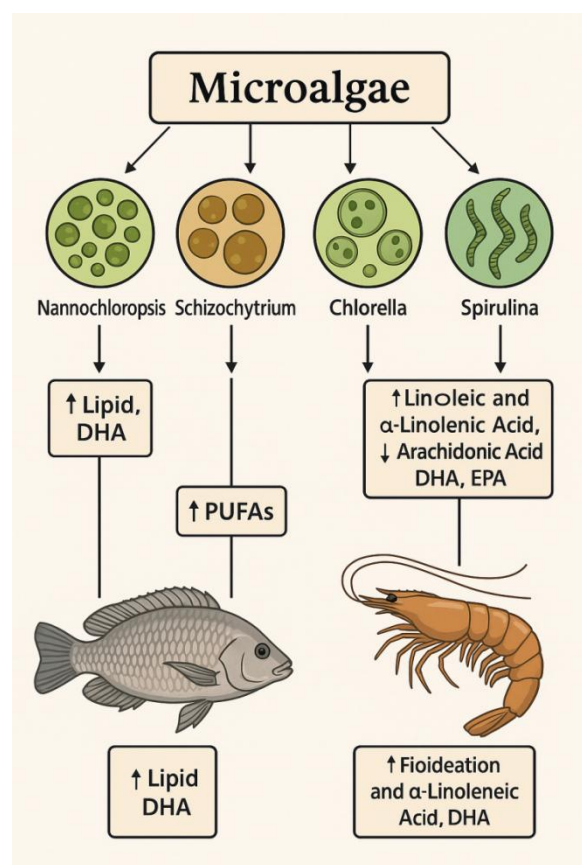


Figure 1 Illustrates the main findings reported in the cited literature

Based on the studies presented, there is a clear convergence regarding the potential of microalgae as viable and sustainable alternatives to traditional sources of fishmeal (FM) and fish oil (FO) in aquafeeds. This substitution has gained prominence not only due to its ecological appeal but also because of the ability of microalgae to provide key nutrients, such as polyunsaturated fatty acids (PUFAs) and essential amino acids, although some nutritional limitations remain.

In the study by Sarker et al. (2020), for example, the total replacement of FM and FO with *Schizochytrium* sp. and *Nannochloropsis oculata* resulted in a significant increase in DHA levels in tilapia fillets, demonstrating the efficiency of these microalgae in supplying beneficial lipids. However, variations in amino acid composition particularly the reduction in methionine and histidine levels in certain diets point to a specific nutritional limitation of these sources, suggesting the need for targeted supplementation.

In the investigations conducted by Karapanagiotidis et al. (2022), although an increase in n-6 PUFA levels was observed following FO replacement, there was also a reduction in n-3 fatty acids such as ETA and DPA. This raises concerns regarding the nutritional value of the fish flesh from a human consumption perspective. These results suggest that the lipid composition of microalgae must be carefully balanced to avoid imbalances between omega-3 and omega-6 fatty acids an essential factor in determining the nutritional quality of farmed fish.

In this context, the study by Seong et al. (2021) adds an important dimension to the discussion by demonstrating that combining different species of microalgae (*Nannochloropsis*, *Schizochytrium*, and *Chlorella*) was more effective in promoting adequate levels of n-3 PUFAs, including long-chain PUFAs (LC-PUFAs), in *Pagrus major*. These findings suggest that synergistic interactions between microalgal species may compensate for individual nutritional deficiencies, representing a promising strategy for developing more complete feed formulations.

In the case of shrimp, the findings of Pakravan et al. (2017) and Allen et al. (2019) reveal a dose-dependent response to substitution: intermediate inclusion levels (25%) of *Spirulina platensis*, for example, were the most effective in increasing concentrations of beneficial fatty acids. Furthermore, replacement with *Schizochytrium* sp. led to an increase in DHA content but also a reduction in EPA levels, again reinforcing the importance of lipid balance in diet formulation.

Finally, the study by Li et al. (2022) reveals a critical limitation: the total replacement of FM with *Chlorella sorokiniana* significantly impaired the essential amino acid profile in shrimp, resulting in a considerable reduction in their nutritional value. This finding underscores the need for a careful assessment of the protein quality of microalgae, with particular attention to the amino acid profile in formulations with high inclusion levels of these biomasses.

In addition to the nutritional assessment, it is essential to analyze the impact of partial or total replacement of fishmeal (FM) and fish oil (FO) on the immunological parameters of fish and shrimp, as well as to investigate the potential antimicrobial activity that microalgae may exert against organisms with pathogenic potential.

### 3 Microalgae in Aquaculture: Ommunomodulation, Antimicrobial Activity, and Antioxidant Effects

Studies have shown that the inclusion of microalgae such as *Spirulina platensis*, *Chlorella vulgaris*, *Nannochloropsis* spp., and *Haematococcus pluvialis* in diets with reduced fishmeal (FM) and fish oil (FO) promotes positive effects on immune parameters. For example, in experiments with *Clarias gariepinus* and *Carassius auratus*, the partial replacement of FM by *Spirulina* sp. and *Chlorella* sp. resulted in significant increases in red and white blood cell levels, hematocrit, hemoglobin, and expression of the genes *TLR2*, *IL-1 $\beta$* , and *TNF- $\alpha$* , as well as improved survival rate after challenge with *Aeromonas hydrophila* (Raji et al., 2018; Cao et al., 2018). Similarly, in Nile tilapia (*Oreochromis niloticus*), the replacement of 15% to 20% of fishmeal by *Nannochloropsis oculata* led to increased lysozyme activity, higher IgM (immunoglobulin) concentration, greater protection against infection by *A. hydrophila*, and preservation of intestinal integrity (Salem et al., 2022).

These findings are consistent with those observed in salmonids, in which the combination of *Schizochytrium* spp. and *Nannochloropsis gaditana* in diets formulated for *Salmo salar* promoted activation of innate immunity, evidenced by increased expression of the genes *C3* and *NK-lysin*, as well as elevation in the number of monocytes and immature erythrocytes (Sánchez et al., 2023). Similarly, the inclusion of *Haematococcus* sp. in diets for trout (*Oncorhynchus mykiss*) resulted in higher myeloperoxidase activity and increased survival rate after challenge with *Vibrio anguillarum*, reinforcing the immunomodulatory potential of microalgae (Aulia et al., 2024).

Furthermore, a study with *Oncorhynchus mykiss* evaluated six diets containing progressive FO replacements by *Schizochytrium* sp. The best zootechnical performance was observed in the T20 diet (20% FO replacement), which resulted in weight gain, specific growth rate, and feed efficiency significantly higher ( $p < 0.05$ ). This same diet showed the highest lysozyme activity level among treatments and provided greater survival rate of fish after challenge with *Lactococcus garvieae*, compared to the CON (control, 100% FO), T80 (80% replacement), and T100 (100% replacement) groups, indicating a relevant immunoprotective effect of the microalga even with partial FO replacement (Lee et al., 2022). Immune system modulation is considered one of the main benefits associated with the use of microalgae, which are rich in polyunsaturated fatty acids (PUFAs),  $\beta$ -glucans, and natural antioxidants (Bahi et al., 2023).

Regarding the antimicrobial aspect, both extracts from *Microchloropsis gaditana* and *Tetraselmis suecica* demonstrate effective activity (Parra-Riofrio et al., 2023; Díaz et al., 2025). Specifically, *M. gaditana* can increase the antibacterial activity of *Salmo salar* serum against *Piscirickettsia salmonis* by more than 85% (Díaz et al., 2025). Additionally, extracellular polysaccharides from *T. suecica* and *Porphyridium cruentum* showed antiviral action against VHSV (Viral Hemorrhagic Septicemia Virus) in cell cultures, interfering at different stages of the viral cycle (Parra-Riofrio et al., 2023).

In general, microalgae are rich sources of compounds with antimicrobial potential, including peptides, long-chain fatty acids, pigments (such as carotenoids and astaxanthin), phenols, and sulfated polysaccharides (Ahmed et al., 2022; Ilieva et al., 2024). These compounds may act directly or indirectly in reducing bacterial load and inhibiting common aquaculture pathogens. Antimicrobial activity related to the content of sulfated polysaccharides, for example, may be associated with alteration of bacterial cell wall integrity and inhibition of pathogen adhesion to the host (Rajasekar et al., 2019).

Regarding antioxidant effects, several microalgae have demonstrated the ability to reduce oxidative stress and improve antioxidant enzyme activity. In *Scophthalmus maximus*, inclusion of *Nannochloropsis* sp. in the diet significantly increased the activities of the enzymes SOD (superoxide dismutase), GSH-Px (glutathione peroxidase), and total antioxidant capacity, while reducing hepatic levels of MDA (malondialdehyde) (Qiao et al., 2019). Similarly, in tilapia fed with different microalgae strains, an increase in T-AOC (total antioxidant capacity) in muscle tissue was observed, reduction in reactive oxygen species production, and positive regulation of the expression of the genes *GSH-Px*, *CAT* (catalase), and *SOD*, as well as higher resistance to infection by *Aeromonas hydrophila* (Ibrahim et al., 2022).

Similar results were observed in mullet (*Mugil liza*) subjected to partial replacement of oil and FM by flaxseed oil and *Spirulina* sp. In this study, the 50% replacement treatment resulted in increased antioxidant capacity and improved zootechnical performance, without compromising the fatty acid profile of the fillet. These findings suggest that the combination of plant-based and microalgal ingredients can positively modulate the antioxidant response and contribute to maintaining product quality (Rosas et al., 2019).

Modulation of intestinal microbiota is also a recurring effect associated with microalgae use. In *Sparus aurata*, for example, diets containing microalgae altered the bacterial profile of the intestine, promoting growth of the genera *Pseudomonas* and *Bacillus* (Katsoulis-Dimitriou et al., 2024). These effects may be related to the presence of complex polysaccharides, such as fucose, which act as selective substrates for probiotic bacteria.

Besides fish, partial replacement of FM by microalgae has shown positive effects in other groups of aquatic organisms. In shrimp *Litopenaeus vannamei*, for example, inclusion of *Chlorella sorokiniana* as a partial FM substitute was effective at levels up to 28%, maintaining zootechnical performance, fillet quality, and antioxidant parameters (Li et al., 2022). The results obtained in multiple species and different experimental contexts reinforce the multifunctional potential of microalgae as promising ingredients in aquaculture. Their application contributes not only to reducing dependence on traditional marine resources but also to strengthening biosafety and sustainability in aquaculture production systems. Although further research is needed to standardize ideal concentrations, evaluate synergistic combinations among microalgal species, and elucidate the mechanisms of action involved, the data available so far are promising and point to a more sustainable and resilient aquaculture (Figure 2).

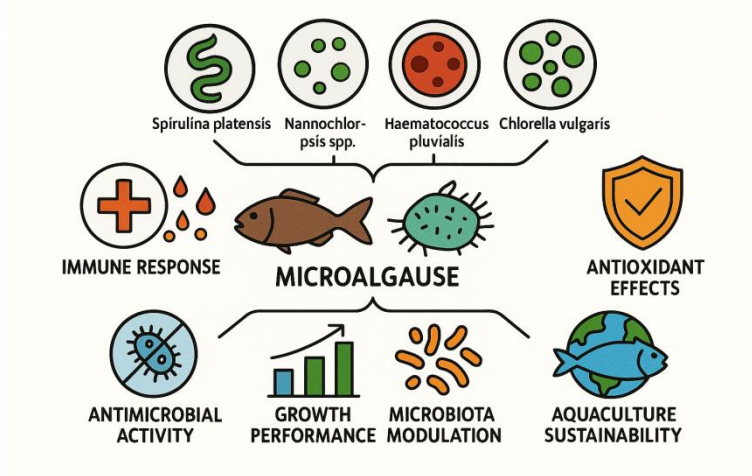


Figure 2 Graphical representation of the information compiled from different literature sources

#### 4 Final Considerations

In summary, this review highlights the high potential of microalgae as dietary additives for fish and shrimp, contributing to improvements in lipid composition, strengthening of the immune system, antioxidant and antimicrobial activity, and modulation of the microbiota. Several studies have demonstrated that microalgae can partially replace fish oil and fishmeal, establishing themselves as a promising alternative to traditional, non-sustainable ingredients. Notably, *Spirulina* sp., *Nannochloropsis* sp., *Schizochytrium* sp., and *Haematococcus pluvialis* stand out for their nutritional, immunological, and antimicrobial potential. However, further research is needed to determine the optimal inclusion level of microalgae in diets, evaluate combinations of different species to fully meet the physiological and nutritional requirements of fish and shrimp, and investigate the effects of biomass processing prior to inclusion, particularly in relation to the complete replacement of fish oil and fishmeal.

#### Authors' Contributions

Costa, D.S. was primarily responsible for the conceptualization and methodological design of the study, as well as for validation, investigation, and data curation. In addition, he contributed to the drafting of the original manuscript and the preparation of visualizations. Pereira-Júnior J.A. also participated in the conceptualization and methodological design, played an important role in the investigation, and assisted in drafting the original manuscript and creating visualizations. Martins M.L. supervised the overall research process.

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