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The implementation of *Chlorella* microalgae for sustainable fish and shellfish farming

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Abstract

Aquaculture relies heavily on the symbiotic relationship between microalgae and the aquatic organisms that consume them. From an energy-efficiency perspective, the consumption of microalgae biomass by filter-feeders is highly advantageous, as microalgae serve as the primary producers and the foundational energy source for the vast majority of aquatic food webs. Within this framework, *Chlorella* has become a leading, scalable solution for modern aquaculture. Beyond its role as a nutrient-dense feed supplement, *Chlorella* acts as both a natural probiotic and a stabilizer for water quality. It is widely utilized in the cultivation of commercially significant fish, crustaceans, and mollusks both in marine and freshwater environments either as a direct food source or as a nutritional enrichment for live prey like rotifers, copepods, and *Artemia*.

Keywords: Artemia, rotifer, aquaculture, green algae, biomass, nutrition

Introduction

Projections indicate that the global population will expand by 2.3 billion individuals by 2050, necessitating a roughly 70% surge in agricultural output to meet rising demand. Microalgae have emerged as a promising solution to this challenge; these photosynthetic organisms are noted for their fast reproduction rates, ability to synthesize high-value nutrients, and remarkable environmental resilience. Because they can be cultivated using waste streams, industrial runoff, or low-cost substrates, they offer a dual benefit: they facilitate sustainable, high-yield biomass production while simultaneously functioning as a tool for bioremediation (Sulaymon *et al*., 2025) [21].

The aquaculture industry is a pillar of international food security and economic stability. By supplying vital protein through the cultivation of finfish and various crustaceans, the sector sustains both global nutrition and countless livelihoods. As the human population expands, the reliance on aquaculture to provide reliable and healthy protein sources continues to intensify. Consequently, the adoption of sustainable operational frameworks is essential to ensure both industrial longevity and ecological integrity (Turchini *et al*., 2019) [22]. Emerging innovations—specifically the integration of algal technologies provide a promising avenue for optimizing biological performance within these systems. By leveraging both microalgae and macroalgae, producers can enhance aquatic health and environmental stability, thereby advancing the industry's commitment to resource efficiency and responsible stewardship (Srirengaraj *et al*., 2024) [20].

As photosynthetic organisms, algae function as primary producers, providing the vital carbon and energy that sustain other life forms. They are typically divided into two groups: macroalgae (seaweed) and microalgae (single-celled organisms). Microalgae rely on nutrients, light, and carbon dioxide to grow. Because they can be cultivated for food, high-value chemical production, and wastewater purification, they are highly versatile in industries ranging from cosmetics to aquaculture. Additionally, their ability to grow quickly and store large amounts of oil makes them a compelling candidate for future biofuel development (Velichkova *et al*., 2012; Sharma *et al*., 2013; Hattab and Ghaly, 2014) [6, 17, 23]. Green algae are instrumental in tackling ecological challenges, notably by scrubbing surplus nutrients from ecosystems to curb pollution and bolster environmental health (Singh *et al*., 2024) [18]. Beyond their critical function in carbon cycling and oxygen generation, these organisms are increasingly valued across various sectors, including pharmaceuticals, food production, cosmetics, and sustainable biofuel development (Abdel, 2024) [18].

Among these applications, *Chlorella vulgaris* has emerged as a particularly versatile and scalable solution for aquaculture. It serves effectively as a natural probiotic, a water quality stabilizer, and a high-quality nutritional additive for farmed fish (Li *et al*., 2021; Slaniv *et al*., 2021) [19]. As the aquaculture industry grows, it faces mounting pressure to solve issues related to feed efficiency and environmental stability. Conventional feed components like soy protein and fishmeal are increasingly viewed as both cost-prohibitive and environmentally taxing. *C. vulgaris* provides a greener, renewable substitute, functioning as a "bio-factory" packed with vital nutrients including essential amino acids, proteins, pigments like carotenoids and chlorophyll, and polyunsaturated fatty acids which collectively enhance growth, elevate stress tolerance, and promote overall health in fish populations.

Chlorella

Belonging to the phylum Chlorophyta, *Chlorella* encompasses a broad range of single-celled freshwater green algae, categorized through both molecular analysis and physical structure. These non-motile, spherical organisms typically measure between 2 and 10 microns in diameter and possess a robust cell wall made of polysaccharides and cellulose. Internally, each cell houses a solitary, cup-shaped chloroplast containing chlorophyll-a and chlorophyll-b, which facilitate the rapid conversion of sunlight, water, carbon dioxide, and minimal minerals into energy. Because of their impressive photosynthetic efficiency and quick maturation rates, *Chlorella* species are highly valued for their capacity to store a variety of beneficial biocompounds. Consequently, they serve as a versatile resource across multiple sectors, ranging from biofuels and the pharmaceutical industry to agricultural feed and human nutrition (Salah *et al*., 2024) [16].

Recognized for its sustainability, safety, and potent antimicrobial activity, *Chlorella* a genus of single-celled green algae is increasingly viewed as a viable replacement for conventional treatments against bacterial pathogens in fish. Taxonomically situated within the Chlorellaceae family, this genus comprises more than 30 recognized species distinguished by specific molecular and physical traits. These microscopic, spherical organisms measure between 2 and 10 μm in diameter and house a solitary, cup-shaped chloroplast equipped with chlorophyll types a and b, alongside accessory pigments like carotenoids and phycobiliproteins. Notably, *Chlorella* is defined by a robust cell wall made of cellulose and various polysaccharides; as noted by Fu *et al*., (2019), this structural composition provides the algae with significant resilience against environmental challenges, including acidic conditions and high salinity.

Genetic classification of *Chlorella* relies primarily on DNA sequencing, specifically targeting the 18S rRNA gene to facilitate accurate species identification and evolutionary mapping. Molecular studies have categorized the genus into distinct phylogenetic lineages, most notably *C. vulgaris*, *C. sorokiniana*, *C. pyrenoidosa*, *C. ellipsoidea*, *C. minutissima*, and *C. protothecoides* (Vello *et al*., 2014) [24]. Due to their rapid biomass production and significant photosynthetic output, *Chlorella* species are considered highly versatile for industrial use (Liu and Chen, 2014) [11]. Nutritionally, these microalgae serve as excellent sources of proteins, essential amino acids, and vital micronutrients for both human and animal diets. Beyond nutrition, their capacity to synthesize substantial lipid reserves positions them as a viable feedstock for biodiesel production, while their secondary metabolites—including polysaccharides, carotenoids, and phycobiliproteins offer therapeutic properties that are increasingly utilized in cosmetic and pharmaceutical sectors (Koyande *et al*., 2019) [8].

Culture techniques of Chlorella

Successfully transitioning *Chlorella vulgaris* to industrial-scale production necessitates a precise mastery of its reproductive mechanisms within controlled settings. By conducting laboratory experiments, researchers can systematically refine key variables such as temperature, light properties, pH levels, nutrient availability, and CO_2 supplementation to bolster biomass yields, ensure culture robustness, and enhance biological potency. Although microalgae have been the subject of significant investigation for twenty years, current literature regarding the specific reproductive kinetics of *C. vulgaris* particularly concerning its practical utility in aquaculture remains notably sparse (Akgul and Akgul 2024) [2]. Consequently, diverse cultivation methodologies, from simple batch systems to sophisticated photobioreactors, are being developed to leverage these biological insights for optimized mass production in aquaculture.

Chlorella can be cultured in various types of media, including freshwater, seawater, and artificial media. The choice of media depends on the desired application and the characteristics of the Chlorella strain being used. For example, freshwater Chlorella strains grow well in media containing nitrates and phosphates, while marine Chlorella strains require a high concentration of sodium and magnesium (Chia *et al*., 2013) [3]. Chlorella can be cultured in open or closed systems. Open systems, such as raceways and ponds, are simple and cost-effective but are vulnerable to contamination from other microorganisms and require a large land area. Closed systems, such as photobioreactors and fermenters, offer better control over the culture conditions, minimize contamination, and have higher productivity but are more expensive to construct and maintain (Rodolfi *et al*., 2009) [15].

Chlorella vulgaris can also be cultivated using open and closed cultivation methods. Open systems such as raceways and ponds are the simplest and most popular type, as the construction and functioning of such structures are inexpensive and fast but long-lasting. Essentially, they are large vessels in which the microalgae are contained. It is permitted to grow under environmental conditions. They are simply maintained under conditions such that they flow or move in ways that are in contact with nutrients within the media and do not settle at the bottom of the tanks. Among the limitations that these systems present, the cells are not constantly in contact with light, which limits the efficiency of photosynthesis; the culture medium evaporates; a large size is necessary for the construction of the systems; and there is a risk of being infected by other organisms. Due to these limitations, they are only suitable for resistant species (de Godos *et al*., 2009) [4].

In contrast to open configurations, closed setups including fermenters and photobioreactors offer superior regulation over cultivation environments. By utilizing artificial lighting, sunlight, or a combination of both, these systems can achieve significantly higher biomass productivity, provided that contamination is effectively mitigated. Common designs for these closed units include helical, tubular, conical, stirred, airlift, and bubble column tanks. The primary benefits of this approach are the ability to maintain stringent experimental parameters, the ease of ensuring a sterile environment, and improved protection against photo-oxidation. Nevertheless, as noted by Kunjapur and Eldridge (2010) [9], these systems carry a higher capital cost compared to their open-air counterparts.

Research by Iriani *et al*., (2021) [7] demonstrated that utilizing Bean Sprouts Extract Media (BSEM) under constant illumination maximizes both the cell density and the specific growth rate of *Chlorella* sp. Similarly, Rahardini *et al*., (2018) [13] highlighted the importance of nutrient formulation, noting that an inorganic fertilizer ratio of 3:3:1 yielded peak population growth. Furthermore, Mtaki *et al*., (2021) [12] proved that aquaculture wastewater (AWW) enriched with NPK fertilizer serves as an effective, economical alternative to premium growth media, simultaneously enhancing the biomass's vitamin and mineral profiles. Because light quality acts as a critical regulator of photosynthetic efficiency, it remains a focal point in microalgae studies; as noted by Ren *et al*., (2023) [14], different wavelengths provide varying energy levels, directly influencing the photosynthetic development and overall proliferation of *Chlorella* sp.

Conclusion

Microalgae represent a vital frontier for enhancing both global food security and ecological sustainability, largely owing to their impressive nutritional density and versatility.

Specifically, *Chlorella* stands out as a significant candidate for imminent integration into the food supply chain. Its robust profile of proteins, lipids, carbohydrates, minerals, and vitamins significantly boosts the functional and nutritional quality of various food products. Despite this promise, widespread adoption remains hindered by obstacles such as inconsistent antibacterial efficacy, expensive cultivation processes, difficulties in industrial scaling, and unfavourable organoleptic characteristics.

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