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# Microalgae as Functional Feed in Fish Larval Rearing: Nutritional Value, Ecological Functions, and Future Prospects for Sustainable Aquaculture

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## ABSTRACT

As global fish stocks decline and aquaculture expansion intensifies, sustainable larval rearing remains a critical challenge due to the high dependency on live feed such as rotifers and *Artemia*. Microalgae, as the foundational feed component, play a pivotal role in supporting larval nutrition, health, and water stability. While numerous reviews have discussed microalgae as nutritional supplements or live feed, few have comprehensively analyzed their multifunctional role as both nutritional and ecological components within larval rearing systems. This review uniquely integrates current understanding on microalgae's biochemical composition, functional bioactivity, and ecosystem-level interactions that enhance larval survival, immunity, and water quality. It emphasizes the dual role of microalgae in nutrition and bioremediation, presenting an updated synthesis of species-specific applications and their suitability based on biochemical and physiological traits. Additionally, this review identifies emerging technological and bioprocessing innovations such as strain improvement, cell-wall modification, and integration with biofloc and circular bioeconomy systems that address limitations of cost, digestibility, and biochemical variability. By bridging nutritional, physiological, and environmental perspectives, this paper offers a holistic and practice-oriented framework for using microalgae as functional feed to enhance larval growth, health, and rearing sustainability in aquaculture.

**Keywords:** Microalgae, Phytoplankton, Sustainable Aquaculture, Health benefit, Aquafeed, Fish Larvae Nutrition

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# INTRODUCTION

The global population continues to increase rapidly, driving a growing demand for food, especially high-quality protein sources. According to the Food and Agriculture Organization (FAO, 2024), global food demand is projected to rise from approximately 2.1 billion tonnes to nearly 3 billion tonnes by 2050. As capture fisheries have reached their maximum sustainable yield, aquaculture has become one of the fastest growing food production sectors, providing nearly half of the fish consumed worldwide. This expansion, however, has intensified the need for sustainable, nutritionally balanced, and cost-effective feeds to support the growing aquaculture industry (Sarker, 2023). In 2022, global aquafeed production reached 52.9 million tonnes, accounting for about 4.2% of total compound feed production, with China, Vietnam, India, Norway, and Indonesia ranking among the top producers (Dikel and Demirkale, 2024).

Traditionally, aquaculture has relied heavily on fishmeal and fish oil derived from wild caught fish as primary feed ingredients. Fishmeal is valued for its high protein content (60 to 72%), excellent digestibility, and balanced amino acid profile, while fish oil provides essential long chain polyunsaturated fatty acids (LC PUFAs), particularly eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are critical for fish growth, reproduction, and immunity (Siddik et al., 2024). Despite their nutritional superiority, the increasing use of fishmeal and fish oil poses major sustainability concerns due to overexploitation of marine resources, fluctuating prices, and ecological impacts associated with their harvesting and processing (Boyd and McNevin 2022). It is essential to identify alternative feed ingredients that can deliver comparable nutritional value while minimizing environmental impact and production cost to ensure the future sustainability of aquaculture.

Among the most critical stages in aquaculture production is larval rearing, which often determines the overall success of hatchery operations (El-Sayed et al., 2024). Fish larvae, such as those of the Asian seabass (*Lates calcarifer*), are highly vulnerable during early development due to their small size, limited mouth gape, and immature digestive systems (Islam et al., 2024). Consequently, recent study by Safiin et al. (2021) stated that the Asian seabass are unable to ingest or efficiently digest conventional formulated feeds and instead depend on live feeds such as rotifers (*Brachionus plicatilis*) and *Artemia nauplii.* Although these live feeds remain indispensable in larval culture, they present several limitations, including variable nutritional composition, the need for enrichment with essential fatty acids, susceptibility to contamination, and high production costs. Moreover, their culture can be labor intensive and environmentally sensitive, often leading to inconsistent supply. These challenges underscore the urgent need for alternative or

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supplementary feed resources that can improve larval survival, growth, and overall hatchery efficiency.

Microalgae play a critical ecological role in larval rearing systems through the greenwater effect. This phenomenon refers to the presence of suspended microalgae in rearing tanks which improves water quality by stabilizing dissolved oxygen, reducing harmful nitrogen compounds, and promoting beneficial microbial communities that outcompete pathogenic bacteria (Pascon et al., 2021). The green coloration of the water also diffuses light intensity, reducing visual stress and improving feeding behavior in fish larvae with transparent bodies (El-Sayed et al., 2024). Furthermore, microalgae can secrete extracellular compounds with antibacterial and antioxidant properties, enhancing larval stress tolerance and immunity (Fan et al., 2022). Besides, these effects contribute to improved larval survival, growth, and overall system stability, making microalgae a multifunctional component of sustainable hatchery management (Ma and Hu, 2024).

The effectiveness of microalgae in larval nutrition and health has been supported by numerous studies demonstrating their ability to enhance growth performance, feed utilization, pigmentation, and immune response in various fish species. For instance, enrichment of live feeds with microalgae such as *Nannochloropsis*, *Isochrysis*, *Tetraselmis*, and *Chlorella* has been shown to improve their fatty acid profiles, thereby enhancing the nutritional quality of feed consumed by larvae (Siddik et al., 2024). Direct feeding of microalgae to larvae has also yielded positive outcomes, particularly in early stages where microalgal cells can be ingested whole (de Moraes et al., 2022). These findings highlight the potential of microalgae as both a primary and supplementary feed source for larval rearing, providing not only essential nutrients but also bioactive metabolites that promote overall larval fitness.

Despite these benefits, several challenges remain in the large-scale application of microalgae for aquaculture feed. Production costs, nutrient variability among strains, and limitations in digestibility due to rigid cell walls are among the key barriers (Machado et al., 2022). However, advances in biotechnology and bioprocessing such as strain improvement, cell wall modification, and integration of microalgae cultivation into biofloc or circular bioeconomy systems offer promising solutions to enhance efficiency and reduce costs (Ahmad et al., 2022; Zimmermann et al., 2023). Furthermore, comprehensive biochemical characterization and performance evaluation of different microalgal species are essential to identify optimal strains for specific aquaculture applications (Zhang et al., 2023).

Therefore, this review provides a comprehensive synthesis of current knowledge on the functional role of microalgae as feed in fish larval rearing. It discusses their nutritional value, bioactive properties, and ecological contributions to larval culture systems, with emphasis on the greenwater

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effect and species-specific applications. The review also highlights technological advances and future directions for improving microalgae utilization, aiming to strengthen the foundation for sustainable and resilient aquaculture practices.

## Aquaculture and Sustainable Feed

The global population is projected to increase by 2.3 billion people between 2009 and 2050, leading to a sharp rise in food demand, including cereals (FAO, 2024). In line with this, aquaculture has become the fastest-growing food production sector. According to the FAO (2024), global aquaculture production reached 130.9 million tonnes in 2022, consisting of 94.4 million tonnes of aquatic animals and 37.8 million tonnes of algae, surpassing capture fisheries for the first time in history. This shift highlights the increasing reliance on aquaculture to meet global protein demand while alleviating pressure on overexploited wild fish stocks.

As summarised in Table 1, global aquaculture production is largely dominated by freshwater species such as carps and tilapia, while marine species like salmon and seabass contribute substantially to high-value markets. Carps remain vital for ensuring global food security, especially in Asia, while tilapia continues to expand due to its resilience, fast growth, and cost-effectiveness. Meanwhile, salmon and seabass farming continues to grow, driven by technological and genetic advancements in aquaculture operations in regions such as Norway, Chile, and the Mediterranean (Næve et al., 2022; Zoli et al., 2023; FAO, 2024; Meurer et al., 2025). These trends point to an increasing need for high-quality, species-specific feeds capable of supporting optimal growth and health in intensively farmed fish.

The sustainability of aquaculture depends heavily on the development of nutritionally balanced and environmentally friendly feed sources (Tacon et al., 2022). Traditionally, fishmeal and fish oil have served as the primary protein and lipid sources in aquafeeds (Kousoulaki et al., 2022). However, the rising cost, limited availability, and ecological concerns associated with these ingredients have intensified the search for alternative feed components, including microalgae (Gao et al., 2024). Microalgae, in particular, offer a promising solution because they can simultaneously provide essential nutrients and contribute to environmental sustainability through carbon sequestration and minimal reliance on arable land or freshwater resources.

Microalgae are microscopic photosynthetic organisms that play a crucial role in aquatic ecosystems and are regarded as a promising sustainable feed resource (Sarıtaş et al., 2024). The term “algae” broadly encompasses diverse eukaryotic organisms capable of oxygenic photosynthesis, excluding higher plants (Barsanti and Gualtieri, 2022). Marine microalgae typically thrive in

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seawater environments, whereas freshwater species inhabit lakes, rivers, and ponds (Ramlee et al., 2021) as described in Figure 1.

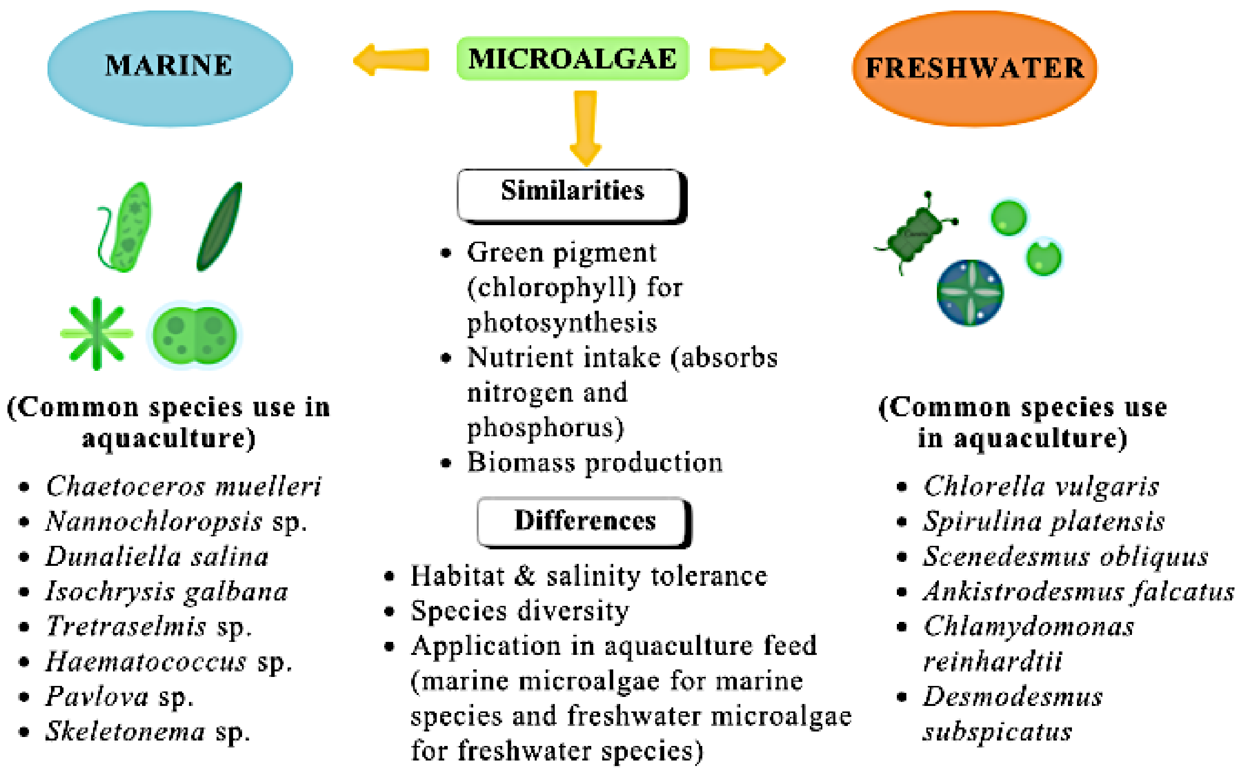


**Figure 1** Different species of microalgae based on their respective habitats.

In aquaculture, species such as *Nannochloropsis sp.*, *Isochrysis sp.*, *Tetraselmis sp.*, and *Chaetoceros sp.* are commonly used due to their high nutritional value and suitability as live feeds or as components in formulated diets for various aquatic organisms (Batista et al., 2020). These species provide essential nutrients, including proteins, lipids, pigments, and bioactive compounds, that not only enhance growth, immunity, and survival of fish larvae but also contribute to water quality and ecosystem stability in rearing systems. Collectively, these attributes position microalgae as a multifunctional, sustainable feed component capable of addressing both nutritional and environmental challenges in modern aquaculture.

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**Table 1** Most Frequently Farmed Shellfish and Fish

| Species Group | Top Species | Production | Ref. |
|---|---|---|---|
| Freshwater Finfish (carps) | Silver carp (*Hypophthalmichthys molitrix*) and grass carp (*Ctenopharyngodon idellus*) | The largest overall output, leading in global freshwater production, particularly in Asia (China, India). Essential for ensuring global food security. | FAO. (2024) |
| Freshwater finfish (Tilapia) | Nile Tilapia (Oreochromis niloticus) | Ranked as the third most cultivated finfish species worldwide. Known for its resilience, rapid growth, and cost-effectiveness in various markets. | Meurer et al., (2025) |
| Marine finfish (Salmonids) | Atlantic salmon (*Salmo salar*) | Mainly cultivated in Chile and Norway. The strong demand propels ongoing advancements in genetics and operations. | Næve et al., (2022) |
| Marine Finfish (Asian Seabass) | Asian Seabass (*Lates calcarifer*), European Sea Bass (*Dicentrarchus labrax*) | High-value, high-end market species. Notable growth in Asia (Asian Seabass) and the Mediterranean region (European Sea Bass). | Zoli et al., (2023) |

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## Nutritional Requirement of Fish Larval

Fish life cycle progresses from eggs, embryo, larvae, juvenile and adult stages as stated in Figure 2. Among these stages, the larval phase is the most critical and vulnerable, with high mortality rates often limiting overall aquaculture productivity. The early developmental stages of fish larvae and juveniles require highly digestible and nutritionally balanced diets due to rapid organ formation, intense growth, and high metabolic activity (Joly et al., 2021). Compared to adult fish, larvae possess an immature digestive system, which makes the nutrient composition and physical presentation of feed crucial for ensuring efficient digestion and nutrient absorption (Ribeiro et al., 2022). Feed inefficiency at this stage not only affects growth but can also compromise immune function and long-term survival, demonstrating the importance of precision nutrition in larval rearing systems. Many studies have emphasized the importance of three major macronutrients, proteins, lipids, and carbohydrates, in supporting larval development, although the optimal proportions vary among species and developmental stages (Li et al., 2021; Meurer et al., 2025).

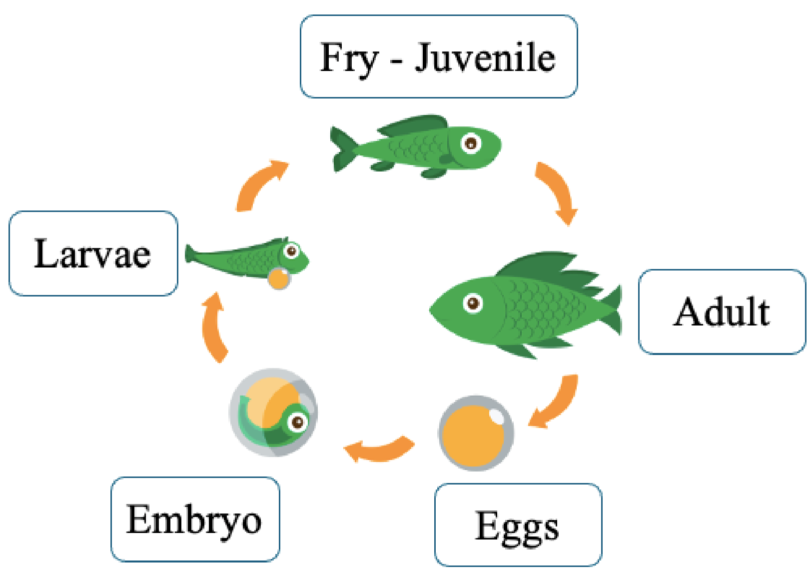


**Figure 2** Fish development from early phase until adult.

Protein is the main dietary component influencing larval growth, muscle development, and tissue synthesis. Research suggests that crude protein requirements generally range from 45 to 55 percent, with attention to a

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balanced amino acid profile that includes essential amino acids such as lysine and methionine (Zhang et al., 2022; Jang et al., 2022). Insufficient or imbalanced protein can impair growth, reduce survival, and increase susceptibility to stress and disease.

Lipids serve as a critical energy source and provide essential fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are important for neural development, visual function, and cell membrane integrity (Mejri et al., 2021; Koven et al., 2024). Recommended lipid inclusion levels between 10 and 20 percent have been shown to support optimal energy metabolism and larval growth (Hossain et al., 2023; Figueroa et al., 2025). Moreover, the balance between n-3 and n-6 fatty acids can influence stress tolerance, inflammatory responses, and long-term performance in aquaculture species.

Carbohydrate utilization, on the other hand, remains limited due to low amylase activity in larvae, and excessive intake may lead to poor digestion and liver glycogen accumulation. Therefore, carbohydrate levels are typically maintained below 20 percent in larval diets (Zhao et al., 2022; Zheng et al., 2023). However, carbohydrates can provide readily available energy when formulated appropriately with other macronutrients. This emphasizes the importance of diet formulation tailored to species-specific digestive capacities.

In addition to macronutrients, micronutrients such as vitamins and minerals are critical for maintaining larval health and supporting metabolic functions. Vitamin C supports collagen synthesis and acts as an antioxidant, while vitamin E protects cell membranes from oxidative damage caused by the breakdown of highly unsaturated fatty acids (El-Sayed et al., 2022; Medagoda et al., 2023). Deficiencies in these vitamins may result in skeletal deformities, poor wound healing, and reduced stress tolerance (Singh et al., 2021; Mourad et al., 2022; Dey et al., 2025). Likewise, minerals such as phosphorus, zinc, copper, and selenium play important roles in bone formation, enzyme function, and antioxidant defense. Inadequate intake of these minerals often leads to growth retardation, cataracts, and skeletal abnormalities (Fraser et al., 2019; Lall and Kaushik, 2021; Martínez et al., 2024). The precise balance and bioavailability of these micronutrients are increasingly recognized as essential for optimizing larval performance and resilience, particularly under intensive aquaculture conditions.

Overall, the literature indicates that while significant progress has been made in understanding the nutrient requirements of fish larvae, inter-species variation, developmental stage-specific needs, and limited knowledge of nutrient interactions continue to present challenges for formulating efficient, balanced, and cost-effective larval diets. Emerging strategies such as functional feed additives, microalgae supplementation, and live feed enrichment are showing promise in addressing these challenges.

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## Feeding Limitation in Larval Rearing

Feeding during the early stages of larval rearing remains one of the most critical challenges in aquaculture nutrition. Numerous studies have highlighted that first-feeding larvae exhibit limited success when reared solely on conventional microdiets such as formulated, finely ground, or microencapsulated dry feeds (Melaku et al., 2024). Given their impact on growth, survival, and long-term development, these limitations bring attention to the critical need for feeding strategies tailored to the specific nutritional and physiological requirements of larvae. As shown in Figure 3, these limitations are broadly categorized into morphological, physiological, and physical constraints that collectively restrict nutrient intake, assimilation, and survival rates.

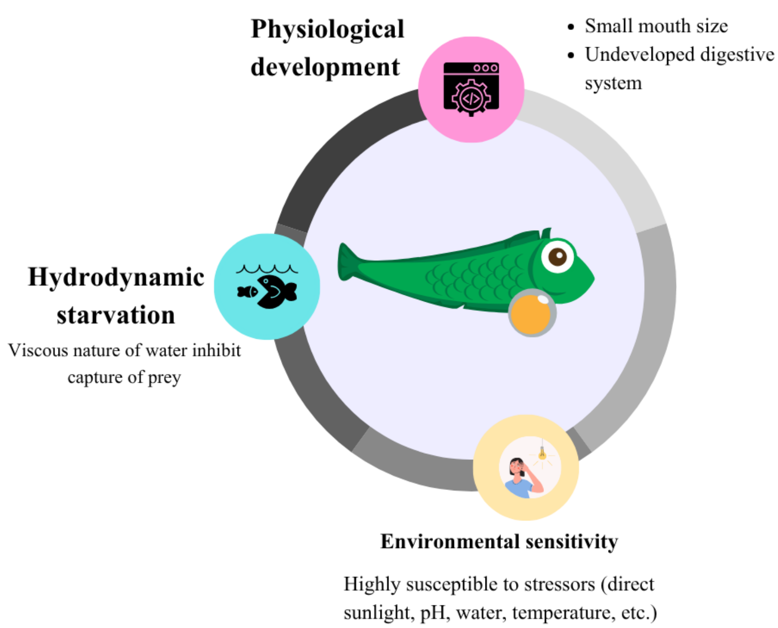


**Figure 3** Feeding limitation in larval rearing.

Pepin (2023) reported that morphological constraints are mainly due to the extremely small mouth opening (gape size) of newly hatched larvae, which limits their ability to ingest even finely ground or sieved feeds. Similarly, Lahnsteiner et al. (2023) demonstrated that the particle size of most commercial microdiets still exceeds larval ingestion capacity, leading to

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starvation and high mortality during the first-feeding stage. This is the reason why live feeds such as *Brachionus* (rotifers) and *Artemia nauplii* remain essential in early larval culture as they offer optimal particle size, motility, and digestibility. These attributes directly improve feed intake, nutrient assimilation, and survival, despite the higher production costs and labor requirements (Syukri et al., 2022; Melaku et al., 2024).

Physiological limitations further compound feeding challenges, as larval fish possess underdeveloped digestive organs and enzyme systems compared to juveniles and adults (Joly et al., 2021). Many marine species exhibit agastric larval stages where the stomach and associated acid-secreting glands are not yet functional, preventing the secretion of pepsin and hydrochloric acid necessary for effective protein digestion (Goodrich, 2025). As a result, conventional diets containing complex proteins, such as those derived from fish meal, are poorly digested (El-Sayed et al., 2024; Molinari et al., 2025).

Larvae also rely heavily on exogenous enzymes from live prey and on limited pancreatic enzymes such as trypsin and chymotrypsin (Arenas et al., 2024; Khan and Rahman, 2025). Diets lacking pre-digested or hydrolyzed protein sources can therefore lead to poor nutrient absorption, intestinal inflammation, and hepatic stress (Li et al., 2021; Melaku et al., 2024). In addition, Lall and Kaushik (2021) highlighted that larval livers have limited biosynthetic capacity for essential nutrients such as phospholipids and docosahexaenoic acid (DHA). These nutrients are critical for neural and visual development (Ranard and Appel, 2024, Ramena et al. (2025)**.** In order to promote healthy organ development and physiological maturation, feed formulation must take into account both the macronutrient content and the bioavailability of critical functional chemicals.

Physical and behavioral constraints also play a significant role in feed inefficiency. Nutrient leaching from water-soluble compounds such as vitamins and amino acids occurs rapidly once dry microdiets are immersed, leading to nutrient loss and deterioration of water quality due to uneaten particles (Simon et al., 2021; Chuang, 2024; El-Sayed et al., 2024). Furthermore, feed buoyancy and sinking rates often fail to match larval feeding behavior, resulting in low ingestion rates and reduced feed utilization (Melaku et al., 2024). In contrast, live prey remain suspended in the water column and provide visual and chemical cues that stimulate active feeding. The absence of such cues in inert diets not only reduces palatability but also exacerbates feed wastage and environmental stress, highlighting the dual nutritional and ecological roles that live or functional feeds play in early larval rearing (Murray, 2023; Yu et al., 2023; Lim et al., 2024).

## Functional Role of Microalgae in Larval Rearing System

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Microalgae perform multiple integrated roles that make them a critical component of successful larval rearing systems (Figure 4). Beyond providing high-quality protein, essential PUFAs, DHA, EPA, and other key nutrients that support rapid growth, microalgae contribute to maintaining optimal water quality by assimilating toxic nitrogenous wastes (ammonia and nitrite) and stabilizing oxygen and pH levels. The "Greenwater" effect amplifies these benefits, promoting larval survival and disease resistance through behavioral stability, shading, and the provision of bioactive compounds such as antioxidants and prebiotics. These multifunctional roles demonstrate that microalgae are not simply a feed supplement but a foundational ecological and physiological agent, integrating nutritional support, environmental regulation, and immunological modulation to enhance both larval performance and the sustainability of aquaculture systems.

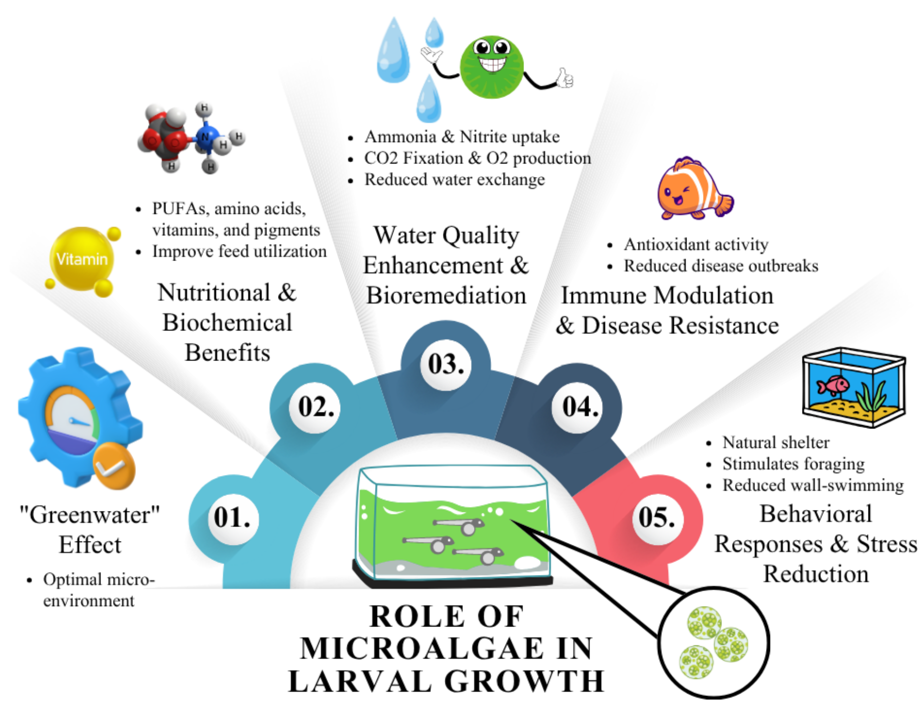


**Figure 4** Role of microalgae in larval rearing system.

## The "Greenwater" Effect in Larvae Rearing

According to Ma and Hu (2023), the inclusion of microalgae in larval rearing systems plays a vital role in the successful cultivation of aquatic species with

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small planktonic larvae such as marine fish and crustaceans. This practice, widely known as the greenwater technique, involves maintaining microalgae, typically species from the genera *Nannochloropsis*, *Isochrysis*, or *Chlorella*, within the rearing tanks at low to moderate densities (Zanella et al., 2020; Mathew et al., 2021; Sales et al., 2022). The resulting greenwater effect offers both nutritional and ecological benefits to the larvae and their live prey, including rotifers and Artemia (Sultana et al., 2025).

Several studies have reported that the greenwater condition enhances larval survival, growth, and health by improving environmental stability and water quality (Basford et al., 2021). Microalgae help assimilate toxic nitrogenous compounds such as ammonia and nitrite, thereby reducing the need for frequent water exchange and maintaining a stable rearing environment (Zhu et al., 2024). Furthermore, the presence of microalgae contributes to microbial balance by promoting beneficial bacterial communities and suppressing harmful pathogens such as Vibrio species, either through competitive exclusion or the release of antimicrobial compounds (Jusidin et al., 2022).

In addition to these water quality and microbial effects, the greenwater condition provides optical and behavioral benefits. The suspended algal cells create a mild turbidity that reduces excessive light penetration, offering visual comfort and minimizing stress and cannibalism among light-sensitive larvae (Chen and Zeng, 2021). The greenwater effect exhibits that microalgae serve not only as a nutritional source but also as a dynamic ecological regulator, stabilizing water quality, supporting beneficial microbial communities, and mitigating environmental stressors. Integrating these ecological principles into larval rearing strategies is therefore essential for enhancing survival, growth, and overall system resilience in aquaculture.

## Nutritional and Biochemical Benefits

Microalgae play a significant role in larval rearing systems by providing a consistent and readily available source of essential nutrients, including proteins, lipids, vitamins, minerals, and immunostimulants (Bahi et al., 2023). Table 2 summarized different microalgae species based on their respective nutritional and biochemical compositions. The figures displayed indicate ranges or representative data obtained in earlier studies because the biochemical composition of microalgae can vary based on species, strain, growth circumstances, and culture phase. Their continuous presence within the culture environment not only supports direct larval nutrition but also benefits zooplankton prey such as rotifers and *Artemia*, thereby enhancing the overall nutritional dynamics of the system.

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According to Wang et al. (2021), microalgae contain 40 to 60 percent protein on a dry weight basis and exhibit a balanced essential amino acid profile comparable to fishmeal, making them an effective protein substitute in formulated diets. Their lipid fractions are rich in long-chain polyunsaturated fatty acids (PUFAs), particularly eicosapentaenoic acid (EPA, 20:5n-3) and docosahexaenoic acid (DHA, 22:6n-3), which are crucial for neural and retinal development in fish and shrimp larvae (Remize et al., 2021; Soto et al., 2023). These fatty acids also promote higher larval survival, improved growth rates, and better stress resistance.

Beyond their macronutrient composition, microalgae provide several biochemical compounds that contribute functional benefits to larval health. Pigments such as astaxanthin from *Haematococcus pluvialis* act as strong antioxidants that help neutralize free radicals and enhance immunity, thereby improving resistance to diseases (Eldessouki et al., 2024). These pigments also contribute to the desirable coloration of salmonids and ornamental species, increasing their market value (Yaqoob et al., 2021). Additionally, microalgal polysaccharides, including β-glucans, function as natural immunomodulators and prebiotics that support gut health and nutrient absorption (Bahi et al., 2023).

However, not all microalgae are equally digestible. Species such as *Chlorella* possess rigid cell walls that can reduce nutrient bioavailability (Wang et al., 2024). To overcome this limitation, cell wall–disrupted or enzymatically treated microalgal products have been developed to improve digestibility and nutrient release, particularly for early larval stages or non-grazing species (Prates, 2025). Overall, the balanced composition of proteins, essential fatty acids, vitamins (including B12, C, and E), and minerals positions microalgae as a sustainable and functional alternative to conventional fishmeal and fish oil in larval rearing systems (Annamalai et al., 2021; Ahmad et al., 2022).

**Table 2** Common species microalgae species with their respective nutritional profiles.

| Microalgae species | Lipid | Protein | Carbohydrate | Ref. |
|---|---|---|---|---|
| *Chlorella* sp. | 23.4% | 45.3% | 34.79% | Nagappan *et al*., 2021 |
| *Chlamydomonas nivalis* | 52.0% | - | 10.4% | Hounslow *et al*., 2021 |
| *Porphyridium* sp. | 2.23% | 14.58 ± 0.35 pg/cell | 23-52% | Tounsi *et al*., 2024 |

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| | | | | |
|---|---|---|---|---|
| *Tetraselmis subcordiformis* | 57% | - | - | Saadaoui *et al.*, 2024 |
| *Chlorella vulgaris* | 31.33 % | 50.8% | - | Liu *et al.*, 2022 |
| *Haematococcus pluvialis* | 40.3-51.31 % | 29-45% | 15-17% | Tosuner & Urek, 2021 |
| *Isochrysis* sp. | - | 17.1-23.2% | 42.7-56.7% | Singh *et al.*, 2021 |
| *Nannochloropsis* sp. | 36.0±0.32% | 54.0±1.05% | 24.0±2.51% | Hossain *et al.*, 2022 |
| *Chlamydomonas rheinhardtii* | 18.1±0.6% | 49.7±0.9% | 21.7±0.5% | López *et al.*, 2023 |
| *Spirulina* sp. | 6.2±0.2% | 66.0±0.8% | 18.1±0.6% | de Morais *et al.*, 2022 |
| *Tetraselmis* sp. | 16.3±0.8% | 34.1±1.4% | 29.1±1.1% | Dammak *et al.*, 2022 |
| *Tisochrysis* sp. | 29.3 ± 0.3% | 42.0 ± 2.5% | 12.6 ± 0.7% | Pagnini *et al.*, 2023 |

## Water Quality Enhancement and Bioremediation

Microalgae play a vital role in maintaining water quality within larval rearing systems through their photosynthetic and nutrient uptake activities. During photosynthesis, microalgae absorb carbon dioxide and release oxygen, contributing to stable dissolved oxygen levels that are essential for larval survival and microbial balance. According to Han et al. (2019), microalgae buffer water pH and maintain alkalinity by utilizing carbon dioxide and acidic compounds, hence reducing the risk of sudden fluctuations commonly observed in intensive rearing environments.

Beyond gas regulation, microalgae act as natural biofilters by assimilating nitrogenous wastes such as ammonia and nitrite, both of which are toxic even at low concentrations (Markou et al., 2023). This nutrient uptake not only improves water quality but also promotes algal growth, creating a self-regulating system that supports a more sustainable culture environment. Additionally, microalgae release dissolved organic compounds that stimulate the growth of beneficial bacteria. These bacteria contribute to a balanced microbial community capable of outcompeting pathogenic species through a process known as competitive exclusion, thereby reducing the risk of disease outbreaks and maintaining a stable and healthy aquatic ecosystem (Smahajcsik et al., 2025).

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## Immune Modulation and Disease Resistance

The immunostimulatory potential of microalgae in larval aquaculture also has been highlighted. Polysaccharides such as β-glucans found in microalgal cell walls can activate the innate immune responses of fish larvae, enhancing their defense mechanisms against pathogens (Shochicha et al., 2025). Pigments including phycocyanin and carotenoids such as astaxanthin further contribute to immune protection by acting as powerful antioxidants that neutralize oxidative stress and promote overall physiological resilience (Zittelli et al., 2023). In addition to these bioactive compounds, larvae consuming microalgae may also ingest beneficial bacteria associated with the algal surface. These bacteria behave similarly to probiotics by strengthening the intestinal barrier, promoting the establishment of a healthy gut microbiota, and inhibiting the colonization of harmful microorganisms (Anjaly et al., 2025). Some microalgae and their symbiotic bacteria also secrete antimicrobial metabolites that suppress pathogenic species within the digestive tract (Smahajcsik et al., 2025). Collectively, these interactions contribute to disease resistance and maintain the microbial equilibrium characteristic of the greenwater system, reducing infection risks and enhancing larval survival.

## Behavioral Responses and Stress Reduction

The optical and physical characteristics of microalgae in greenwater systems influence larval behavior and welfare. The green coloration caused by suspended algal cells reduces water transparency, creating a visually comfortable environment that facilitates prey detection and capture. This improved visibility helps larvae efficiently locate live feed such as rotifers and *Artemia*, leading to better feeding performance and more uniform growth (Chen and Zeng, 2021). Furthermore, the slight turbidity in greenwater mimics natural shaded habitats where larvae typically seek refuge, thereby reducing stress and aggressive behaviors such as cannibalism. A calmer rearing environment minimizes energy expenditure on escape responses and allows larvae to focus on feeding and development. As a result, improved feeding efficiency, enhanced stress tolerance, and better overall health have been observed in larvae reared under greenwater conditions (Pratama et al., 2024).

## Selection Criteria of Microalgae as Aquaculture Feed

The selection of suitable microalgae species for aquaculture feed is a critical step that determines not only the nutritional quality of the rearing system but

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also its overall operational and economic feasibility. As illustrated in Figure 5, this selection involves a combination of biological and practical factors that together determine feed efficiency and sustainability. These factors include physical properties (such as cell size, motility, and water stability), nutritional composition (including protein content, essential fatty acids, vitamins, and minerals), biological characteristics (such as digestibility and palatability), and visual attributes (such as colour contrast, which enhances feed visibility for larvae). Table 3 provides a summary of the microalgae species' biological characteristics and their uses.

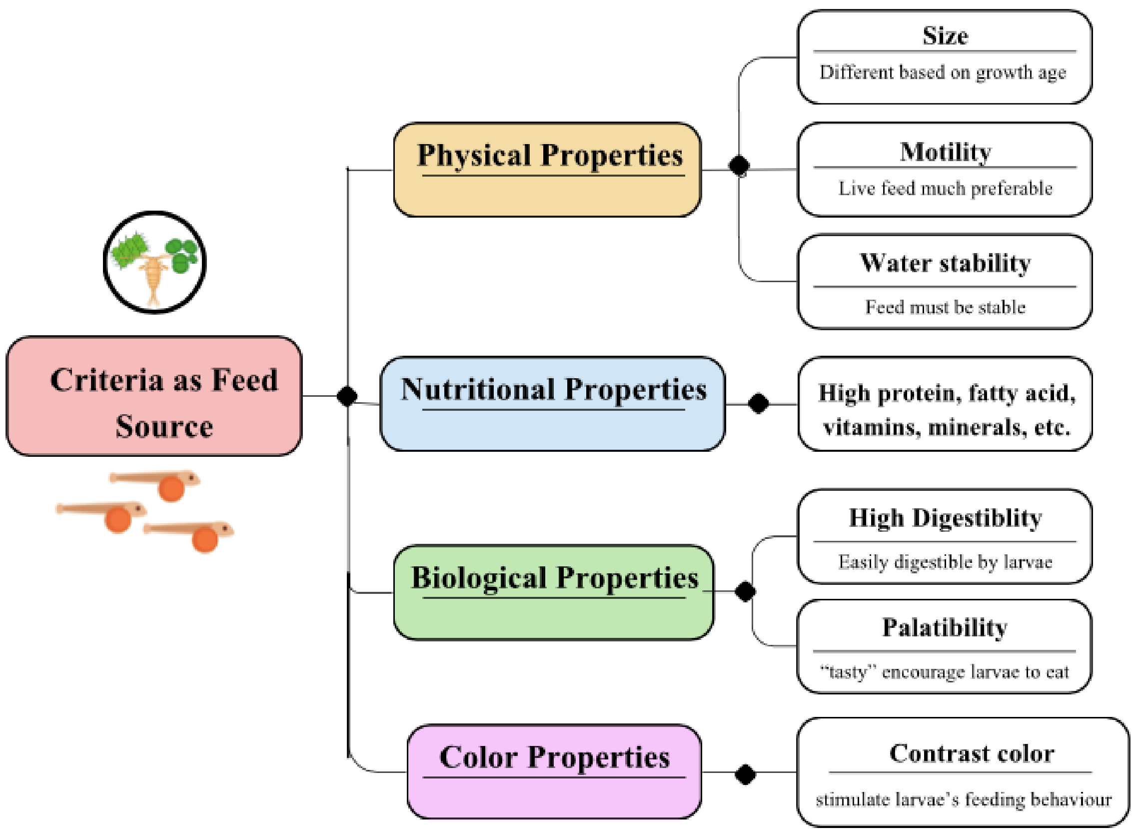


**Figure 5** Feed source criteria for larvae.

The biological properties of microalgae, including cell size, morphology, digestibility, and biochemical composition, are fundamental in determining

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their suitability as feed. Microalgae must fall within an optimal size range and shape for ingestion by the target species, especially during larval stages (Annamalai et al., 2021). Mota et al. (2023) demonstrated that when the physical characteristics of microalgae correspond to the developmental stage of fish larvae, feed intake and growth performance are significantly improved. Nutritionally, superior microalgae strains provide high protein content (40–60% dry weight) with a balanced essential amino acid profile comparable to fishmeal (Wang et al., 2021). In addition, microalgae are rich sources of long-chain polyunsaturated fatty acids (PUFAs) such as eicosapentaenoic acid (EPA, 20:5n-3) and docosahexaenoic acid (DHA, 22:6n-3), which are essential for the growth, neural, and retinal development of fish and shrimp larvae (Santin et al., 2021; Soto et al., 2023). These biochemical qualities position microalgae as an effective and sustainable replacement for traditional fishmeal and fish oil.

In addition to nutritional composition, practical and economic factors play a key role in selecting microalgae species for large-scale production. Ideal strains should exhibit rapid growth and high biomass yield to meet the continuous demand of aquaculture operations (Ma and Hu, 2024). Cultivation feasibility is enhanced when the strain demonstrates resilience to fluctuating environmental conditions such as light intensity, temperature, salinity, and pH (Ansari et al., 2021). The selected microalgae should also be non-toxic, compatible with the target species, and palatable enough to promote consistent feed intake, particularly when used in live feed enrichment for *Artemia* and rotifers (Ma and Hu, 2024).

Several microalgae species have been widely adopted as industry standards due to their proven nutritional efficacy and cultivation advantages. *Nannochloropsis* and *Isochrysis* are particularly valued for their high polyunsaturated fatty acid content, serving as primary sources of EPA and DHA, respectively (Siddik et al., 2024). Asghari et al. (2025) reported that combining *Nannochloropsis oculata* and *Isochrysis galbana* in a biofloc-algal system enhanced PUFA deposition, particularly EPA and DHA, in fish fillets, suggesting synergistic nutritional benefits. *Tetraselmis* species are also frequently preferred for their high protein content, robust growth, and tolerance to environmental fluctuations, making them ideal candidates for large-scale cultivation (Nezafatian et al., 2023). *Tetraselmis tetrathele*, for example, demonstrates exceptional resistance to high ammonium nitrogen concentrations and is commonly used for bioremediation in aquaculture systems, contributing to both water quality improvement and cost reduction (Farahin et al., 2021). Similarly, the diatom *Chaetoceros* has been recognized for its appropriate cell size and balanced nutritional composition, which make it suitable as live feed for mollusk and shrimp larvae (Bhattacharjya et al., 2024). Moreover, the cyanobacterium *Arthrospira platensis* (commonly known

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as *Spirulina*) is often incorporated as a feed additive to enhance immunity and pigmentation in fish and shrimp diets (Reham et al., 2025).

Overall, selecting an ideal microalgal species requires a balance between biological suitability and production efficiency. Species that combine high nutritional value, environmental resilience, and ease of cultivation hold the greatest potential to serve as sustainable alternatives to traditional aquaculture feed components.

**Table 3** Different microalgae species based on biological properites and potential applications

| Microalgae species | Biological properties | Potential applications | Ref. |
|---|---|---|---|
| *Chlorella* sp. | 1. Photosynthetic pigments (chlorophyll, carotenoids (astaxanthin)<br>2. Polysaccharides<br>3. Fatty acids<br>4. Antioxidants | 1. Health and Biomedical Sector (wound healing, drug delivery)<br>2. Environmental and Energy Sustainability (wastewater treatment, biofuel production)<br>3. Food and agriculture | Abreu *et al*., 2023 |
| *Chlamydomonas nivalis* | 1. Carbon shifting (turns its carbon into fat (lipids) to survive) | 1. Biofuel<br>2. Salt-water farming<br>3. Genetic engineering | Hounslow *et al*., 2021 |
| *Porphyridium* sp. | 1. No cell wall.<br>2. Exopolysaccharides<br>3. B-Phycoerythrin (B-PE) pigment<br>4. LC-PUFAs fatty acid | 1. Live feed (aquaculture)<br>2. Cosmetics<br>3. Health supplement<br>4. Medical diagnostic | Bayu *et al*., 2023 |
| *Tetraselmis subcordiformis* | 1. Outdoor resilience<br>2. Lipid diversity (polar and neutral lipids) | 1. Biofuel<br>2. Aquaculture feed<br>3. Nutraceuticals | Saadaoui *et al*., 2024 |
| *Chlorella vulgaris* | 1. Detoxification<br>2. Pigment (lutein and chlorophyll) | 1. Food supplement<br>2. Animal feed<br>3. Medicine/cosmetics | Mendes *et al*., 2024 |
| *Haematococcus pluvialis* | 1. Antioxidants<br>2. Survival mechanism (red pigment) | 1. Health supplements<br>2. Fish feed<br>3. Skin care<br>4. Medicine | Oslan *et al*., 2021 |

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| | | | |
|---|---|---|---|
| *Isochrysis* sp. | 1. ACE Inhibition<br>2. Antioxidant<br>3. High digestibility | 1. Heart-health (anti-hypertension)<br>2. Anti-aging<br>3. Food industry | Bleakley & Hayes, 2021 |
| *Nannochloropsis* sp. | 1. Digestibility<br>2. Bioactive peptides<br>3. Lipid quality (EPA)<br>4. Antihypertensive activity | 1. General nutrition<br>2. Heart health<br>3. Chronic disease prevention | Paterson *et al*., 2023 |
| *Chlamydomonas rheinhardtii* | 1. Pigment (Lutein, B-carotene) | 1. Nutraceuticals<br>2. Medicine<br>3. Vision health<br>4. Food industry | Masi *et al*., 2023 |
| *Spirulina* sp. | 1. Pigment (C-Phycocyanin (C-PC))<br>2. Antihyperlipidemic | 1. Pharma/Food industry<br>2. Heart health<br>3. Brain health | Bortolini *et al*., 2022 |
| *Tetraselmis* sp. | 1. Antioxidant<br>2. Antimicrobial<br>3. Enzymatic (Superoxide Dismutase (SOD)) | 1. Natural preservative<br>2. Food industry<br>3. Nutraceuticals | Carrillo & Anchundia, 2024 |
| *Tisochrysis* sp. | 1. DHA Powerhouse<br>2. Pigment (Fucoxanthin)<br>3. Morphological Flexibility (cells changed their size and shape during co-cultivation to optimize nutrient uptake.) | 1. Brain health<br>2. Infant formula<br>3. Weight management | Maglie *et al*., 2021 |

## CHALLENGERS

Despite the promising nutritional and functional benefits discussed in previous sections, the widespread commercial application of microalgae as an aquaculture feed ingredient remains constrained by several biological, technical, and economic challenges**.** While microalgae offer exceptional protein content, balanced amino acids, and valuable PUFAs such as EPA and DHA,

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their large-scale production and consistent nutritional delivery are yet to reach full industrial maturity.

### Current Limitations and Technical Barriers

One of the most pressing limitations lies in the high production cost associated with large-scale cultivation, harvesting, and downstream processing. Compared with conventional fishmeal-based feeds, microalgal biomass production remains energy-intensive, particularly in closed photobioreactor systems that require stringent environmental control (Ma and Hu, 2024). Furthermore, batch-to-batch variability in biochemical composition is a major constraint. Since nutrient profiles are strongly influenced by light intensity, nutrient availability, and temperature, the resulting inconsistency can affect the feed's nutritional reliability and larval performance. Another significant challenge is cell wall rigidity in certain microalgae, such as *Chlorella*, which reduces digestibility and nutrient bioavailability to fish larvae (Wang et al., 2024). Similarly, the oxidative instability of essential PUFAs during storage leads to rapid degradation, compromising both feed quality and larval health. The risk of biological contamination, particularly by competing algal species or harmful microorganisms, also complicates mass culture operations and poses potential biosecurity risks for aquaculture systems. Addressing these barriers requires not only process optimization but also an understanding of species-specific physiology and biochemical dynamics to ensure consistent feed quality and larval performance.

## FUTURE PROSPECTS

### Technological and Biological Innovations

Addressing these limitations will require technological advancements and strategic innovation across multiple fronts. Ongoing research in genetic engineering, strain improvement, and metabolic optimization holds significant potential for producing microalgae with enhanced digestibility, faster growth, and higher yields of target compounds such as DHA, EPA, and pigments (Prates, 2025). Selective breeding and omics-based approaches can further identify resilient strains capable of maintaining stable nutrient profiles under variable culture conditions. Moreover, the use of low-cost and sustainable culture media, such as wastewater, agricultural runoff, or aquaculture effluent, offers a dual advantage of bioremediation and cost reduction (Farahin et al., 2021). Integrating microalgae cultivation into circular bioeconomy frameworks could transform waste management challenges into value-generating systems, simultaneously improving environmental sustainability

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and production efficiency. These innovations highlight the dual potential of microalgae as both a high-quality feed ingredient and a tool for environmental management, demonstrating that technological and biological solutions must be synergistically applied to overcome current production constraints.

## Future Directions and Collaborative Frameworks

The successful industrial adoption of microalgae-based feeds hinges on coordinated efforts among researchers, industry stakeholders, and policymakers. Establishing standardized cultivation protocols, ensuring feed safety, and developing clear regulatory frameworks are essential steps for achieving reliable large-scale production and market acceptance. Collaboration between academia, commercial producers, and government agencies can accelerate technology transfer, encourage innovation-driven investment, and foster the development of resilient supply chains. Technological advancements, including automation, AI-assisted monitoring, and bioprocess engineering, are expected to optimize production efficiency, reduce operational costs, and maintain consistent nutritional quality. By integrating these innovations with strategic policy and industry frameworks, microalgae can transition from a supplementary feed to a core functional ingredient, offering a renewable, nutrient-rich, and environmentally responsible alternative to conventional fishmeal. This positions microalgae not merely as a nutritional resource but as a strategic tool for advancing resilient, resource-efficient, and sustainable aquaculture systems, capable of meeting the growing global demand for high-quality aquatic products.

## CONCLUSION

In summary, microalgae play a crucial functional role in fish larval rearing systems as both nutritional and ecological components that support sustainable aquaculture. Through the greenwater effect, microalgae enhance water quality, reduce toxic nitrogen compounds, and promote the growth of beneficial microbial communities. They also supply essential nutrients such as proteins, polyunsaturated fatty acids, vitamins, and bioactive compounds that strengthen larval health, immunity, and feeding efficiency. As aquaculture continues to expand, addressing challenges related to large-scale cultivation, nutrient variability, and digestibility remains critical. Future progress in strain improvement, bioprocess optimization, and circular bioeconomy integration will help unlock the full potential of microalgae. Ultimately, these

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advancements position microalgae as a key component in developing sustainable and resilient fish larval rearing systems.

## REFERENCES

Abreu, A. P., Martins, R., & Nunes, J. (2023). Emerging applications of Chlorella sp. and Spirulina (Arthrospira) sp. *Bioengineering*, *10*(8), 955.

Ahmad, A., W. Hassan, S., & Banat, F. (2022). An overview of microalgae biomass as a sustainable aquaculture feed ingredient: food security and circular economy. *Bioengineered*, *13*(4), 9521-9547.

Anjaly, M. A., Sarasan, M., Kachiprath, B., Sukumaran, V., Singh, I. S. B., & Puthumana, J. (2025). Engineering the fish gut microbiome: Could it serve as future-proof strategy for sustainable aquaculture? Blue Biotechnology, 2, Article 6.

Annamalai, S. N., Das, P., Thaher, M. I., Abdul Quadir, M., Khan, S., Mahata, C., & Al Jabri, H. (2021). Nutrients and energy digestibility of microalgal biomass for fish feed applications. *Sustainability*, *13*(23), 13211.

Ansari, F. A., Guldhe, A., Gupta, S. K., Rawat, I., & Bux, F. (2021). Improving the feasibility of aquaculture feed by using microalgae. *Environmental Science and Pollution Research*, *28*(32), 43234-43257.

Arenas-Pardo, M. A., Gaxiola-Cortés, M. G., Barreto-Altamirano, A. F., Del Carmen Paredes-Medina, A., Palomino-Albarrán, I. G., Balam-Uc, P. M., Maldonado-Flores, J. C., & Álvarez-González, C. A. (2024). Changes in Digestive Enzyme Activities during Larval Development of Spotted Seatrout (Cynoscion nebulosus). *Aquaculture Nutrition*, *2024*, 1–12. https://doi.org/10.1155/2024/1309390

Asghari, M., Yeganeh, S., & Hafezieh, M. (2025). Effect of Nannochloropsis oculata and Isochrysis galbana on growth, water quality, biofloc, carcass fatty acids profile, and intestinal bacteria in Nile tilapia (Oreochromis niloticus) raised in zero-water exchange system. *Iranian Journal of Fisheries Sciences*, *24*(2), 305-331.

Bahi, A., Ramos-Vega, A., Angulo, C., Monreal-Escalante, E., & Guardiola, F. A. (2023). Microalgae with immunomodulatory effects on fish. *Reviews in Aquaculture*, *15*(4), 1522-1539.

Barsanti, L., & Gualtieri, P. (2022). *Algae: anatomy, biochemistry, and biotechnology*. CRC press.

Basford, A. J., Makings, N., Mos, B., White, C. A., & Dworjanyn, S. (2021). Greenwater, but not live feed enrichment, promotes development, survival, and growth of larval Portunus armatus. *Aquaculture*, *534*, 736331.

*e-ISSN 2716-697X*

Batista, S., Pintado, M., Marques, A., Abreu, H., Silva, J. L., Jessen, F., Tulli, F., & Valente, L. M. (2020). Use of technological processing of seaweed and microalgae as strategy to improve their apparent digestibility coefficients in European seabass (Dicentrarchus labrax) juveniles. *Journal of Applied Phycology*, *32*(5), 3429–3446. https://doi.org/10.1007/s10811-020-02185-2

Bayu, A., Noerdjito, D. R., Rahmawati, S. I., Putra, M. Y., & Karnjanakom, S. (2023). Biological and technical aspects on valorization of red microalgae genera Porphyridium. *Biomass Conversion and Biorefinery*, *13*(14), 12395-12411.

Bhattacharjya, R., Marella, T. K., Kumar, M., Kumar, V., & Tiwari, A. (2024). Diatom-assisted aquaculture: Paving the way towards sustainable economy. *Reviews in Aquaculture*, *16*(1), 491-507.

Bleakley, S., & Hayes, M. (2021). Functional and bioactive properties of protein extracts generated from Spirulina platensis and Isochrysis galbana T-Iso. *Applied Sciences*, *11*(9), 3964.

Bortolini, D. G., Maciel, G. M., Fernandes, I. D. A. A., Pedro, A. C., Rubio, F. T. V., Branco, I. G., & Haminiuk, C. W. I. (2022). Functional properties of bioactive compounds from Spirulina spp.: Current status and future trends. *Food Chemistry: Molecular Sciences*, *5*, 100134.

Boyd, C. E., & McNevin, A. A. (2022). Overview of aquaculture feeds: Global impacts of ingredient production, manufacturing, and use. In *Feed and feeding practices in aquaculture* (pp. 3-28). Woodhead Publishing.

Carrillo, M., & Anchundia, M. (2024). "Antimicrobial and antioxidant capacity of Dunaliella salina, Tetraselmis chuii and Isochrysis galbana and their potential use in food." a systematic review. *CABI Agriculture and Bioscience*, *5*(1), 108.

Chen, J. Y., & Zeng, C. (2021). The effects of live prey and greenwater on the early larval rearing of orchid dottyback *Pseudochromis fridmani*. *Aquaculture, 543*, 737008. https://doi.org/10.1016/j.aquaculture.2021.737008

Chen, J. Y., & Zeng, C. (2021). The effects of live prey and greenwater on the early larval rearing of orchid dottyback Pseudochromis fridmani. *Aquaculture*, *543*, 737008. https://doi.org/10.1016/j.aquaculture.2021.737008

Chuang, K. M. (2024). *Development and Evaluation of Novel Microparticulate Technologies for the Delivery of Essential Nutrients to Marine Fish Larvae*. The University of Maine.

Dammak, M., Hlima, H. B., Tounsi, L., Michaud, P., Fendri, I., & Abdelkafi, S. (2022). Effect of heavy metals mixture on the growth and physiology of Tetraselmis sp.: Applications to lipid production and bioremediation. *Bioresource Technology*, *360*, 127584.

*e-ISSN 2716-697X*

de Moraes, L. B. S., Santos, R. F. B., Gonçalves Junior, G. F., Mota, G. C. P., Dantas, D. M. D. M., de Souza Bezerra, R., & Olivera Galvez, A. (2022). Microalgae for feeding of penaeid shrimp larvae: an overview. *Aquaculture International*, *30*(3), 1295-1313.

de Morais, E. G., Nunes, I. L., Druzian, J. I., de Morais, M. G., da Rosa, A. P. C., & Costa, J. A. V. (2022). Increase in biomass productivity and protein content of Spirulina sp. LEB 18 (Arthrospira) cultivated with crude glycerol. *Biomass Conversion and Biorefinery*, *12*(3), 597-605.

Dey, T., Hossain, M. S., Kamal, M. M., Ghosh, P. K., Uddin, M. S., Alam, M. T., Mian, S., & Islam, M. J. (2025). Impact of Vitamin C on Growth, Haemato-Immunological Characteristics and Stress Tolerance Capability of Climbing Perch, Anabas testudineus (Bloch, 1792). *Aquaculture Fish and Fisheries*, *5*(2). https://doi.org/10.1002/aff2.70048

Dikel, S., & Demirkale, I. (2024). Global aquaculture feed market: Trends and challenges. In Proceedings of the 15th International Conference on Agriculture, Animal Science & Rural Development (pp. 24). Aydın, Türkiye.

El-Sayed, H. S., Ghanem, S. F., & Barakat, K. M. (2024). Role of recent feeding protocols, rearing water systems and microbial trends in improving marine larviculture: insights into water quality and larval performance. *International Aquatic Research*, *16*(3).

El-Sayed, A. F. M., & Izquierdo, M. (2022). The importance of vitamin E for farmed fish—A review. *Reviews in Aquaculture*, *14*(2), 688-703.

Eldessouki, E. A., Elshopakey, G. E., Elbahnaswy, S., Shakweer, M. S., Abdelwarith, A. A., Younis, E. M., ... & Eissa, E. S. H. (2024). Influence of astaxanthin-enriched Haematococcus pluvialis microalgae on the growth efficacy, immune response, antioxidant capacity, proinflammatory cytokines, and tissue histomorphology of hybrid red tilapia. *Aquaculture International*, *32*(6), 7447-7468.

Fan, J., Bao, Q., Ma, K., Li, X., Jia, J., & Wu, H. (2022). Antioxidant and innate immunity of Danio rerio against Edwardsiella tarda in response to diets including three kinds of marine microalgae. *Algal Research*, *64*, 102689.

Farahin, A. W., Natrah, I., Nagao, N., Yusoff, F. M., Shariff, M., Banerjee, S., ... & Toda, T. (2021). Tolerance of Tetraselmis tetrathele to high ammonium nitrogen and its effect on growth rate, carotenoid, and fatty acids productivity. *Frontiers in Bioengineering and Biotechnology*, *9*, 568776.

Figueroa Villalobos, E., Pereira, W. A., Pérez-Atehortúa, M., Sandoval-Vargas, L., Romero, J., Oliveira, R. P., ... & Villasante, A. (2025). Influence of dietary fatty acids on fish sperm tolerance to Cryopreservation. *Reviews in Aquaculture*, *17*(1), e12968.

*e-ISSN 2716-697X*

Food and Agriculture Organization of the United Nations. (2024). The State of World Fisheries and Aquaculture 2024. FAO.

Food and Agriculture Organization of the United Nations. (2025). Review of the State of World Marine Fishery Resources – 2025. FAO. https://www.fao.org/family-farming/detail/en/c/1742236/

Fraser, T. W., Witten, P. E., Albrektsen, S., Breck, O., Fontanillas, R., Nankervis, L., Thomsen, T. H., Koppe, W., Sambraus, F., & Fjelldal, P. G. (2019). Phosphorus nutrition in farmed Atlantic salmon (Salmo salar): Life stage and temperature effects on bone pathologies. *Aquaculture*, *511*, 734246. https://doi.org/10.1016/j.aquaculture.2019.734246

Gao, S., Chen, W., Cao, S., Sun, P., & Gao, X. (2024). Microalgae as fishmeal alternatives in aquaculture: Current status, existing problems, and possible solutions. *Environmental Science and Pollution Research*, *31*(11), 16113-16130.

Goodrich, H. R. (2025). Fish gut plasticity and its role as a potential mechanism for coping with warming and hypoxia. *Journal of Experimental Biology*, *228*(14), jeb249672.

Han, P., Lu, Q., Fan, L., & Zhou, W. (2019). A review on the use of microalgae for sustainable aquaculture. *Applied Sciences, 9*(11), 2377. https://doi.org/10.3390/app9112377

Hossain, M. S., Small, B. C., & Hardy, R. (2023). Insect lipid in fish nutrition: Recent knowledge and future application in aquaculture. *Reviews in Aquaculture*, *15*(4), 1664-1685.

Hossain, S., Khatoon, H., Jamal, F., Islam, Z., & Kasan, N. A. (2022). Characterization of nitrogen stress-induced growth proximate and pigment contents of Nannochloropsis sp. *Journal of Aquaculture Livestock Production*, *115*(3), 2-9.

Hounslow, E., Evans, C. A., Pandhal, J., Sydney, T., Couto, N., Pham, T. K., ... & Wright, P. C. (2021). Quantitative proteomic comparison of salt stress in Chlamydomonas reinhardtii and the snow alga Chlamydomonas nivalis reveals mechanisms for salt-triggered fatty acid accumulation via reallocation of carbon resources. *Biotechnology for Biofuels*, *14*(1), 121 *International*. https://doi.org/10.1007/s10499-023-01228-y

Islam, S. I., Mahfuj, S., Baqar, Z., Asadujjaman, M., Islam, M. J., Alsiwiehri, N., Almehmadi, M., Sanjida, S., & Ahammad, F. (2024). Bacterial diseases of Asian sea bass (Lates calcarifer): A review for health management strategies and future aquaculture sustainability. *Heliyon*, *10*(9),e29793. https://doi.org/10.1016/j.heliyon.2024.e29793

Jang, B. I., Olowe, O. S., & Cho, S. H. (2022). Evaluation of the optimal protein required in granulated microdiets for rockfish (Sebastes schlegeli) larvae. *Aquaculture Nutrition*, *2022*(1), 2270384.

Joly, L. J., Loots, C., Meunier, C. L., Boersma, M., Collet, S., Lefebvre, V., ... & Giraldo, C. (2021). Maturation of the digestive system of Downs herring larvae (Clupea harengus, Linnaeus, 1758): identification of critical periods through ontogeny. *Marine Biology*, *168*(6), 82.

Jusidin, M. R., Othman, R., Shaleh, S. R. M., Ching, F. F., Senoo, S., & Oslan, S. N. H. (2022). In Vitro Antibacterial Activity of Marine Microalgae Extract against Vibrio harveyi. *Applied Sciences*, *12*(3), 1148. https://doi.org/10.3390/app12031148

Khan, N. S., & Rahman, M. S. (2025). Zooplankton in Aquaculture: A Perspective on Nutrition and Cost-Effectiveness. *Aquaculture Research*, *2025*(1), 5347147.

Kousoulaki, K., Sveen, L., Norén, F., & Espmark, Å. (2022). Atlantic salmon (Salmo salar) performance fed low trophic ingredients in a fish meal and fish oil free diet. *Frontiers in Physiology*, *13*, 884740.

Koven, W., Yanowski, E., Gardner, L., Nixon, O., & Block, B. (2024). Docosahexaenoic acid (DHA) is a driving force regulating gene expression in bluefin tuna (Thunnus thynnus) larvae development. *Scientific Reports*, *14*(1), 23191.

Lahnsteiner, F., Lahnsteiner, E., & Duenser, A. (2023). Suitability of different live feed for first feeding of freshwater fish larvae. *Aquaculture Journal*, *3*(2), 107–120. https://doi.org/10.3390/aquacj3020010

Lall, S. P., & Kaushik, S. J. (2021). Nutrition and metabolism of minerals in fish. *Animals*, *11*(9), 2711. https://doi.org/10.3390/ani11092711

Li, X., Zheng, S., & Wu, G. (2021). Nutrition and functions of amino acids in fish. In *Amino acids in nutrition and health: amino acids in the nutrition of companion, zoo and farm animals* (pp. 133-168). Cham: Springer International Publishing.

Lim, C. E., Webster, C. D., & Li, M. H. (2024). Feeding practices. In *Tilapia* (pp. 547-559). CRC Press.

Liu, T., Chen, Z., Xiao, Y., Yuan, M., Zhou, C., Liu, G., ... & Yang, B. (2022). Biochemical and morphological changes triggered by nitrogen stress in the oleaginous microalga Chlorella vulgaris. *Microorganisms*, *10*(3), 566.

López-Pacheco, I. Y., Ayala-Moreno, V. G., Mejia-Melara, C. A., Rodríguez-Rodríguez, J., Cuellar-Bermudez, S. P., González-González, R. B., ... & Parra-Saldívar, R. (2023). Growth behavior, biomass composition and fatty acid methyl esters (FAMEs) production potential of Chlamydomonas reinhardtii, and Chlorella vulgaris cultures. *Marine Drugs*, *21*(8), 450.

*e-ISSN 2716-697X*

Ma, M., & Hu, Q. (2024). Microalgae as feed sources and feed additives for sustainable aquaculture: Prospects and challenges. *Reviews in Aquaculture*, *16*(2), 818-835.

Machado, L., Carvalho, G., & Pereira, R. N. (2022). Effects of innovative processing methods on microalgae cell wall: prospects towards digestibility of protein-rich biomass. *Biomass*, *2*(2), 80-102.

Maglie, M., Baldisserotto, C., Guerrini, A., Sabia, A., Ferroni, L., & Pancaldi, S. (2021). A co-cultivation process of Nannochloropsis oculata and Tisochrysis lutea induces morpho-physiological and biochemical variations potentially useful for biotechnological purposes. *Journal of Applied Phycology*, *33*(5), 2817-2832.

Markou, G., Economou, C. N., Petrou, C., Tzovenis, I., Doulgeraki, A., Zioga, M., Saganas, N., Kougia, E., & Arapoglou, D. (2023). Biofloc technology combined with microalgae for improved nitrogen removal at lower C/N ratios using artificial aquaculture wastewater. *Aquaculture*

Martínez-Antonio, E. M., Salgado-García, R. L., Peña-Rodríguez, A., Ruvalcaba-Márquez, J. C., Kraffe, E., Racotta, I. S., & Magallón-Barajas, F. (2024). Implications of Dietary Phosphorus Sources On Zootechnical Performance And Stress Response of The Pacific White Shrimp Litopenaeus vannamei. *Animal Feed Science and Technology*, 115889. https://doi.org/10.1016/j.anifeedsci.2024.115889

Masi, A., Leonelli, F., Scognamiglio, V., Gasperuzzo, G., Antonacci, A., & Terzidis, M. A. (2023). Chlamydomonas reinhardtii: A factory of nutraceutical and food supplements for human health. *Molecules*, *28*(3), 1185.

Mathew, R. T., Alkhamis, Y. A., Rahman, S. M., & Alsaqufi, A. S. (2021). Effects of Microalgae Chlorella vulgaris Density on the Larval Performances of Fresh Water Prawn Macrobrachium rosenbergii (De Man, 1879). *Indian Journal of Animal Research*, *55*(3).

Medagoda, N., Chotikachinda, R., Hasanthi, M., & Lee, K. J. (2023). Dietary supplementation of a mixture of nucleotides, β-glucan and vitamins c and e improved the growth and health performance of olive flounder, Paralichthys olivaceus. *Fishes*, *8*(6), 302.

Mejri, S. C., Tremblay, R., Audet, C., Wills, P. S., & Riche, M. (2021). Essential fatty acid requirements in tropical and Cold-Water marine fish larvae and juveniles. *Frontiers in Marine Science*, *8*. https://doi.org/10.3389/fmars.2021.680003

Melaku, S., Geremew, A., Getahun, A., Mengestou, S., & Belay, A. (2024). Challenges and prospects of using live feed substitutes for larval fish. *Fisheries and Aquatic Sciences*, *27*(8), 475–487. https://doi.org/10.47853/fas.2024.e45

*e-ISSN 2716-697X*

Mendes, A. R., Spínola, M. P., Lordelo, M., & Prates, J. A. (2024). Chemical compounds, bioactivities, and applications of Chlorella vulgaris in food, feed and medicine. *Applied Sciences*, *14*(23), 10810.

Meurer, F., Novodworski, J., & Bombardelli, R. A. (2025). Protein requirements in Nile tilapia (Oreochromis niloticus) during production and reproduction phases. *Aquaculture and Fisheries*, *10*(2), 171-182.

Molinari, G. S., Wojno, M., Wick, M., & Kwasek, K. (2025). New approach to the development of tailor-made feed for fish larvae using Zebrafish Danio rerio as a model. *PLoS ONE*, *20*(6), e0326665. https://doi.org/10.1371/journal.pone.0326665

Mota, C. S., Pinto, O., Sá, T., Ferreira, M., Delerue-Matos, C., Cabrita, A. R., ... & Maia, M. R. (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.

Mourad, M. M., Shahin, S. A., El-Ratel, I. T., & El Basuini, M. F. (2022). Effect of treating eggs with coenzyme Q10 (CoQ10) on growth variables, histomorphometry, and antioxidant capacity in red tilapia (Oreochromis aureus× Oreochromis mossambicus) larvae. *Animals*, *12*(17), 2219.

Murray, C. (2023). *Minimizing the use of live feeds during the larviculture of five ornamental fish species*. University of Florida.

Næve, I., Korsvoll, S. A., Santi, N., Medina, M., & Aunsmo, A. (2022). The power of genetics: Past and future contribution of balanced genetic selection to sustainable growth and productivity of the Norwegian Atlantic salmon (Salmo salar) industry. *Aquaculture*, *553*, 738061.

Nagappan, S., Das, P., AbdulQuadir, M., Thaher, M., Khan, S., Mahata, C., ... & Kumar, G. (2021). Potential of microalgae as a sustainable feed ingredient for aquaculture. *Journal of Biotechnology*, *341*, 1-20.

Nezafatian, E., Farhadian, O., Yegdaneh, A., Safavi, M., Daneshvar, E., & Bhatnagar, A. (2023). Enhanced production of bioactive compounds from marine microalgae Tetraselmis tetrathele under salinity and light stresses: A two-stage cultivation strategy. *Bioresource Technology*, *376*, 128899.

Oslan, S. N. H., Tan, J. S., Oslan, S. N., Matanjun, P., Mokhtar, R. A. M., Shapawi, R., & Huda, N. (2021). Haematococcus pluvialis as a potential source of astaxanthin with diverse applications in industrial sectors: current research and future directions. *Molecules*, *26*(21), 6470.

Pagnini, C., Sampietro, G., Santini, G., Biondi, N., & Rodolfi, L. (2023). Tisochrysis lutea as a substrate for lactic acid fermentation: biochemical composition, digestibility, and functional properties. *Foods*, *12*(6), 1128.

*e-ISSN 2716-697X*

Pascon, G., Messina, M., Petit, L., Valente, L. M. P., Oliveira, B., Przybyla, C., Dutto, G., & Tulli, F. (2021). Potential application and beneficial effects of a marine microalgal biomass produced in a high-rate algal pond (HRAP) in diets of European sea bass, Dicentrarchus labrax. *Environmental Science and Pollution Research*, *28*(44), 62185–62199. https://doi.org/10.1007/s11356-021-14927-x

Paterson, S., Gómez-Cortés, P., de la Fuente, M. A., & Hernández-Ledesma, B. (2023). Bioactivity and digestibility of microalgae Tetraselmis sp. and Nannochloropsis sp. as basis of their potential as novel functional foods. *Nutrients*, *15*(2), 477.

Pepin, P. (2023). Feeding by larval fish: how taxonomy, body length, mouth size, and behaviour contribute to differences among individuals and species from a coastal ecosystem. *ICES Journal of Marine Science*, *80*(1), 91-106.

Pratama, I., Susanto, R., Nopriyanto, R., & Nurhafid, M. (2024). Effectiveness of green water system as larval gourami (*Osphronemus gouramy*) cultivation technology—Efforts to increase larval productivity. *International Journal of Agriculture and Biosciences, 13*(3), 469–473.

Prates, J. a. M. (2025). The role of microalgae in providing essential minerals for sustainable swine nutrition. *Frontiers in Animal Science*, *6*. https://doi.org/10.3389/fanim.2025.1526433

Ramena, Y., Kurapati, R. B., Bosteels, T., & Ramena, G. (2025). Artemia Enrichment Strategies: A comprehensive review of nutritional enhancements with emphasis on fatty acid profiles in aquatic species. *Reviews in Aquaculture*, *17*(4). https://doi.org/10.1111/raq.70080

Ramlee, A., Rasdi, N. W., Wahid, M. E. A., & Jusoh, M. (2021). Microalgae And The Factors Involved In Successful Propagation For Mass Production. *Journal of Sustainability Science and Management*, *16*(3), 21–42. https://doi.org/10.46754/jssm.2021.04.003

Ranard, K. M., & Appel, B. (2024). Creation of a novel zebrafish model with low DHA status to study the role of maternal nutrition during neurodevelopment. *Journal of Lipid Research*, 100716. https://doi.org/10.1016/j.jlr.2024.100716

Reham, A. A., Mounes, H. A., Abd El-Ghaffar, H. A., Nasr, R., & Al-Zahaby, M. A. (2025). Using Spirulina platensis as Feed Additive to Improve Color and Immunity in Goldfish (Carassius auratus). *Egyptian Academic Journal of Biological Sciences. B, Zoology*, *17*(1).

*e-ISSN 2716-697X*

Remize, M., Brunel, Y., Silva, J. L., Berthon, J. Y., & Filaire, E. (2021). Microalgae n-3 PUFAs production and use in food and feed industries. *Marine drugs*, *19*(2), 113.

Ribeiro, L., Hubert, F. N., Rodrigues, V., Rojas-Garcia, C., & Dinis, M. T. (2022, March). Understanding fish larvae's feeding biology to improve aquaculture feeding protocols. In *Oceans*(Vol. 3, No. 1, pp. 94-113). MDPI.

Saadaoui, I., Cherif, M., Siddiqui, S. A., Esakkimuthu, S., AbdulQuadir, M., El Anbari, M., & Sayadi, S. (2024). Unveiling Tetraselmis subcordiformis lipidome dynamics during large-scale cultivation in open raceway pond. *Journal of Applied Phycology*, *36*(3), 1125-1134.

Safiin, N. S. Z., Mustafa, S., Ching, F. F., & Shapawi, R. (2021). Palm oil-based enriched diets for the rotifer, Brachionus plicatilis, improved the growth of Asian seabass (Lates calcarifer) larvae. Frontiers in Marine Science, 8, 613312.

Sales, R., Lopes, R. G., Derner, R. B., & Tsuzuki, M. Y. (2022). Concentrated microalgal biomass as a substitute for fresh microalgae produced on site at hatcheries. *Aquaculture Research*, *53*(17), 5771-5786.

Santin, A., Russo, M. T., Ferrante, M. I., Balzano, S., Orefice, I., & Sardo, A. (2021). Highly valuable polyunsaturated fatty acids from microalgae: strategies to improve their yields and their potential exploitation in aquaculture. Molecules, 26(24), 7697.

Sarıtaş S., Kalkan A.E., Yılmaz K., Gurdal S., Göksan T., Witkowska A.M., Lombardo M., and Karav S., 2024, Biological and nutritional applications of microalgae, Nutrients, 17(1): 93.

Sarker, P. K. (2023). Microorganisms in fish feeds, technological innovations, and key strategies for sustainable aquaculture. *Microorganisms*, *11*(2), 439.

Shochicha, A. N., Satyantini, W. H., & Md. Yassin, I. S. (2025). Microalgae-derived bioactives as immunonutrients in *Litopenaeus vannamei* aquaculture: Mechanisms, efficacy, and future prospects. *Egyptian Journal of Aquatic Biology & Fisheries, 29*(4), 2759–2774.

Siddik, M. A., Sørensen, M., Islam, S. M., Saha, N., Rahman, M. A., & Francis, D. S. (2024). Expanded utilisation of microalgae in global aquafeeds. *Reviews in Aquaculture*, *16*(1), 6-33.

Simon, C. J., Truong, H., Habilay, N., & Hines, B. (2021). Feeding behaviour and bioavailability of essential amino acids in shrimp Penaeus monodon fed fresh and leached fishmeal and fishmeal-free diets. *Animals*, *11*(3), 847.

Singh, P. K., Bhattacharjya, R., Saxena, A., Mishra, B., & Tiwari, A. (2021). Utilization of wastewater as nutrient media and biomass valorization in

*e-ISSN 2716-697X*

marine Chrysophytes-Chaetoceros and Isochrysis. *Energy Conversion and Management: X*, *10*, 100062.

Singh, S. K., Baidya, S., Das, P., & Biswas, P. (2021). Functional role of dietary supplements on reproductive physiology of fishes. In *Recent updates in molecular Endocrinology and Reproductive Physiology of Fish: An Imperative step in Aquaculture* (pp. 243-258). Singapore: Springer Singapore.

Smahajcsik, D., Roager, L., Strube, M. L., Zhang, S.-D., & Gram, L. (2025). Stronger together: Harnessing natural algal communities as potential probiotics for inhibition of aquaculture pathogens. *Microbiology Spectrum, 13*(7). https://doi.org/10.1128/spectrum.00421-25

Soto-Sánchez, O., Hidalgo, P., González, A., Oliveira, P. E., Arias, A. J. H., & Dantagnan, P. (2023). Microalgae as raw materials for Aquafeeds: Growth kinetics and improvement Strategies of Polyunsaturated fatty acids production. *Aquaculture Nutrition*, *2023*,119. https://doi.org/10.1155/2023/5110281

Sultana, M. S., Haque, M. M., Hossain, M. Y., Ahmed, M. K., Sumon, M. a. I., Akhi, M. S. N., & Khan, S. (2025). Improved growth and survival of Catla catla larvae using cultured microalgae and zooplankton as initial feed. *Aquaculture Reports*, *44*, 103011. https://doi.org/10.1016/j.aqrep.2025.103011

Syukri, F., Hassan, N. H., & Azaman, S. N. A. (2022). Performances of Fs Feed, Artemia Nauplii And Commercial Diet on Early Development of Clarias gariepinus LARVAE. *Journal of Sustainability Science and Management*, *17*(2), 35–45. https://doi.org/10.46754/jssm.2022.02.004

Tacon, A. G., Metian, M., & McNevin, A. A. (2022). Future feeds: suggested guidelines for sustainable development. *Reviews in Fisheries Science & Aquaculture*, *30*(2), 135-142.

Tosuner, Z. V., & Urek, R. O. (2021). Effects of nutrients on lipids and biodiesel production potential of Haematococcus pluvialis. *Environmental Engineering & Management Journal (EEMJ)*, *20*(8).

Tounsi, L., Ben Hlima, H., Derbel, H., Duchez, D., Gardarin, C., Dubessay, P., ... & Abdelkafi, S. (2024). Enhanced growth and metabolite production from a novel strain of Porphyridium sp. *Bioengineered*, *15*(1), 2294160.

Wang, C. A., Onyeaka, H., Miri, T., & Soltani, F. (2024). Chlorella vulgaris as a food substitute: Applications and benefits in the food industry. *Journal of food science*, *89*(12), 8231-8247.

Wang, Y., Tibbetts, S. M., & McGinn, P. J. (2021). Microalgae as sources of high-quality protein for human food and protein supplements. *Foods*, *10*(12), 3002.

*e-ISSN 2716-697X*

Yaqoob, S., Riaz, M., Shabbir, A., Zia-Ul-Haq, M., Alwakeel, S. S., & Bin-Jumah, M. (2021). Commercialization and marketing potential of carotenoids. In *Carotenoids: structure and function in the human body* (pp. 799-826). Cham: Springer International Publishing.

Yu, Z. L., Yang, M. J., Song, H., Zhang, T., & Yuan, X. T. (2023). Gastropod chemoreception behaviors—Mechanisms underlying the perception and location of targets and implications for shellfish fishery development in aquatic environments. *Frontiers in Marine Science*, *9*, 1042962.

Zanella, L., & Vianello, F. (2020). Microalgae of the genus Nannochloropsis: Chemical composition and functional implications for human nutrition. *Journal of Functional Foods*, *68*, 103919. https://doi.org/10.1016/j.jff.2020.103919

Zhang, J. X., Ran, Z. S., Xie, H. X., Kong, F., Zhang, M. Q., Zhou, Y., ... & Xu, J. L. (2023). A systematic analysis and evaluation of nutritional composition of 23 strains of marine microalgae commonly used in aquaculture. *Algal Research*, *72*, 103122.

Zhang, Y., Liang, X., Zhan, W., Han, M., Liu, F., Xie, Q., Guo, D., Chen, L., & Lou, B. (2022). Effects of dietary protein levels on growth performance, muscle composition and fiber recruitment of juvenile small yellow croaker (Larimichthys polyactis). *Aquaculture Reports*, *27*, 101335. https://doi.org/10.1016/j.aqrep.2022.101335

Zhao, W., Wei, H., Wang, Z., He, X., & Niu, J. (2022). Effects of Dietary Carbohydrate Levels on Growth Performance, Body Composition, Antioxidant Capacity, Immunity, and Liver Morphology in Oncorhynchus mykiss under Cage Culture with Flowing Freshwater. *Aquaculture Nutrition*, *2022*, 1–11. https://doi.org/10.1155/2022/7820017

Zheng, L., Wang, Z., Zhang, B., Yan, L., Wang, P., Zhao, C., ... & Zhou, C. (2023). Effects of high dietary carbohydrate levels on growth performance, enzyme activities, expression of genes related to liver glucose metabolism, and the intestinal microbiota of Lateolabrax maculatus Juveniles. *Fishes*, *8*(9), 431.

Zhu, Y., Zhang, Y., Chen, H., Zhang, L., & Shen, C. (2024). Stress Responses and Ammonia Nitrogen Removal Efficiency of Oocystis lacustris in Saline Ammonium-Contaminated Wastewater Treatment. *Toxics*, *12*(5), 353. https://doi.org/10.3390/toxics12050353

Zimmermann, S., Kiessling, A., & Zhang, J. (2023). The future of intensive tilapia production and the circular bioeconomy without effluents: biofloc technology, recirculation aquaculture systems, bio-RAS, partitioned aquaculture systems and integrated multitrophic aquaculture. *Reviews in Aquaculture*, *15*, 22-31.

*e-ISSN 2716-697X*

Zittelli, G. C., Lauceri, R., Faraloni, C., Benavides, A. M. S., & Torzillo, G. (2023). Valuable pigments from microalgae: Phycobiliproteins, primary carotenoids, and fucoxanthin. *Photochemical & Photobiological Sciences, 22*(7), 1733–1789.

Zoli, M., Rossi, L., Bibbiani, C., & Bacenetti, J. (2023). Life cycle assessment of seabass and seabream production in the Mediterranean area: a critical review. Aquaculture, 573, 739580.