Microalgae: The Green gold for Blue Aquaculture

A. Asiisa[1], S. Aanand[1], S. Selvaraj[1], D. Kaviarasu[1], and R. Somu Sunder Lingam[2]
[1]Dr. MGR Fisheries College and Research Institute, Tamil Nadu
Dr. J. Jayalalithaa Fisheries University, Ponneri – 601 204
[2]Krishnagiri Barur Centre for Sustainable Aquaculture, Barur – 635201
Corresponding author email : a.asiisa18@gmail.com

Introduction

Microalgae are single-celled photosynthetic organisms that play fundamental roles in aquatic ecosystems. They occur ubiquitously in both freshwater and marine environments, inhabiting the water column as plankton and benthic sediments. Depending on the species, microalgae may exist as solitary cells, chains, or colonies, with sizes generally ranging from 2–200 µm. Despite their minute size, microalgae are metabolically and nutritionally rich, containing high concentrations of proteins, carbohydrates, lipids, vitamins, minerals, and an array of biologically active compounds, including carotenoids, sterols, and polyunsaturated fatty acids (PUFAs). These biochemical attributes position microalgae as vital components of aquatic food webs and promising resources for aquaculture. Several species, such as *Arthrospira platensis, Chlorella, Pavlova, Dunaliella, Haematococcus, and Nannochloropsis, are widely used for their superior nutritional value. Over 20 species have been studied, with Nannochloropsis, Phaeodactylum tricornutum, Desmodesmus, Tetraselmis, Chlorella,* and *A. platensis* showing consistent benefits, including improved growth, feed efficiency, reproduction, and immunity in cultured fish and shellfish.

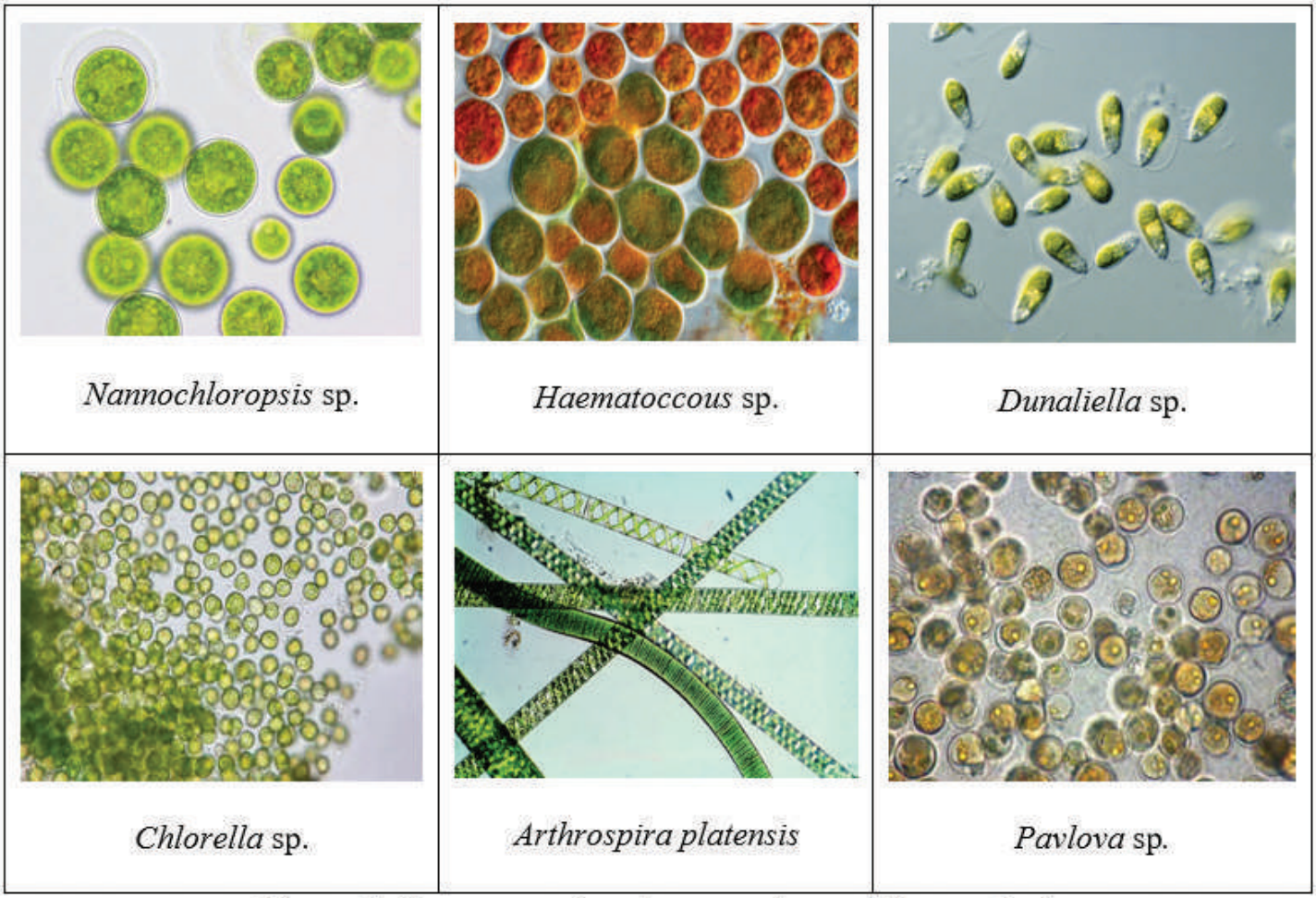

Figure 1: Common microalgae species used in aquafeed

Why Microalgae are the Green Gold

Microalgae are nutritionally rich, containing 30–40% protein, 10–20% lipids, 5–15% carbohydrates, and essential minerals such as calcium, magnesium, phosphorus, iron, iodine, and zinc. They are also abundant in bioactive compounds, including ω-3 LC-PUFAs, pigments, polysaccharides, and vitamins, and a balanced amino acid profile that is often lacking in conventional, plant-based feeds. Microalgae play vital ecological, nutritional, and industrial roles in aquaculture. Ecologically, they enhance system stability by assimilating nitrogen and phosphorus, converting carbon dioxide to oxygen, and improving water quality. Nutritionally, they form the base of the aquatic food chain and serve as indispensable live feed for the larvae and juveniles of fish, molluscs, and crustaceans, as well as for zooplankton, such as rotifers, Artemia, and copepods used in hatcheries. Beyond live feed, microalgae are emerging as sustainable alternatives to fishmeal and fish oil, providing high-quality proteins, essential fatty acids, and valuable bioactives, such as astaxanthin. Their versatility as feed ingredients and nutraceutical sources underscores their growing significance in aquaculture research.

Uses of Microalgae in Blue Aquaculture

Microalgae are nature's first food source in water, forming the foundation of aquatic life. Tiny but powerful, they not only feed wild fish that end up as fishmeal and fish oil but also serve as the perfect live feed for delicate fish and shellfish larvae. They even nourish tiny creatures like rotifers, Artemia, and copepods, which are the key "starter diets" in hatcheries, making microalgae the true super food of aquaculture.

1. Microalgae as Aquafeed: Live microalgae are the first natural food for many aquatic animals. Packed with proteins, essential amino acids, minerals, vitamins, pigments, and PUFAs, they form the best first natural food for all aquatic organisms. In hatcheries, microalgae such as *Tetraselmis, Nannochloropsis, Isochrysis, Thalassiosira, Pavlova* and *Chaetoceros* are widely used to boost larval growth and survival. In addition to live feed, dried microalgae serve as sustainable alternatives to fishmeal and fish oil in aquafeeds.

• Replacing Fishmeal with Microalgae: Fishmeal is prized in aquafeeds for its protein, omega-3, and balanced amino acids; however, alternatives such as plant meals (soybean, corn, and wheat) and animal by-products (poultry offal and meat meal) have drawbacks. Plants often carry anti-nutritional factors, and animal proteins can be fatty and unbalanced. Microalgae, as a single-cell proteins, provide high-quality proteins with a perfectly balanced amino acid profile. Species such as Spirulina and Chlorella have already proven to be sustainable, nutrient-rich alternatives to fishmeal, making aquaculture more eco-friendly and future-ready.

• Replacing Fish Oil with Microalgae: Fish oil plays a key role in aquafeeds, providing energy and vital omega-3 fatty acids that support growth, health, and quality in farmed fish. Although plant and animal oils have been explored as alternatives, they generally lack sufficient EPA and DHA, thereby limiting their benefits. Microalgae, which are rich in lipids and omega-3 fatty acids, offer a sustainable solution, and species such as Schizochytrium are now used to replace fish oil, boosting growth, immunity, and omega-3 levels in farmed fish and shellfish.

2.Lipid-Extracted Microalgae as Aquafeed Supplement:

After extracting oils, the remaining microalgal biomass is packed with proteins, carbohydrates, and micronutrients. This nutrient-rich residue can replace traditional protein sources, such as fishmeal and soybean meal, in aquafeeds. Farmers use it as a microalgal paste or in pellet form, with centrifugation being the most common preparation method. Pelletizing, especially with extruders, is a popular choice, whereas chemical flocculation is avoided because of unwanted residues. This clever reuse makes microalgae not only a feed ingredient but also a model of sustainable aquaculture.

3.Microalgae as Aquafeed Additives

Aquafeed additives are substances added to aquaculture diets to enhance the immune response, disease resistance, palatability, and product quality. Microalgae are rich in ω-3 PUFAs, carotenoids, polysaccharides, and

vitamins, and are used as feed additives because of their potential to boost aquatic animal health.

• Carotenoids: Carotenoids are natural pigments found in animals, plants, and microorganisms that do much more than provide color; they are vitamin A precursors, powerful antioxidants, immune boosters, and growth promoters. Microalgae are ideal carotenoid factories, producing diverse pigments depending on the species and growth conditions. For example, *Haematococcus pluvialis* and *Chlorococcum produce astaxanthin, Dunaliella salina* and *Spirulina platensis* produce β-carotene, *Botryococcus braunii* produces lutein, *Nannochloropsis* yields canthaxanthin, and diatoms produce fucoxanthin.

• β-Glucan: β-glucan is a natural compound that strengthens both specific and non-specific immunity in fish, shrimp, and crabs. It also supports healthy gut flora and increases the number of beneficial bacteria. Microalgae are rich in β-glucans, such as paramylons in Euglenophyta and Chrysolaminarin in Heterokontophyta, which enhance growth, immunity, and disease resistance. Unlike other sources, microalgal β-glucans are abundant, easy to extract, and highly effective, making them ideal natural immunostimulants.

• Vitamins: Vitamins are essential for growth, development, and overall health in aquatic animals, but they cannot produce sufficient amounts on their own. Vitamin C is a powerful antioxidant and is especially important. Microalgae are rich sources of vitamins and provide a complete vitamin profile, making them a natural and nutritious supplement for aquafeeds.

Role of Microalgae in Aquaculture

Microalgae, such as *Chlorella, Nannochloropsis, Tetraselmis, Arthrospira, Pavlova, Haematococcus,* and *Thalassiosira,* are widely used in aquaculture to improve larval survival, feed intake, growth, immunity, and reproduction in fish and shellfish.

1. Survival of Larvae: Microalgae are important sources of nutrients for the early stages of fish, shellfish, and other invertebrates. They are required for a short period for larval nutrition, either directly or indirectly. The use of microalgae in fish hatcheries is essential for both the production of live prey and sustaining the quality of the larval rearing medium. *Chaetoceros, Thalassiosira, Tetraselmis, Isochrysis, Nannochloropsis, Pavlova,* and *Skeletonema* are popular microalgal genera used for fish nutrition.

2. Growth Performance: Adding microalgae to aquafeeds can significantly improve the growth of fish and shellfish, especially at low to moderate levels (2%–10%). Species such as Arthrospira, used as a fishmeal substitute, have shown notable benefits for various farmed species. These improvements are associated with better protein assimilation, enhanced lipid metabolism, and healthier liver function. However, too many microalgae in the diet (over 10%) can slow growth, making the right balance the key to success.

3. Enzyme Secretion: Microalgae do more than provide nutrients; they can stimulate digestion. Even in small amounts, they help trigger digestive enzyme production in young fish, supporting both pancreatic and intestinal function. This early boost plays a crucial role in developing a healthy digestive system, enhancing enzyme activity, and improving the overall performance and growth of fish and shellfish.

4. Antioxidant Response: Microalgae are rich in phenolic compounds and carotenoids that act as natural antioxidants, protecting cells from damage and boosting disease resistance. Species such as Arthrospira are especially prized for their carotenoids, phenolic acids, tocopherols, and phycocyanin. These antioxidants not only enhance the health and immunity of fish and shellfish but also make microalgae a valuable and sustainable ingredient for the growing global aquafeed industry.

5. Immunity and Disease Resistance: Blending microalgae into aquafeeds can strengthen immunity and boost disease resistance in fish and shellfish. Although the exact mechanisms are not fully understood, studies have shown that microalgae diets can improve blood cell counts, especially immune cells such as lymphocytes, and increase red blood cell levels. They also increase

blood protein content, reflecting better nutrition. This makes microalgae a powerful and natural method for supporting aquatic animal health.

6. Fillet Quality & Pigmentation: Carotenoids, such as astaxanthin and canthaxanthin, are widely used in fish diets to enhance fillet color. Feeding astaxanthin-rich microalgae (Haematococcus pluvialis) intensifies flesh color and boosts carotenoid levels. This makes microalgae a natural way to improve the appearance and nutritional value of farmed fish.

Challenges and the Road Ahead for Microalgae in Blue Aquaculture

Although microalgae hold great promise as sustainable aquafeed ingredients, several challenges currently limit their large-scale use. High production costs, from cultivation to processing, remain a major challenge. Improper drying can also reduce nutritional value, limiting its effectiveness as feed. Microalgal biomass can be used as whole cells or extracts. Whole cells offer a rich nutrient profile, but their tough cell walls can slow nutrient release and absorption, making cell disruption technologies crucial for their better utilization. In contrast, extracts improve feed performance but risk losing valuable nutrients. Careful research is needed to determine the right dosage, formulation, stability, and ingredient interactions for optimal benefit. Policy and regulatory challenges also play important roles. Only a few algal species are officially recognized for feed use, which restricts their diversity, availability, and competitiveness. Updating and harmonizing regulations is essential to unlock the full potential of microalgae in aquafeeds.

Conclusion

Microalgae are a sustainable alternative to various ingredients commercially used in aquafeeds because of their nutritional and functional properties. Packed with proteins, lipids, vitamins, carotenoids, antioxidants, and energy, they support healthy growth, immunity, and product quality in fish and in shellfish. However, microalgae-based diets have not been utilized to their full potential due to the high costs associated with production, harvesting, processing, and extraction of nutrients or other compounds. Further studies are required to examine the viability of various microalgae as potential feed ingredients for supporting growth and health. With continued research, microalgae is anticipated to play a strong role in the continued transition towards a more sustainable fish farming industry.

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