



Microalgae: A key player in fish farming for healthy food and a greener environment

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Abstract

Microalgae have the potential to address global challenges, including food security, environmental sustainability, and the progress of aquaculture. This literature review examines the various roles of microalgae in aquaculture, with a focus on their nutritional value and environmental advantages. Microalgae contain essential nutrients such as proteins, lipids, vitamins, and minerals, making them advantageous as supplements in aquafeed and as direct feed for fish larvae, thereby promoting fish growth and health. They play a part in sustainable aquaculture through the improvement of water quality, reduction of antibiotic usage, and substitution of fishmeal in feeds. Furthermore, their capacity to eliminate pollutants, capture carbon, and recycle nutrients is crucial in wastewater management and ecosystem rehabilitation. Despite their potential, widespread adoption of microalgae faces obstacles such as scalability, cost, regulations, and consumer acceptance, thus necessitating technological advancements, optimization, and policy backing. Prospective trends in microalgae research and their integration with sustainable aquaculture practices present opportunities for collaboration and advancement. The implementation of supportive policies and partnerships within the industry can drive a more sustainable and resilient future, ultimately realizing the full potential of microalgae in aquaculture and environmental preservation.

Keywords: Microalgae, aquaculture, sustainability, nutritional value, environmental benefits, challenges, future prospects, innovation, collaboration.

Introduction

The importance of aquaculture in ensuring food security has increased due to population growth (Grafton *et al.*, 2015; Tilman *et al.*, 2011). Fish and shrimp heavily depend on fishmeal rich in high-quality protein, encountering difficulties arising from market fluctuations (Olsen *et al.*, 2012; Jannathulla *et al.*, 2019). Fulfilling the demand for premium fish is impeded by the necessity of omega-3 fatty acids and fish-derived proteins (Ruxton *et al.*, 2007; Yaakob *et al.*, 2014). Maintaining a well-rounded nutrient provision is imperative for ensuring production excellence (Miranda *et al.*, 2020; Gupta, 2020; Kumar & Sonwani, 2023). The global market for aquafeed is estimated at US\$60 billion annually, with compound feed constituting 70% of the expenses (Tibbetts *et al.*, 2015b). Although fishmeal is indispensable, its high cost has led to investigations into substitute options (Hass *et al.*, 2016; Palmegiano *et al.*, 2005). Excessive reliance on fishmeal has adverse effects on marine sustainability (Tibbetts *et al.*, 2015c; 2017). Microalgae play a crucial role in the global food chain, offering rich nutrients to both humans and animals and serving as natural additives and protein substitutes (Anderson, 1996; Wiessner *et al.*, 1995; Yaakob *et al.*, 2014). With the increasing need for protein, the aquaculture industry has been investigating algae as alternative sources, particularly for the nutrition of small fish larvae (Yaakob *et al.*, 2014). Developments in the cultivation of microalgae, especially *Chlorella* sp., since the late 1800s, have been instrumental in addressing challenges related to energy, the environment, and food security (Preisig & Andersen, 2005). Aquaculture, constituting 56% of global fish consumption in 2020 and led by Asia, can benefit from microalgae as a sustainable feed alternative, reducing reliance on fish meal (FAO, 2022a). This review delves into microalgae's roles in aquaculture, including their nutrition, environmental

benefits, challenges, and future potential. Through analyzing current research and trends, we aim to understand microalgae's potential in addressing global food security, environmental sustainability, and aquaculture progress.

Nutritional content of microalgae: Microalgae are rich in essential nutrients such as proteins, carbohydrates, lipids, amino acids, fatty acids, vitamins, and pigments, which are important for their growth (Jiaxing *et al.*, 2023; Rabia *et al.*, 2022). Nutrients like nitrogen, phosphorus, trace metals, and vitamins play a crucial role in their growth (Fabian *et al.*, 2021). Species such as *Nannochloropsis* and *Porphyra* provide a varied and abundant source of nutrients depending on the conditions (Rocio *et al.*, 2022). Microalgae powders such as *Anaplasma* and *Chlorella* can improve the growth performance of aquaculture feed by providing proteins, omega-3 fatty acids, vitamins, and minerals (Michela *et al.*, 2023; Sudeshna *et al.*, 2015).

1. Macronutrients

A. Protein and amino acids: Microalgae and seaweed are rich sources of protein, accounting for 70% of dry weight (Amorim *et al.*, 2022; Schade *et al.*, 2020; Thiviya *et al.*, 2022). They provide essential amino acids and other nutrients that benefit human health (Fabian *et al.*, 2023). Algae, including microalgae and macroalgae, are valuable supplements to animal feeds, especially in aquaculture, due to their protein, carbohydrate, lipid and nutrient content (Helena *et al.*, 2019). Algae with a protein content ranging from 5% to 47% of dry weight are considered important sources of protein (Monika and Cerna, 2011).

B. Lipids and fatty acids: Algae create a range of lipids and fatty acids with different nutritional compositions (Francisca *et al.*, 2023). The nutritional diversity of marine

microalgae is reflected in their unique lipid, vitamin, and pigment profiles (Syed *et al.*, 2018). The lipid content of algae is influenced by growth conditions and the availability of macronutrients (Rabia *et al.*, 2022). Edible seaweeds provide proteins, carbohydrates, and lipids, offering a sustainable source of macronutrients with various uses (Francisca *et al.*, 2023; Rabia *et al.*, 2022).

C. Carbohydrates: Carbohydrates are crucial for the growth and energy storage of algae, such as *Chlorella*

vulgaris and *Dunaliella salina*, and are important for their biofuel potential (Mee *et al.*, 2020; Juliana *et al.*, 2022). The polysaccharides found in microalgae and macroalgae have properties like biodegradability, antioxidants, and antimicrobial effects, making them suitable for use in food, agriculture, and aquaculture (Anna *et al.*, 2021; Helena *et al.*, 2019). The diverse carbohydrates in macroalgae have applications in various industries and medicine due to their immunostimulating and antioxidant properties (Valérie *et al.*, 2016).

Table 1: Protein, lipid, and carbohydrate makeup of several microalgae types:

Microalgae Species	Lipids (%)	Protein (%)	Carbohydrates (%)	Pigment (%)	References
<i>Haematococcus pluvialis</i>	15	48	27	-	Bleakley <i>et al.</i> 2017
<i>Dunaliella</i>	25–75	50–80	10–25	-	Ahmed <i>et al.</i> & Gomes, 2017
<i>Botryococcus braunii</i>	33	39.61	2.38	-	Sydney <i>et al.</i> 2010
<i>Nannochloropsis sp.</i>	22–31	33–44	8–14	-	Milledge 2011
<i>Scenedesmus quadricauda</i>	1.9	47	21–52	-	Van Krimpen <i>et al.</i> 2013
<i>Chlamydomonas</i>	20–25	47–50	15–20	-	Shuba & Kifle 2018; Zullaikah <i>et al.</i> 2019
<i>Synechococcus sp.</i>	11	63	15	-	Becker 1994
<i>Chlorella vulgaris</i>	14–22	12–17	1–58	-	Wolkers <i>et al.</i> 2011
<i>Arthrospira platensis</i>	7–23	57–65	20–30	-	Tandon & Jin 2017; Mata <i>et al.</i> 2016
<i>Isochrysis galbana</i>	12–14	50–56	10–17	-	Milledge 2011
<i>Porphyridium cruentum</i>	5.78–7.55	27.7–40.8	22.8–39.3	-	Fuentes <i>et al.</i> 2000
<i>Spirulina maxima</i>	6–7	60–71	13–16	-	Milledge 2011
<i>Tetraselmis maculata</i>	3	52	15	-	Van Krimpen <i>et al.</i> 2013
<i>Nannochloropsis granulata</i>	33.5	23.6	36.2	-	Tibbetts <i>et al.</i> 2015; Tibbetts <i>et al.</i> 2015; Tibbetts <i>et al.</i> 2015
<i>Phaeodactylum tricornutum</i> CCMP-1327	18.2	39.6	25.2	-	
<i>Tetraselmis chuii</i> PLY-429	12.3	46.5	25	-	
<i>C. minutissima</i>	16.32	43.78	14.59	-	Prajapati <i>et al.</i> 2014
<i>C. pyrenoidosa</i>	13.65	40.92	25.3	-	Prajapati <i>et al.</i> 2014
<i>C. vulgaris</i> (Becker, 2007)	14-22	51-58	17-Dec	-	Becker 2007
<i>C. vulgaris</i> (Ren <i>et al.</i> , 2017)	21.5	52	-	-	Ren <i>et al.</i> 2017
<i>C. vulgaris</i> (Viegas <i>et al.</i> , 2021)	14.4	37.5	26.6	-	Viegas <i>et al.</i> 2021
<i>C. sorokiniana</i>	26	29.46	29.74	-	Guldhe <i>et al.</i> 2017
<i>C. sorokiniana</i>	31.85	28.81	35.43	-	Ansari <i>et al.</i> 2017a
<i>Chlorella sp.</i>	14	52	19.5	1.64 µg/ml	Yadav <i>et al.</i> 2020
<i>S. obliquus</i>	30.85	19.52	35.05	-	Ansari <i>et al.</i> 2017a
<i>S. obliquus</i>	21.43	50	12.43	-	Ansari <i>et al.</i> 2015
<i>S. obliquus</i>	22.6	21	48	-	Viegas <i>et al.</i> 2021
<i>A. obliquus</i>	15.34	40.56	16.97	-	Ansari <i>et al.</i> 2021
<i>Dunaliella salina</i>	-	-	-	14	D'Alessandro and Filho 2016
<i>Dunaliella salina</i>	11	55	30	-	Chen <i>et al.</i> 2013
<i>N. salina</i>	28	35	28	-	Chen <i>et al.</i> 2013
<i>N. oculata</i>	5.6	42.2	-	-	Gamboa-Delgado <i>et al.</i> 2019
<i>N. gaditana</i>	20-25	30-40	-	-	Sepúlveda <i>et al.</i> 2015
<i>A. falcatus</i>	35.9	30.59	33.83	-	Ansari <i>et al.</i> 2017a
<i>H. pluvialis</i>	---	8-Jan	-	-	D'Alessandro and Filho 2016
<i>Phaffia rhodozyma</i>	-	-	-	0.4	Hemaiswarya <i>et al.</i> 2011
<i>Muriellopsis sp.</i>	-	-	-	0.4-0.6	D'Alessandro and Filho 2016
<i>Spirulina plantensis</i>	1.75	66.93	-	-	Macias-Sancho <i>et al.</i> 2014
<i>Isochrysis galbana</i>	36.6	23.2	34.5	-	He <i>et al.</i> 2018

2. Micronutrients

A. Vitamins: The significance of vitamins such as thiamine, biotin, and cobalamin for the growth of microalgae has been underscored in research (Ying *et al.*, 2010). Microalgae are abundant in vitamin K1 and present themselves as natural

remedies, catering to deficiencies such as vitamin B12 (Thomas *et al.*, 2018; Angelo *et al.*, 2020). They hold potential as a valuable reservoir of various micronutrients for animal health and nutritional purposes (Thomas *et al.*, 2018).

Table 2: Vitamins of the microalgae (Beardall *et al.* 2022)

Vitamin	<i>Tetraselmis</i>	<i>Pavlova</i>	<i>Stichococcus</i>	<i>Nannochloropsis sp. CS-246</i>	<i>LSD sp. CS-362</i>	<i>pinguis sp. CS-92</i>
Ascorbic Acid	3.0 ± 0.1	1.3 ± 0.1	2.5 ± 0.4	2.5 ± 0.2	1.0 ± 0.1	3.2 ± 0.2
β-carotene	1.05 ± 0.03	0.6 ± 0.03	0.37 ± 0.03	0.50 ± 0.01	1.1 ± 0.20	0.29 ± 0.04
α-tocopherol	0.07 ± 0.005	0.14	0.16 ± 0.01	0.29	0.18	0.35 ± 0.02
Thiamine (B1)	109 ± 18	36 ± 5	29 ± 2	70 ± 8	51 ± 6	70 ± 10
Riboflavin (B2)	26 ± 4	50 ± 10	25	25 ± 3	48 ± 3	62 ± 2
Folate	20 ± 2	23	24 ± 3	17	26	18 ± 8
Pyridoxine (B6)	5.8 ± 0.4	8.4	17	3.6	6	9.5 ± 0.5
Cobalamin (B12)	1.95 ± 0.05	1.7	1.95 ± 0.05	1.7	1	0.85 ± 0.35
Biotin	1.3 ± 0.7	1.9	1.3	1.1	1	0.95 ± 0.35
Retinol (A)	2.2 ± 0.5	<0.25	<0.25	<0.25	<0.25	<0.25
Ergocalciferol	<0.35	<0.35	<0.35	<0.35	0.45	<0.35
Cholecalciferol	<0.35	<0.35	<0.35	<0.35	<0.35	<0.35

B. Minerals: Microalgae and seaweeds have varied mineral compositions determined by their surroundings (Silva *et al.*, 2015; Jimenez *et al.*, 2020). They contain important minerals such as Na, K, Ca, Mg, Fe, Zn, and Se, which are crucial for human health (Zaida *et al.*, 2020; Ana *et al.*, 2018). Creating ideal growing conditions can increase the accumulation of minerals, as observed in supplements like *Spirulina* and *Chlorella*, ultimately boosting overall mineral consumption (Piotr *et al.*, 2019).

C. Bioactive Compounds: Microalgae are rich in bioactive compounds like carotenoids, phycobiliproteins, and sulfur-coated polysaccharides, showing promise in fighting cancer and pathogens. They produce important substances such as sugars, peptides, lipids, and carotenoids with anti-tumor, anti-inflammatory, and antioxidant properties. In summary, microalgae are valuable sources of bioactive compounds with potential uses in pharmaceuticals, food, cosmetics, and nutraceuticals.

Table 3: Bioactive compounds of microalgae:

Carotenoid	IUPAC Name	Source	Therapeutic Indication	References
β-carotene	β,β-carotene	<i>D. salina</i>	Antioxidant, Provitamin A, AMD, Liver fibrosis, anti-inflammatory	Guedes <i>et al.</i> 2011 [6]; Gong & Bassi 2016
Astaxanthin	3,3'-dihydroxy-β,β-carotene-4,4'-dione	<i>H. pluvialis</i> , <i>C. zofigiensis</i> , <i>C. vulgaris</i>	Antitumoral, antioxidant, anti-inflammatory	Raposo <i>et al.</i> 2015; Talero <i>et al.</i> 2015; Zhang <i>et al.</i> 2014; Gong & Bassi 2016) (10)
Lutein	β,ε-carotene-3,3'-diol	<i>D. salina</i> , <i>C. pyrenoidosa</i> , <i>C. protothecoids</i>	AMD, Atherosclerosis, retinal neural damage	Talero <i>et al.</i> 2015; Granado <i>et al.</i> 2009
Zeaxanthin	β,β-carotene-4,4'-diol	<i>D. salina</i> , <i>P. cruentum</i> , <i>C. protothecoids</i>	Antioxidant, Maculopathy, cataracts, anti-inflammatory	Granado <i>et al.</i> 2009; Raposo <i>et al.</i> 2015; Talero <i>et al.</i> 2015
Violaxanthin	5,6,5',6'-diepoxy-5,6,5',6'-tetrahydro-β,β carotene-3,3'-diol	<i>D. tertiolecta</i> , <i>C. ellipsoidea</i>	Anti-inflammatory, anti-cancer	Raposo <i>et al.</i> 2015; Zhang <i>et al.</i> 2014
Fucoxanthin	(3S,3'S,5R,5'R,6S,6'R,8'R)-3,5'-dihydroxy-8-oxo-6',7'-didehydro-5,5',6,6',7,8-hexahydro-5,6-epoxy-β,β caroten-3'-yl acetate	<i>P. tricornutum</i>	Antioxidant, anti-inflammatory, anti-cancer	Mikami & Hosokawa 2013; Talero <i>et al.</i> 2015

Applications of Microalgae in aquaculture

Microalgae in aquaculture help to reduce nitrogen pollution and improve water quality, as well as provide nutrients and enhance the growth and disease resistance of aquatic specie

Their use also benefits water quality, wastewater treatment, and aquaculture sustainability, leading to increased efficiency and environmental stewardship. (Danni *et al.*, 2023; Muhammad *et al.*, 2023; Qian *et al.*, 2023).

Table 4: Commonly Used Microalgae in Aquaculture Applications (Kaparapu 2018)

Area of Application	Commonly Used Microalgae
Feed Ingredient in Formulated Feed	<i>Arthrospira platensis</i> , <i>Chlorella vulgaris</i> , <i>C. minutissima</i> , <i>C. virginica</i> , <i>Dunaliella tertiolecta</i> , <i>D. salina</i> , <i>Haematococcus pluvialis</i>
Feed for Bivalve Mollusks	<i>Thalassiosira pseudonana</i> , <i>Pavlova lutheri</i> , <i>Isochrysis galbana</i>
Feed for Rotifer and Artemia Live Prey	<i>Cryptocodinium cohnii</i> , <i>Schizochytrium sp.</i> , <i>Ulkenia sp.</i> , <i>Chlorella sp.</i> , <i>Chlamydomonas sp.</i> , <i>Nannochloris oculata</i> , <i>Tetraselmis tetraathele</i> , <i>T. chuii</i>
Feed for Crustacean Larvae (Shrimps, Lobsters)	<i>Tetraselmis suecica</i> , <i>T. chui</i> , <i>Chaetoceros calcitrans</i> , <i>C. gracilis</i> , <i>Skeletonema costatum</i> , <i>Thalassiosira pseudonana</i>
Feed for Gastropod Molluscs and Sea Urchins	<i>Nitzschia sp.</i> , <i>Navicula sp.</i> , <i>Amphora sp.</i>
"Green Water" for Finfish Larvae	<i>Isochrysis galbana</i> , <i>Nannochloropsis oculata</i>

1. Microalgae as a direct feed for fish: Various types of microalgae offer cost-effective alternatives to fishmeal in aquafeed and can improve the nutritional value for fish and prawns (Brown *et al.*, 1997; Apandi *et al.*, 2018). Mixing different types of microalgae has been found to boost growth and nutrient retention in fish (Spolaore *et al.*, 2006; Hemaiswarya *et al.*, 2011) ^[13]. Additionally, even small amounts of whole algae can enhance fish growth, protein retention, and fatty acid levels, benefiting aquaculture production (Abdulrahman, 2014a; Radhakrishnan *et al.*, 2014; Brune, 2011). Including *Spirulina* biomass in feed has been proven to enhance utilization, decrease mortality, and promote shrimp growth (Nakagawa & Gomez-Diaz, 1995).

2. Microalgae- based aquafeed formulation: Microalgae added to aquafeed offer crucial nutrients such as fatty acids, amino acids, proteins, fibers, antioxidants, vitamins, and minerals. These nutrients help in the growth and immunity of fish and shellfish. They replace fish meal and oil, thereby improving sustainability and lowering expenses. Photobioreactors generate abundant microalgae biomass and fatty acids, providing a viable hatchery feed option and promoting nutritional value and sustainability in aquafeed.

3. Functional benefits of microalgae in fish health and growth: *Schizochytrium* and *Spirulina* improve fish health and development by enhancing immune systems, lipid metabolism, and stress tolerance (Tamsyn *et al.*, 2023; Margarida *et al.*, 2022). *Spirulina* contributes to growth, while *Schizochytrium* helps maintain omega-3 levels in fish fillets (Ana *et al.*, 2022). These microalgae are abundant in bioactives such as astaxanthin, phycobiliproteins, and antioxidants, which are crucial for fish health and aquafeed (Ana *et al.*, 2022). Marine macroalgae also provide fish health benefits and may offer protection against genetic damage (Ana *et al.*, 2022).

4. Use of microalgae in larviculture and fry rearing: Microalgae play a crucial role in the field of aquaculture by offering essential protein, fatty acid, vitamin, and pigment-rich food sources, which contribute to the growth and well-being of aquatic organisms (De-Sing *et al.*, 2023; Muhammad *et al.*, 2023). Their use in green water techniques significantly improves growth performance and larval activity, and they are essential for the production of live food resources such as rotifers and *Artemia* in hatcheries (Dantas *et al.*, 2022; Robert *et al.*, 2022).

5. Environmental benefits of Microalgae in Aquaculture: Microalgae play a significant role in aquaculture by reducing dependency on conventional resources, enhancing sustainability, and removing waste nutrients (Pei *et al.*, 2023). They are utilized as alternatives to fish oil and meal in feed, which not only improves ecological aspects and fish growth but also reduces nitrogen emissions (Nur *et al.*, 2023; Qian *et al.*, 2023). Furthermore, microalgae contribute to the creation of a favorable aquaculture environment by eliminating toxins and enhancing the immunity of aquatic species (Pei *et al.*, 2023).

A. Sustainability aspects of micro algae cultivation Sustainable cultivation of microalgae provides environmentally friendly alternatives for biofuels,

bioproducts, and food sources (Neha *et al.*, 2023). Techniques such as media manipulation and genetic engineering enhance the productivity of microalgae (Kricelle *et al.*, 2022). Advanced approaches like magnetic biostimulation contribute to the sustainable enhancement of biomass production, thus offering solutions to food requirements and environmental issues.

B. Environmental footprint compared to traditional feed sources: Evaluating the use of algae-based feed as an alternative to fishmeal is crucial for sustainable aquaculture (Pietro *et al.*, 2022). Although algae feeds are a viable replacement, they may have a more significant impact on climate change and water consumption (Brandi *et al.*, 2023; Senthil *et al.*, 2021). Enhancing methods with sustainable technology and energy can enhance the environmental performance of algae feed (Brandi *et al.*, 2023). Algae-based feed holds promise for ethical aquaculture (Ashfaq *et al.*, 2022).

C. Role of microalgae in carbon sequestration and nutrient recycling: Microalgae have important functions in capturing carbon and recycling nutrients by using CO₂ from wastewater and flue gases (Gang *et al.*, 2023). Their carbon sequestration capacity is improved through genetic engineering and optimized growth conditions, supporting waste management and biofuel production in circular economy models (Juliana *et al.*, 2023; Randhir *et al.*, 2022). In summary, microalgae offer a sustainable solution for recycling nutrients, capturing carbon, and generating renewable energy.

D. Application in wastewater treatment and ecosystem restoration: Microalgae play a crucial role in wastewater treatment by effectively eliminating nutrients and decreasing pollution (Ines *et al.*, 2023). Introducing them into treatment facilities helps address water scarcity, produces biomass for biofuels, and contributes to ecosystem restoration (Wen *et al.*, 2023). Their ability to adapt and their contribution to sustainability is evident in their reduction of pollution and the generation of valuable products such as food and biodiesel.

Challenges and Limitation: Microalgae have advantages in aquaculture such as enhancing water quality and decreasing the need for antibiotics (Qian *et al.*, 2023). However, there are challenges like contamination risks and environmental effects that call for improved cultivation techniques and lifecycle assessments for sustainable use (Grazia *et al.*, 2022; Van *et al.*, 2016). The potential for large-scale aquaculture can be improved through industrial symbiosis exploration (Benoit *et al.*, 2021).

1. Scalability and cost- effectiveness of microalgae production: Challenges in microalgae production involve complexity, lack of data, and high energy expenditures (Marcin *et al.*, 2022; Britta & Greenshields, 2022). Inadequate biomass output due to inefficient photosynthesis and expensive CO₂ control inhibits expansion (Ehsan *et al.*, 2022). Strategies to address these issues comprise refining processes, genetic engineering, and implementing advanced surveillance to enhance competitiveness (Ana *et al.*, 2022; Olabi *et al.*, 2022).

2. Regulatory considerations and market barriers:

Regulatory obstacles for using microalgae in food concern consumer approval, digestibility, and legal matters (Qian *et al.*, 2023; Shu *et al.*, 2023), with economic viability and flavor improvement as significant market hurdles (Qian *et al.*, 2023). Advancements in processing, genetic editing, and consumer awareness are crucial to surmount these challenges (Linqing *et al.*, 2023).

3. Addressing misconceptions and consumer acceptance:

The acceptance of microalgae-based fish farming by consumers faces challenges related to sensory perceptions, safety concerns, and economic viability, despite the sustainability and abundance of bioactive substances in microalgae (Ângelo *et al.*, 2023). To integrate microalgae into food systems, addressing safety, taste, and societal approval is necessary. Strategies such as genetic modification and innovative processing are being pursued to improve sensory attributes and financial feasibility, requiring collaboration across different disciplines (Salman & Ashraf, 2023) ^[2].

Future perspective and opportunities: Microalgae are a sustainable and highly nutritious option in aquaculture, serving as substitutes for fish oil and meal. They supply important nutrients necessary for fish growth and aid in the purification of aquaculture wastewater. Specific types of microalgae are also valuable as live food for fish hatcheries, and their significance is anticipated to increase alongside the expansion of aquaculture.

1. Emerging trends in microalgae research and development:

New developments in microalgae research involve genetic manipulation for valuable products, combining algal biology with cultivation engineering for biofuel production, and investigating pharmaceutical uses for drug delivery and wastewater treatment. These endeavors work together to maximize the potential of microalgae across various fields through innovative research and development efforts.

2. Potential for integration with other sustainable aquaculture practices:

Integrated aquaculture systems, such as Integrated Fish Farming (IFF) and rice-fish farming, have been shown to improve production efficiency and economic feasibility (Deogratias *et al.*, 2022; Vishal *et al.*, 2022; Priyanka *et al.*, 2022). The use of stunted fingerlings and combining fish farming with crop cultivation can result in higher yields, resistance to diseases, and improved socio-economic stability for farmers (Gyan *et al.*, 2023; Juned *et al.*, 2022). These integrated methods demonstrate the potential to increase overall productivity and profitability in the agricultural sector through sustainable practices.

3. Innovation in microalgae-based products and value-added applications:

Advancements in products from microalgae include biofuels, nutraceuticals, and pharmaceuticals, presenting sustainable options (Kelemu & Mulluye, 2023). Approaches such as genetic manipulation and culinary methods improve consumer reception by tackling flavor and appearance obstacles. The abundance of antioxidants and proteins in microalgae makes them valuable assets for the food, pharmaceutical, and environmental preservation sectors.

4. Policy recommendation and industry collaboration

Sustainably developing microalgae-based products requires sector cooperation and policy recommendations (Vaibhav *et al.*, 2022). The commercialization of algae biomass should be supported by institutional frameworks that replicate the advantages of traditional agriculture (Emily *et al.*, 2015). Modernizing seaweed-related sectors and promoting economic growth require collaboration among stakeholders, including the government and business (Scott & Vince, 2010).

Conclusion: Microalgae are promising for addressing global food security and environmental sustainability due to their nutritional richness and diverse applications. They can be used as a substitute for traditional fish oil and meal in aquafeed, improve water quality, and lower nitrogen release. Future research should focus on sustainable cultivation methods, utilizing wastewater for cultivation, and exploring microalgae's role in nutrient elimination, immune system fortification, and protein replacement in aquaculture feeds to promote sustainable methodologies and improve production efficiency.

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