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Harnessing microalgae for sustainable nutrition and ecosystem services in aquaponic systems: a blue–green approach to ecosystem health

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Aquaponics is a soilless farming approach that integrates aquaculture with hydroponics to produce food. In regions with limited arable land, aquaponics can help address food insecurity challenges. Both fish and plants are produced using aquaponic systems. The aquafeeds used to feed the fish in aquaponic systems are also the main source of nutrition for the plants. Currently, commercial aquafeeds such as fishmeal and fish oil are used in aquaponics, but they do not completely meet the nutritional requirements of plants. Additionally, commercial aquafeeds are expensive, and their production is unsustainable. This review focuses on the suitability of microalgae as a replacement for commercial aquafeeds and its role in meeting the nutritional requirements of plants growing in aquaponic systems. Microalgae production is sustainable and cost effective compared to commercial aquafeed production. Many studies have been conducted on the impact of microalgae-based feed on fish growth and its role as a biofertilizer and biostimulants for plant growth. However, using microalgae as aquafeed for the development of both fish and plants in aquaponic systems remains underexplored. This review aims to provide insights into the dual role of microalgae in aquaponics—enhancing fish nutrition while supplementing plant nutrient requirements. Although some micronutrient gaps may persist, further optimisation could help make aquaponic systems more efficient and sustainable.

KEYWORDS
microalgae, aquafeed, nutrient cycle, plant nutrition, sustainability, aquaponics

Introduction

Aquaponics is an innovative and sustainable food production system that integrates recirculating aquaculture with hydroponics (König et al., 2016; Okomoda et al., 2023). Aquaponic plants perform comparably to hydroponic plants, despite lower nutrient concentrations (Sreekumar et al., 2023). This system offers numerous benefits, including water conservation, a reduced environmental impact, and the simultaneous production of fish and plants (Mishra et al., 2020). Aquaponics can be implemented in various settings, ranging from urban to rural areas, and at different scales, ranging from small-scale farms to industrial production units (König et al., 2016). This system is particularly valuable for addressing food security challenges as it can be utilised on non-arable land and in areas with limited water resources (Shreejana et al., 2022). Furthermore, as aquaponics is a closed-loop system that includes both hydroponic and aquaculture systems, it presents potential solutions for food production in the face of climate change-related challenges such as global warming, desertification, water scarcity, famine, and increased pests and diseases. Aquaponics is an eco-friendly cultivation system that has gained interest in various fields and industries including ecology, agriculture, and fisheries (Hao et al., 2020). Several areas of aquaponic systems need to be explored further to fully understand their potential. These areas include nitrogen cycling, nutrient recovery from fish waste, plant nutrition, plant pathogens, pest control strategies, and sustainable aquafeed (Goddek et al., 2019). This review focuses on microalgae as a sustainable alternative to commercial aquafeeds in aquaponic systems. Additionally, this review examines how microalgae can fulfil the nutritional requirements of both plants and fish in aquaponic systems., In aquaponic systems, residual fish feed and fish waste provide nutrients for plant growth. Current aquaponic systems that use commercial aquafeeds such as fish oil, fishmeal, and fish waste do not completely meet the nutritional requirements for plant growth (Eck et al., 2019; Yep and Zheng, 2019). Macronutrients such as potassium, phosphorus, sulphur, and calcium, along with micronutrients such as manganese, iron, zinc, copper, boron and molybdenum, often accumulate in inadequate amounts or disproportionate ratios in the water. Consequently, plants do not receive sufficient nutrients for their growth (Delaide et al., 2017; Suhl et al., 2016). Furthermore, commercial aquafeeds are expensive and unsustainable. I The water footprint of commercial aquafeeds was estimated to be between31–35 km^3 in 2008, with the top five species alone accounting for 18.2 km^3. For example, fisheries that provide commercial aquafeeds, such as fish oil and fishmeal, emitted 4.6 million tons of carbon dioxide-equivalent greenhouse gases in 2014 (Cashion et al., 2017). The carbon footprints of extruded and pelleted grass carp aquafeeds were 1334 and 1071 kg CO_2 eq/t, respectively, with raw material production being the largest contributor. To overcome these challenges, sustainable sourcing of raw materials and the utilisation of renewable energy in aquafeed production can substantially reduce the environmental impact (Wang et al., 2022). Additionally, exploring alternative aquafeed sources, such as single-cell proteins and insects, can help address sustainability concerns (D'Abramo, 2021). Microalgae have emerged as promising alternative aquafeed ingredients because of their nutritional profile and sustainability benefits. They contain essential amino acids, fatty acids, vitamins, pigments, and bioactive compounds that enhance fish health, survival, and product quality (Nagappan et al., 2021; Sagaram et al., 2021). Compared to traditional feed sources, such as fishmeal and soymeal, microalgae offer a more diverse set of fatty acids, pigments, sterols, and vitamins (Dixit et al., 2022). Microalgae production has a lower environmental footprint than terrestrial crops in terms of water use and land requirements (Nagappan et al., 2021; Mahata et al., 2022). Additionally, microalgae can positively influence gut microbiota and immune responses in aquatic species (Sagaram et al., 2021). Microalgae, small but powerful photosynthetic organisms, are emerging as a sustainable solution to a range of global challenges—from clean energy and environmental protection to food security and human health. Rich in nutrients and bioactive compounds, microalgae are being explored for use in biofuels (Akhtar et al., 2023), functional foods (Andrade-Bustamante et al., 2025), and health supplements (Ayub et al., 2025), offer benefits like antioxidant, anti-inflammatory, and heart-protective effects. Their ability to treat wastewater, capture CO_2, and support circular practices makes them valuable in aquaculture (Dasari et al., 2025) and environmental cleanup, including antibiotic pollution removal (Wani et al., 2024). They use minimal land and water, making them eco-friendly alternatives to traditional crops, and contribute significantly to achieving climate goals and UN Sustainable Development Goals (Ahmad and Ashraf, 2024). Despite challenges like high production costs, regulatory hurdles, and taste issues in food applications, advances in biotechnology, AI, and strain development are paving the way for large-scale, sustainable use of microalgae across industries. This review examines the potential of microalgae as sustainable components of aquafeed formulations. It also provides valuable insights into the utilisation of microalgae aquafeeds as replacements for commercial aquafeeds such as fish oil and fishmeal. Microalgae may provide complete nutrition for plant growth in aquaponic systems, and its use will enhance the efficiency and sustainability of these systems and contribute to global food security.

Aquaponics: an overview

Aquaponics is a climate-smart technology used for sustainable food production (Nishanth et al., 2024). Aquaponic systems use less than 90% of the water used in conventional fish and plant farming which support sustainable food production and facilitate complete biological processes between fish, plants, and microbes. Aquaponic systems are composed of three main components that work together: the growing bed (hydroponic unit) for plant growth, biofilter for microbes to perform nitrification, and aquaculture tank to rear fish. All three components must function in coordination to support fish and plant growth. Fish waste is the primary nutrient component for plant growth in aquaponics. Fish waste acts as a primary nutrient source undergoing microbial nitrification to convert ammonia into plant-available nitrates. Based on the designs of the hydroponic and aquaculture units, aquaponic systems are classified into coupled and decoupled systems. Common hydroponic designs include Nutrient Film Technique (NFT), floating raft or deep-water culture, and media-based grow beds. peat moss and perlite are used as plant growth media. Media-based systems use substrates like peat moss and perlite and are ideal for vegetables and fruits due to their capacity to support high root density. NFT systems are typically used for smaller vegetables, while floating raft systems are most common, allowing roots to freely absorb nutrients. To maintain a stable environment, it is essential to monitor water quality, pH, temperature, water-use efficiency, waste management, and nutrient cycling (Goddek et al., 2019).

Nutrient cycling in an aquaponic system has many advantages because it is a recirculating system combining hydroponics and aquaculture. Because no effluent is discharged, it prevents environmental pollution. Additionally, the nutrient-rich aquaculture water can be reused as an organic fertiliser for plants in the hydroponic units. Some studies have indicated that aquaponics produces plant growth and yields comparable to or even exceeding those of soil-grown plants (Yogev et al., 2016). Nutrient cycling in aquaponic systems is influenced by multiple factors such as the aquafeed type, fish species, fish density, plant type, and microbial community. The main nutrient sources in aquaponic systems are aquafeed and aquaculture water, which contribute essential elements such as magnesium, calcium, and sulphur (Delaide et al., 2017; Schmautz et al., 2016). The two main types of aquafeed are plant-based and fishmeal-based feeds. After being introduced into the system, aquafeed is partly consumed and excreted by the fish, while some residual feed remains in the tank. Fish excreta and uneaten feed dissolve in the water, releasing nutrients that are absorbed by plants. To support optimal plant growth, additional supplements like potassium and iron may be introduced—without harming the fish (Schmautz et al., 2016). Residual aquafeed, which accounts for less than 5%, and fish excreta also contribute to carbon dioxide and ammonia production, increasing the nutrient load of the water and influencing plant development (Yogev et al., 2016). Water quality and fish biomass are strongly influenced by aquafeed type, highlighting the importance of selecting feed that meets the nutritional needs of both fish and plants (Schmautz et al., 2016).

Microbial communities in aquaponic systems undergo many biological processes that convert fish waste and residual aquafeed into nutrient rich solutions for plant growth. One such process is solubilisation carried out by bacteria that break down complex organic compounds into ionic forms absorbable by plants. Heterotrophic bacteria such as *Pseudomonas* sp., *Flavobacterium* sp., *Rhizobium* sp., *Aeromonas* sp., and *Sphingobacterium* sp. are involved in this solubilisation process. Additionally, some γ-proteobacteria can solubilise phytates making phosphorus available to plants. The primary nitrogen source in aquaponic systems is the proteins present in aquafeeds. However, fish utilise only about30% of the nitrogen present in aquafeed, and the remaining is excreted in the form of ammonia (Ru et al., 2017; Wongkiew et al., 2017; Yavuzcan Yildiz et al., 2017). This ammonia is oxidised to nitrite by ammonia-oxidising bacteria such as *Nitrosococcus*, *Nitrosospira*, *Nitrosomonas*, *Nitrosolobus*, *and Nitrosovibrio*, and subsequently converted to nitrate by nitrite-oxidising bacteria such as *Nitrobacter*, *Nitrococcus*, *Nitrospina*, *and Nitrospira* (Wongkiew et al., 2017). Understanding the nutrient cycles is essential for the effective operation of aquaponic systems, as plants require different nutrients at various growth stages. Some of these nutrients can be supplemented either as foliar application or by adding nutrients directly to the water. Macronutrients, such as carbon, are supplied through the organic compounds in the aquafeed then metabolised by both fish and microbes, releasing carbon dioxide(CO_2) as a byproduct. This CO_2 is then absorbed by plants and used in photosynthesis via carbon fixation. Plants uptake nitrogen as nitrate or ammonium ions (Wongkiew et al., 2017), Phosphorus as orthophosphate (Resh, 2022), and potassium which is important for growth and accumulates especially in fruit (Schmautz et al., 2016). Other essential elements such as calcium, magnesium, and sulphur typically present in tap water, while micronutrients like manganese, iron, and zinc, are derived from aquafeed., Copper and boron are also present in tap water (Delaide et al., 2017). Overall, aquaponic systems foster a symbiotic relationship among fish, plants, and microbes in a recirculating sustainable food production process.

Nutrient imbalance and aquafeed unsustainability in aquaponics

In aquaponic systems, nutrients are transferred from fish waste to plants through biological processes; however, an imbalance often exists between the nutrient content in fish waste and the nutrient requirements for optimal plant growth. Factors such as fish tank size, biofilter capacity, and system design influence the nutrient availability Therefore, the nutrient composition of aquafeed, and the specific requirements of each plant species must be carefully considered (Resh, 2022). Monitoring nutrient availability is challenging, as nutrients originate primarily from fish waste and residual aquafeed. Processes such as fish waste removal, water renewal, and denitrification contribute to nutrient loss in the system. Research studies has shown that fish waste and residual aquafeed contain 86% manganese, 22% copper, 89% magnesium, 24% iron, 16% calcium, 6% potassium, 6% nitrogen, and 18% phosphorus. However, not all these nutrients are efficiently utilised by plants, particularly macronutrients like potassium, phosphorus, iron, manganese, and sulphur. Nitrogen released from fish protein metabolism enters nitrogen cycle and is transformed into usable forms usable by plants. Since aquafeed and fish waste are the main nutrient sources their selection and utilisation are crucial for supporting both fish and plant growth in integrated aquaponic systems (Zhanga et al., 2021).

Some studies have shown that, minerals added as supplements to aquafeed, can be utilised by plants in aquaponic systems. Soluble minerals are not absorbed by fish may be taken up by plants, enhancing nutrient recovery. However, the mineral requirements and metabolism in aquaculture species has not been extensively investigated. The addition of anions and their accompanying cations to aquafeed has been shown to improve nutrient availability for plants (Ng and Koh, 2017). Plant-based minerals in aquafeed may contain phosphorus in phytate form, which is not readily metabolised by plants. The exogenous addition of enzymes to aquafeed can help release phosphorus from improving bioavailability. However, this approach has some limitations, such as potential release of undesirable compounds that may affect fish health. Further research is needed to evaluate the safe and effective use of these enzymes. Moreover, adding supplements to aquafeed or directly into hydroponic systems is expensive. To reduce this cost it is essential to understand the amount of aquafeed required to meet both fish and plant nutritional requirements. In aquaponic systems, plant physiological processes such as photosynthesis, flowering, defence, and seed germination are regulated in a circadian rhythm pattern which ideally should work in coordination with circadian rhythm patterns of fish. However, when commercial aquafeed is used, this rhythm is not always well-coordinated and plants nutritional requirements may not be fully met. Some microalgae like *Chlamydomonas reinhardtii* has been widely studied for its role in research on photosynthesis, metabolism, and cilia function. Beyond its laboratory significance, it is increasingly recognised for its biotechnological potential due to its fast growth, metabolic flexibility, and low-cost cultivation. It has been applied in biofuel production, nutraceutical development, and wastewater treatment, where it contributes to contaminant removal and resource recovery. Recent studies have also explored the synergistic benefits of co-cultivating *Chlamydomonas* with bacteria to enhance detoxification and bioproduction processes. Although challenges such as genome editing remain, ongoing technological progress continues to expand the industrial and environmental applications of this versatile alga (Salomé and Merchant, 2019; Scranton et al., 2015; Bellido-Pedraza et al., 2024; Bellido-Pedraza, Torres and Llamas, 2024). In addition to its utility in biofuels and bioremediation, microalgae are increasingly explored as sustainable alternatives to commercial aquafeeds.

Moreover, commercial aquafeed production relies heavily on wild fisheries, making it environmentally unsustainable. Some studies have shown that plant-based alternatives like soybean meal and corn gluten meal commonly used to replace fishmeal, contain anti-nutritional factors that limit their effectiveness as aquafeeds (Gerile and Pirhonen, 2017). Additionally, most plant-based aquafeeds contain phosphorus in phytate form, which is unavailable to plants, necessitating the supplementation of nutrients like phosphorus and zinc in aquaponic systems. Selecting appropriate aquafeed is critical, and supplements should be added carefully to avoid harming both fish and plant health in aquaponics. While plant-based aquafeeds are often promoted as eco-friendly option, they are not fully sustainable due to their negative ecological impacts such as destruction of plant communities for feed production. Animal-based aquafeeds, such as animal proteins sourced from slaughterhouses that are free from anti-nutritional factors, can serve as viable fishmeal substitutes. Additionally, insect-based feeds such as those derived from black soldier flies, have emerged as promising alternatives due to their high protein content, low land and water requirements, reduced greenhouse gas emissions, and superior feed conversion efficiency. However, further research is necessary to evaluate the quality, efficacy, and safety of using insects as aquafeed in aquaponic systems. Recently, the use of microalgae such as *Arthrospira platensis*, *Chlorella vulgaris*, *Schizochytrium* sp., *Nannochloropsis* sp., *Dunaliella salina.*, *Haematococcus pluvialis.*, and *Isochrysis galbana* as a replacement for commercial aquafeeds has gained increasing attention because microalgae can produce higher biomass than plants. As shown in Figure 1, the global average water footprint varies significantly among different aquafeed ingredients, highlighting the need for more sustainable alternatives such as microalgae (Pugazhendhi et al., 2020).

Microalgae exhibit remarkable adaptability and rapid growth rates, which make them valuable for various applications. They can thrive in extreme conditions, such as highly alkaline environments, with growth rates of 1.10–1.30/d (Praveen et al., 2023). Thermally tolerant mutant species of *Nitzschia inconspicua* microalgae have shown 1.4- to 6.7-fold higher growth rates than wild types at different temperatures. Adaptive laboratory evolution has been used to enhance the growth rate, stress tolerance, and product yield of microalgae (LaPanse, 2024). These fast-growing organisms have diverse applications as functional foods and in biofuel production, greenhouse gas mitigation, and wastewater treatment. Their ability to efficiently remove carbon (70–80%) and other nutrients (80–90%) from wastewater demonstrates their potential in environmental remediation (Praveen et al., 2023). The high adaptability and rapid growth rate of microalgae make them promising candidates for sustainable biotechnology and industrial innovation across various sectors. Their diverse nutritional compositions makes them valuable in aquaculture, food and other industries. The protein, carbohydrate, and lipid contents of microalgae typically range from 18 to 52%, 18 to 46%, and 12 to 48%, respectively (Zhang et al., 2023; Tibbetts et al., 2017). Most species also contain abundant essential amino acids with high digestibility (>80%) (Tibbetts et al., 2017). Their fatty acid profiles vary, with marine species being rich in monounsaturated fatty acids and freshwater species being rich in polyunsaturated fatty acids. Microalgae are also source of various vitamins, particularly B2 and B3, and pigments such as chlorophyll-a and carotenoids (Zhang et al., 2023). Cultivation conditions, including irradiance and residence time, strongly influence the nutritional composition. Species such as *Isochrysis galbana*, *Dunaliella tertiolecta*, and *Tetraselmis gracilis* have shown promising nutritional profiles (Zhang et al., 2023)that meet the United Nations Food and Agriculture Organization nutritional requirements for adults and children, highlighting their potential for food applications.

Impact of microalgae on fish growth

Microalgae have great potential as sustainable aquafeed ingredients, offering high nutritional value and environmental benefits. Microalgal species, such as *Nannochloropsis salina* and

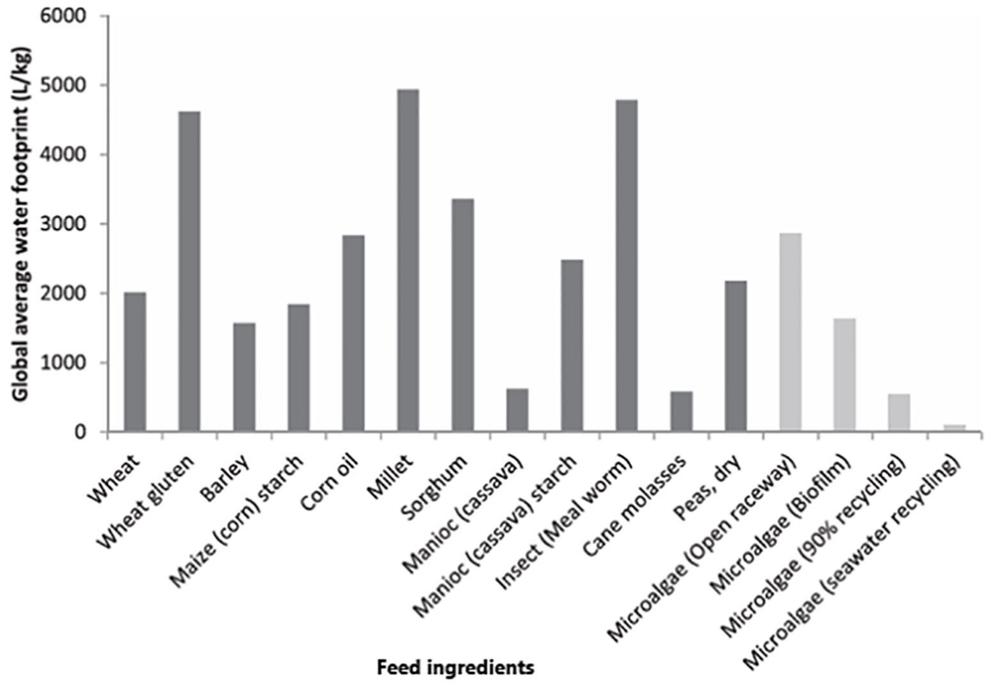

FIGURE 1
Global average water footprint of different aquafeed ingredients. Adapted from Nagappan et al., 2021, licensed CC-BY-4.0.

Dunaliella salina can accumulate substantial lipid and protein contents while fixing carbon dioxide (CO_2) (Chen et al., 2019). While microalgae are often highlighted for their potential to lower the carbon footprint of aquafeed production, current evidence remains limited. Specifically, comprehensive life-cycle assessment (LCA) studies comparing microalgae with conventional feed ingredients such as fishmeal and fish oil are scarce. Further system-level evaluations are needed to substantiate these environmental claims. Nonetheless, the ability of microalgae to fix CO_2 and reduce reliance on fish stocks presents a promising opportunity for developing more sustainable aquafeed strategies. Microalgae are emerging as a sustainable and nutritious alternative to traditional aquafeed ingredients such as fishmeal and fish oil (Nagappan et al., 2021; Ma and Hu, 2024). They offer a high protein content, essential amino acids, omega-3 fatty acids, and bioactive compounds that enhance the growth, colouration, immunity, and survival rates of aquatic species (Dineshbabu et al., 2019; Idenyi et al., 2022). Microalgae play a crucial role in aquaculture by supplying essential nutrients that support the health and growth of fish and shellfish (Kapara, 2018). These microscopic organisms are rich in amino acids, long-chain polyunsaturated fatty acids, vitamins, proteins, and minerals, which are particularly important for enhancing the larval survival, growth, and overall well-being of aquatic species (Siddik et al., 2024). Microalgae are used as live feed for various growth stages of molluscs, crustaceans, and some fish species. Additionally, certain microalgae contain bioactive compounds with antioxidant, anti-inflammatory, and immunomodulatory properties that can improve immunity and disease resistance in farmed aquatic animals (Abdel-Latif et al., 2022). Although microalgae are typically cultivated in-house in hatcheries, commercial concentrates are becoming more widely used. However, the high cost of algal biomass limits its widespread use in commercial aquafeeds (Siddik et al., 2024). Co-cultivation of microalgae with nitrogen-fixing bacteria that release ammonium can significantly reduce the costs of algal biomass. Microalgae are sustainable sources of omega-3 fatty acids, particularly docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA), which are essential for human and animal nutrition (Norzagaray-Valenzuela et al., 2017). These fatty acids provide significant health benefits especially for cardiovascular health and brain function in humans. Since fish oil is the traditional source of these compounds concerns over depletion of global fish stocks has led to an increased interest in alternative sources (Topuz, 2016). Microalgae as primary producers of omega-3 fatty acids can be cultivated at industrial scale and processed into various food products and animal feeds (Norzagaray-Valenzuela et al., 2017). Recent advancements in microalgal biotechnology, such as metabolic engineering and selective breeding, have further enhanced the potential of omega-3 fatty acid production in autotrophic microalgae. As research progresses, microalgal oil is expected to become a viable replacement for fish oil (Topuz, 2016).Among microalgae, *Nannochloropsis* spp., show strong potential as sustainable aquafeed ingredients, capable of replacing fishmeal and fish oil. These species can accumulate high lipid (20–46%) and protein (30–57%) contents while also efficiently fixing carbon dioxide CO_2 (Chen et al., 2020b). They also produce valuable EPA and can be cost-effectively cultivated in solar-powered open ponds (Li et al., 2020). Although *Nannochloropsis* spp. have lower digestibility than *Isochrysis* sp. in rainbow trout, they remain a promising fishmeal substitute (Sarker et al., 2020). Additionally, *Schizochytrium* have shown high digestibility of macronutrients, energy, and fatty acids, particularly DHA, in rainbow trout at both 8°C and 15°C, further supporting its potential as a fish oil substitute in aquafeeds (Bélanger et al., 2021). In Nile tilapia diets, the complete replacement of fish oil with *Schizochytrium* resulted in improved growth, increased feed efficiency, and a higher DHA content in fillets (Sarker et al., 2016).

Schizochytrium supplemented diets have demonstrated higher phosphorus digestibility and lower solid phosphorus discharge in tilapia, indicating potential environmental benefits (Gamble et al., 2021). The optimal inclusion level of *Schizochytrium* in fish feed varies by species, ranging from 20 to 80% fish oil replacement, and has been associated with improved growth, survival, and feed intake across various fish species (Pratiwi and Zidni, 2023). In addition to *Schizochytrium*, *Tetraselmis* spp. have also emerged as promising microalgal ingredients in aquafeeds. For example dietary supplements with *Tetraselmis suecica* has been shown to improve growth performance, feed utilisation, and gene expression in Pacific white shrimp (*Litopenaeus vannamei*) (Sharawy et al., 2020). Furthermore, cultivation of *Tetraselmis striata* has been optimised at both laboratory and pilot scales, yielding biomass rich in proteins, lipids, carbohydrates, pigments and notable high EPA content (Patrinou et al., 2023). *Spirulina*, a cyanobacterium also referred to as blue-green algae, has gained attention as a potential aquafeed ingredient due to its high nutritional value and sustainability (El-Sheekh et al., 2023). It offers a promising alternative to fishmeal, addressing the growing demand for aquaculture feed while reducing environmental impacts (Nagappan et al., 2021). *Spirulina* is rich in proteins, essential amino acids, fatty acids, vitamins, and minerals, making it suitable for use by various aquatic species (Ragaza et al., 2020). In addition, it enhances the innate immunity and disease resistance of fish and shrimp (Rakocy, 2012). Different species of microalgae, such as *Nannochloropsis*, *Schizochytrium*, and *Isochrysis*, have been incorporated into fish diets. In some studies, microalgae-based diets (e.g. *Nannochloropsis* spp. and *Nanochloropsis salina*) resulted in comparable or slightly lower weight gain than the reference diets but showed acceptable growth rates and feed efficiency. Notable exceptions include defatted *Nannochloropsis oculata* and *Schizochytrium* in juvenile Nile tilapia, where the microalgae-based diet resulted in a higher specific growth rate (SGR) and weight gain than the reference diet. *Schizochytrium* spp. fed to Atlantic salmon and Pacific white shrimp resulted in increased weight gain compared with the reference diets, highlighting the high lipid content of microalgae as an effective substitute for fish oil.

Schizochytrium resulted in a higher weight gain (426 g) than fish oil (326 g) in Atlantic salmon (*Salmo salar*) (Wei et al., 2021). Defatted *N. oculata* and *Schizochytrium* sp. diets outperformed the reference diet in terms of weight gain and SGR in juvenile Nile tilapia (*Oreochromis niloticus*) (Ju et al., 2017). Diets with microalgae such as *Schizochytrium* (Allen et al., 2019) have demonstrated competitive growth performance in shrimp (*Litopenaeus vannamei*). Microalgal diets generally maintain feed conversion ratio (FCR) values that are similar to or slightly higher than those of the reference diets. In some cases, a lower FCR (e.g. *Schizochytrium* spp.) for Atlantic salmon indicates efficient feed utilisation. Thus, microalgae show promise as sustainable feed ingredients with growth performance comparable to that of traditional feeds, especially for specific species. Variations in performance suggest that diet formulations need to be species specific and that some microalgae might not completely replace conventional ingredients without compromising efficiency. Data from previous studies support the viability of microalgae as a sustainable alternative to traditional aquafeed, provided that they are tailored to the nutritional needs of the target fish species in aquaponic systems. Table 1 shows the list of microalgae and its effect on fish growth.

Impact of microalgae on plant growth

Studies have shown that the integration of microalgae into aquaponic systems can improve the physicochemical properties of aquaculture water (Addy et al., 2017; Tejido-Nuñez, 2020). Residual fish feed and fish excreta that accumulate in aquaculture water can be used by microalgae to support its growth and biomass production (Delrue et al., 2016). Microalgae cultivation in aquaponics helps to improve water quality by decreasing the pH. Microalgae interactions with bacteria could be the reason for the conversion of fish waste into nutrients, thereby increasing water quality. However, studies on the mechanism of fish waste-to-nutrient conversion through interactions between algae and bacteria are scarce. It has been hypothesised that microalgae facilitate the proliferation of beneficial bacteria and reduce the risk of pathogenic bacteria that could otherwise cause diseases in fish and plants in aquaponic systems. A study evaluating the effects of three microalgal species (*Chlorella vulgaris*, *Scenedesmus* spp., and *Spirulina platensis*), cultivated in an aquaponic system along with Nile tilapia and garlic plants, showed growth similar to that of the control in terms of plant biomass, leaf number, and shoot length. Water quality parameters such as dissolved oxygen, pH, temperature, ammonia, nitrate, and nitrite were maintained at ideal levels for aquaponic systems (Addy et al., 2017; Tejido-Nuñez et al., 2020; Chen et al., 2020a).

A previous study revealed that diverse populations of beneficial microorganisms were significantly higher in fish tanks and biofilters when microalgae were co-cultivated in an aquaponic system. This was a positive outcome owing to the mutual interaction between microalgae and bacteria, which could play an important role in nutrient cycling. Studies have shown that microalgae play a crucial role in atmospheric nitrogen recycling and soil fertility. They can fix atmospheric nitrogen into bioavailable forms like ammonia, particularly through specialized cells called heterocysts in cyanobacteria (Singh, 2021). Many studies have highlighted that bacterial richness is higher in the presence of *Chlorella vulgaris*, which helps in the removal of nitrogen and phosphorus. A stable association between *C. vulgaris* and specific bacterial species such as *Flavobacterium* sp., *Terrimonas* sp., *Sphingobacterium* sp., *Rhizobium* sp., and *Hyphomonas* sp. has been observed (Ramanan et al., 2016; Han et al., 2019). In aquaponic systems, compared with fish tanks, biofilters had a higher bacterial population because they act as a growth substrate for microalgae and bacteria that form biofilm known as a 'phycosphere'. Diverse beneficial bacterial species are attracted to this phycosphere, and this algae–bacteria interaction plays a major role in regulating water quality in aquatic environments. Nitrogen cycling in aquaponic systems occurs because of the presence of the phyla Proteobacteria and Bacteroidetes, which are indicators of the good health status of the system (Schmautz et al., 2017; Wongkiew et al., 2018). Bacteroidetes convert nitrates into various nitrogen compounds that are essential for degrading complex organic matter (Wongkiew et al., 2018). In one study, it was found that Bacteroidetes were more abundant when microalgae were present. Bacteroidetes play a vital role in nutrient cycling and support optimal plant growth in aquaponics (Kasozi et al., 2021). In addition, fish fed microalgae showed resistance to bacterial infection. In a previous study, Nile tilapia fish fed *Spirulina platensis* in an aquaponic system showed lower mortality than the control group. Some studies have shown that microalgae such as *Chlorella vulgaris* can produce the antibacterial compound "chlorellin". Another study showed that when *Spirulina platensis* was given as a feed supplement, the antibacterial compound "phycocyanin" it produces decreased the mortality of Nile tilapia. *Nannochloropsis oculata*, *Schizochytrium* sp., and *Spirulina* sp., the microalgal mix used in Nile tilapia feed, increased immunity against *Vibrio* and *Staphylococcus* bacterial species and enhanced its antioxidant enzyme activity (Falaise et al., 2016). Studies have indicated that purple sulphur bacteria such as those from the genus *Thiobaca* play a key role in the sulphur cycle and were observed to be more abundant in aquaponics water treated with *Chlorella vulgaris*. Studies on iron-reducing bacterial species belonging to the genus *Geothrix* have shown that they oxidise organic compounds by reducing iron (III) to iron (III) oxide, manganese (IV) oxide, and nitrate, thereby preventing the production of environmentally harmful compounds in aquaponic systems. Another study revealed that the bacterial genus *Fusibacter* contributes to the reduction of elemental sulphur, or thiosulfate, to sulphides during the sulphur cycle. Previous studies on the bacterial genus *Treponema* showed that it plays a crucial role in scavenging nutrients through fermentation processes (Buyuktimkin et al., 2019). These biological processes are important for converting fish waste into nutrient solutions in aquaponic systems. In aquaponics, the co-cultivation of microalgae (e.g. *C. vulgaris*, *Scenedesmus* sp., and *Spirulina platensis*) showed better performance of the bacterial genera *Thiobaca*, *Geothrix*, *Fusibacter*, and *Treponema* in terms of nutrient cycling. Further studies on microalgae–bacteria interactions will provide insights into the effects on fish growth and plant development in aquaponics (Schmautz et al., 2021; Kasozi et al., 2021; Bartelme et al., 2019). Microalgae enhance plant growth by acting as biostimulant, biofertilizers, and biopesticides. These properties are due to the presence of bioactive compounds such as phenols, phytohormones, amino acids, polysaccharides, and terpenoids (Lee and Ryu, 2021). Although microalgae play an important role in nutrient uptake and cycling, it's the cyanobacteria often referred as blue green algae that are responsible for nitrogen fixation. Microalgae can mobilize nutrients like phosphate, potassium, and copper Win et al., 2018; Gonçalves, 2021). Another essential micronutrient molybdenum (MO) is a key cofactor for two enzymes: nitrogenase (in nitrogen-fixing microbes like diazotrophs or cyanobacteria) and nitrate reductase (in microalgae and plants). These enzymes are essential for converting atmospheric nitrogen (N_2) into ammonium and nitrate (NO_3^-) into usable nitrogen forms, respectively. In integrated aquaponics systems where microalgae or nitrogen-fixing bacteria are involved, the presence of trace levels of Mo ensures these microbes can effectively perform biological nitrogen fixation and nitrate assimilation (Glass et al., 2012).

Microalgae, particularly cyanobacteria, have a specific mechanism for fixing nitrogen. Cyanobacteria, such as *Cyanothece* spp., *Lyngbya* spp., and *Trichodesmium* spp., colonise the leaves and roots of plants, penetrate cell tissues, and colonise internally with plant host specificity. Microalgae produce enzymes such as alkaline phosphatases, 5'nucleotidases, phytases, and phosphodiesterases that help to release bound phosphorus from organic sources such as phytate. Some species such as *Tetraselmis suecia*, *Nannochloropsis gaditana*, and *Nanochloropsis oceania* adopt a luxury uptake mechanism to store excess or relocate phosphorus by remodelling polar lipids (Cañavate et al., 2017). Microalgal species, such as *Spirulina platensis*, *Chlorella* spp., *Scenedesmus* spp., *Acutodesmus* spp., *Calothrix elenkini*, and *Dunaliella* spp (Ronga et al., 2019; Colla and Rouphael, 2020), enhance crop production by improving nutrient uptake, enhancing resistance to both abiotic and biotic stress, and maintaining essential functions such as respiration, photosynthesis, nucleic acid synthesis, and iron uptake (Lee and Ryu, 2021; Kumar et al., 2022).

Microalgae synthesise phytohormones that play important roles in shoot and root development, plant tissue differentiation, aging, and defence against biotic and abiotic stressors. Studies on microalgal species, such as *Coenochloris* spp., *Chlorella* spp., *Scenedesmus* spp., *Chlorococcum* spp., and *Acutodesmus* spp., have shown that they can synthesise auxin hormones, such as indol-3-acetamide and indole 3-acetic acid, which play roles in the formation and elongation of plant roots (Kapoore et al., 2021). Microalgae that synthesise auxins form colonies with cyanobacteria, which has been observed in wheat and rice plants (Hussain et al., 2017). Recent studies have revealed that the green alga *Chlamydomonas reinhardtii* can synthesize auxin (indole-3-acetic acid, IAA) through an extracellular L-amino acid oxidase (LAO1) under nitrogen-limited conditions (Calatrava et al., 2022). This auxin production plays a role in algal-bacterial mutualism, particularly with Methylobacterium species. *Nannochloropsis* spp. synthesise cytokinin phytohormones that enhance resistance to nitrogen and water stress in tomato plants. Studies on *Chlorella* *vulgaris* extracts containing gibberellic acid phytohormones suggest that the extract could mitigate the harmful effects of heavy metals, such as lead and cadmium, on plant growth. Microalgae belonging to the genera *Chlorella*, *Chlamydomonas*, and *Scenedesmus*, and cyanobacteria including *Anabaena* spp., *Synechococcus* spp., *Calothrix* spp., *Nostoc* spp., *Cylindrospermum* spp., and *Scytonema* spp., have been reported to synthesise ethylene phytohormones that regulate cell division, fruit ripening, aging, and biotic and abiotic stress tolerance (Han et al., 2018). Microalgae can synthesise signalling molecules, such as jasmonic acid, polyamines, brassinosteroids, and salicylic acid, which are associated with stress-tolerance mechanisms that enhance enzymatic and non-enzymatic defence responses in plants (Kapoore et al., 2021; Lee and Ryu, 2021). Some studies have reported that *Spirulina* can produce polyamines which promote the growth of lettuce seedlings (Mógor et al., 2018). Studies on microalgae, such as *Chlorella stigmatophora*, *Chlorella vulgaris*, *Tetraselmis* spp., *Dunaliella salina*, and *Porphyridium cruentum*, have shown that microalgae can synthesise exopolysaccharides (EPS) which stimulate plant growth and metabolism (Chanda et al., 2019). El Arroussi et al. (2018) reported that EPS from *Dunaliella saline* microalgal species enhanced salinity stress tolerance in tomato plants. Studies on protein-rich extracts of *Spirulina platensis* have revealed increased flower number, freshness, and dry weight in *Petunia x hybrida* plants (Plaza et al., 2018). Green algal extracts rich in amino acids enhanced the total solid and organic contents of three hot pepper varieties (Zamljen et al., 2021). Some microalgal species also synthesise phenolic compounds and carotenoids, which support photoprotection and defence responses in plants (Vidyashankar et al., 2017; Cezare-Gomes et al., 2019; Del Mondo et al., 2021). Some microalgae species are a good source of micronutrients, such as calcium,, iron, zinc, a and magnesium (Sandgruber et al., 2021). *Tetraselmis chuii* is rich in total calcium and phosphorus, *Chlorella* has high phosphorus and iron contents, and *Spirulina* is rich in potassium. Microalgae synthesize vitamins that act as plant growth promoting factors. Vitamin C and nicotinic acid are abundant in *Tetraselmis suecia*. Freshwater microalgae, such as *Spirulina platensis* and *Chlorella* spp., are rich in vitamins such as niacin, riboflavin, cyanocobalamin, and folic acid (Edelmann et al., 2019). Studies have shown that plants like soybean, barley, and spinach absorb vitamin B complex when microalgal biomass is applied as biofertilizer. In addition to vitamins and minerals, microalgae produce terpenoids, betaines, humic substances, and peptides that function as biopesticides (Kapoore et al., 2021). Table 2 shows the list of microalgae and its effect on plant growth.

Integration of microalgae in aquaponics

Microalgae serve as excellent nutrient sources for aquatic organisms, providing proteins, omega-3 fatty acids, vitamins, and minerals. They also play crucial roles in water quality management, larviculture, and Integrated Multi-Trophic Aquaculture (IMTA) systems (Hashmi et al., 2023). Algaeponics is a recent innovation in the field of aquaponics (Nair et al., 2025) and it is a novel extension of conventional aquaponics that incorporates microalgae as an integral biological component within the system. Unlike standard aquaponics—where fish waste provides nutrients for higher plants—algaeponics uses microalgae to recycle nutrients, improve water quality, and serve as a supplementary or primary feed source for fish (Zhang et al., 2022). Microalgae enhance aquaponic systems by supporting nutrient removal, improving water quality, and serving as feed for fish like tilapia (Edwards et al., 1981; Kinh et al., 2024). Factors such as fish density, food-to-microorganism ratio (F/M), and hydraulic retention time (HRT) influence algal integration and system stability (Medina and Neis, 2007). While species like *Chlorella* sp. aid in ammonia control and pH balance, their growth may be limited in systems optimized for fish and plant productivity (Addy et al., 2017). Microalgae can interact with nitrogen fixing bacteria called diazotrophs that could possess combined biotechnological applications in a sustainable production system. In aquaponics systems, integrating microalgae with nitrogen-fixing bacteria (diazotrophs) offers a promising, sustainable way to enhance nutrient cycling, water quality, and productivity. While microalgae contribute to carbon fixation, oxygenation, and biomass production, diazotrophs help convert atmospheric nitrogen into plant-available forms like ammonium. Together, they can naturally supplement nitrogen when fish waste is insufficient, reduce the need for synthetic inputs, and support plant growth through biofertilization. Additionally, the protein-rich algal biomass can be harvested and reused as fish feed, creating a closed-loop system that improves efficiency, reduces operational costs, and boosts environmental resilience (Llamas et al., 2023).

Microalgae added to aquaponic systems in the form of aquafeeds is shown in Figure 2, as they can act as an essential food source for fish, but in-depth research is necessary to determine their potential benefits for plant growth in aquaponic systems. Microalgae can effectively remediate aquaculture water acting as nutrient recyclers while producing valuable biomass (Dourou et al., 2020; Han et al., 2019). This integration reduces environmental impacts, improves water quality, and provides a sustainable source of aquafeed (Han et al., 2019). Upscaling the production of microalgae can lead to improved resource efficiency and a reduced carbon footprint. Recent advances in recirculating aquaculture systems (RAS) have focused on incorporating microalgae to close the system loop, thereby enhancing performance and deriving value from waste streams. Microalgae in RAS facilitate oxygenation, carbon dioxide sequestration, and nutrient recovery (Ende et al., 2024). Various cultivation systems, harvesting technologies, and species selection strategies have been explored to optimise microalgae-assisted aquaculture (Han et al., 2019). Microalgal biomass production has a water footprint of 2857 L/kg when using freshwater. This footprint can be reduced considerably by employing wastewater or seawater or recycling growth media, with recycling potentially lowering the footprint by

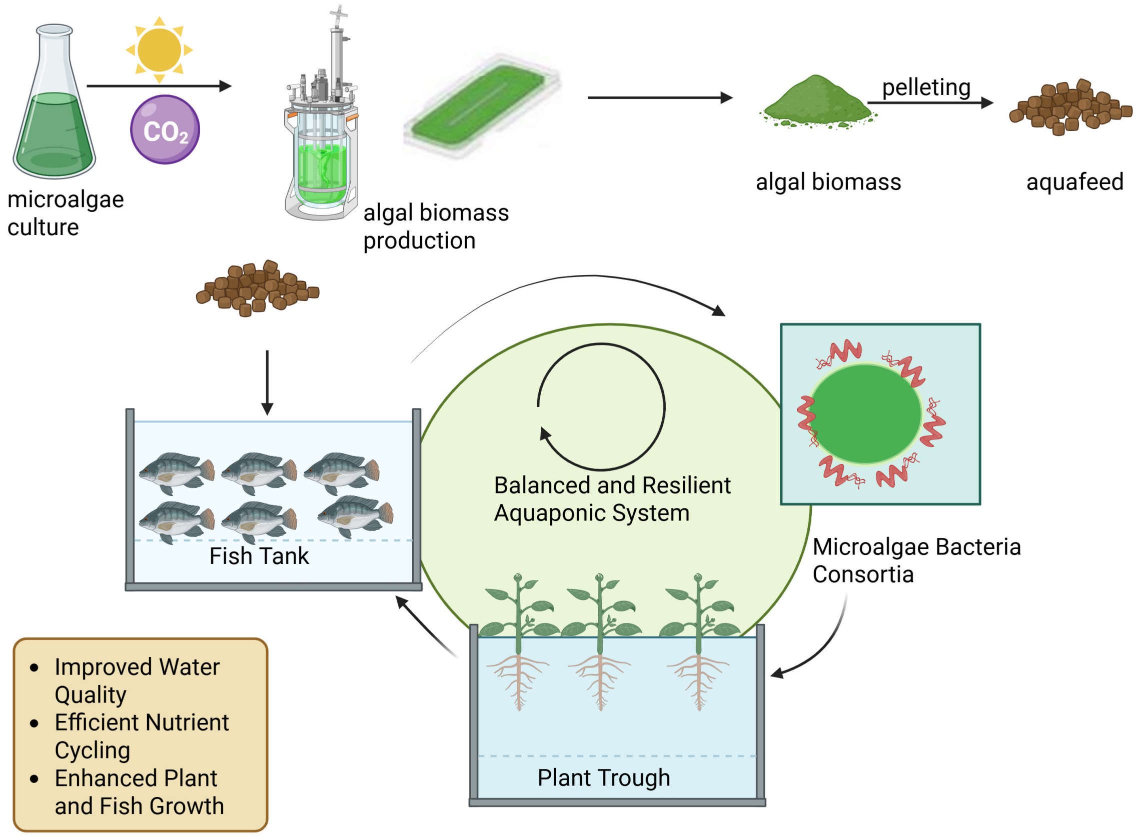

FIGURE 2
Schematic representation of microalgae contributions to Sustainable Aquaponics: From Biomass Cultivation to Aquafeed.

90% (Pugazhendhi et al., 2020). Compared with plant and insect production, microalgae production has a lower water footprint. In open cultivation systems, evaporation is a major contributor to water loss, with evaporation rates reaching up to 2 cm/d in 20 cm deep raceway ponds (Das et al., 2016). Cultivating microalgae using wastewater for human consumption raises legitimate food safety concerns. These concerns stem from the potential accumulation of harmful substances, including heavy metals, pathogens, and emerging contaminants (Markou et al., 2018; Álvarez-González et al., 2023). While treatment processes such as anaerobic digestion can significantly reduce biological and chemical risks, the persistence of certain xenobiotics remains a challenge. Currently, the legal frameworks in most regions—including the European Union—do not support the use of such biomass in food products. However, some studies indicate that treated microalgal biomass may be suitable for non-food applications, such as fertilizers and aquafeed, although elements like cadmium can still exceed allowable limits (Álvarez-González et al., 2023). Continued research and clearer regulatory guidance are essential as the industry evolves (de Oliveira and Bragotto, 2022; Salehipour-Bavarsad et al., 2024).

Major challenges in microalgae cultivation is its biomass productivity which is highly variable due to numerous cultivation factors such as light intensity and spectrum, nutrient availability, temperature, and strain-specific physiological differences. Light is a key determinant, with suboptimal intensity, poor spectral quality, and inefficient distribution significantly reducing photosynthetic efficiency, especially in dense cultures and closed photobioreactors (Ooms et al., 2016; Nwoba et al., 2019). Nutrient limitations, particularly of nitrogen and phosphorus, can both constrain growth and stimulate desired metabolite accumulation, but must be precisely managed to balance productivity and product quality (Chu, 2017). Additionally, different microalgal strains respond uniquely to environmental conditions, making strain selection critical for consistent biomass yield and target compound production (Štěrbová et al., 2023). Innovations such as spectral conversion, temperature control strategies, genetically modified strains, and advanced photobioreactor designs aim to mitigate these inconsistencies and improve biomass uniformity and scalability (Nwoba et al., 2019; Zhang et al., 2024).Freshwater is often required to counteract evaporation and maintain salinity for marine microalgae. However, certain halotolerant microalgal strains (e.g. *Dunaliella* sp., *Tetraselmis* sp., and *Picochlorum* sp.) can adapt to salinity changes, thereby reducing freshwater use and lowering the overall water footprint (Das et al., 2019). Microalgae show potential as sustainable alternatives to fish-based aquafeed in addressing the growing demand for high-quality proteins (Tham et al., 2023; Yarnold et al., 2019). Integrating microalgae cultivation with aquaculture, agriculture, aquaponics, and livestock farming could create a circular bioeconomy based on recycling nutrients and wastewater. This approach offers environmental benefits, resource recovery, and potential socioeconomic improvements in rural areas. However, challenges remain, including developing large-scale production methods and addressing energy-intensive harvesting and processing methods. Some studies have shown that freshwater microalgae like spirulina might contain contaminants like microcystins (MCs) which have raised increasing concern due to their potential health risks. Spirulina, a cyanobacterial supplement —has been examined for safety, especially in France where over 180 small-scale farms contribute to local production. A review of data from 95 producers between 2013 and 2021, showed that MCs levels generally remained within safe limits. These findings support the relative safety of French spirulina and other microalgae while emphasizing the importance of refining cultivation practices to prevent contamination (Scoglio, 2018; Pinchart et al., 2023). Further research on life cycle assessment and pilot-scale demonstrations is needed to establish the feasibility and sustainability (Figure 3) of integrating algae-based systems into aquaculture, aquaponics, and related sectors (Vishwakarma et al., 2022).

Conclusion

Aquaponics holds immense potential to address global food and nutrition security challenges by integrating fish and plant production in a sustainable manner. However, one of the key limitations of current systems lies in the inefficient conversion of fish effluent into complete nutrient solutions for plant growth, often necessitating external fertiliser inputs. Recent studies suggest that microalgae could offer a promising solution to this bottleneck by serving dual roles as functional aquafeed for fish and as biostimulants or biofertilizers for plants. Certain species, such as *Spirulina* and *Chlorella*, have demonstrated benefits in nutrient recycling, water purification, and enhancement of fish health and plant biomass. While some microalgae species needs to be optimised for its application as aquafeed. Despite these promising insights, the research on microalgae as sustainable aquafeed in aquaponics system remains fragmented and limited in scope. Most existing studies are either species-specific or focused on isolated benefits rather than on integrated system-wide performance. Additionally, the long-term stability, scalability, and economic viability of incorporating microalgae in aquaponics remain underexplored. Future research should aim to systematically evaluate a broader range of microalgal species in aquaponic settings, including their interactions with microbial communities, effects on nutrient dynamics, and their contribution to overall

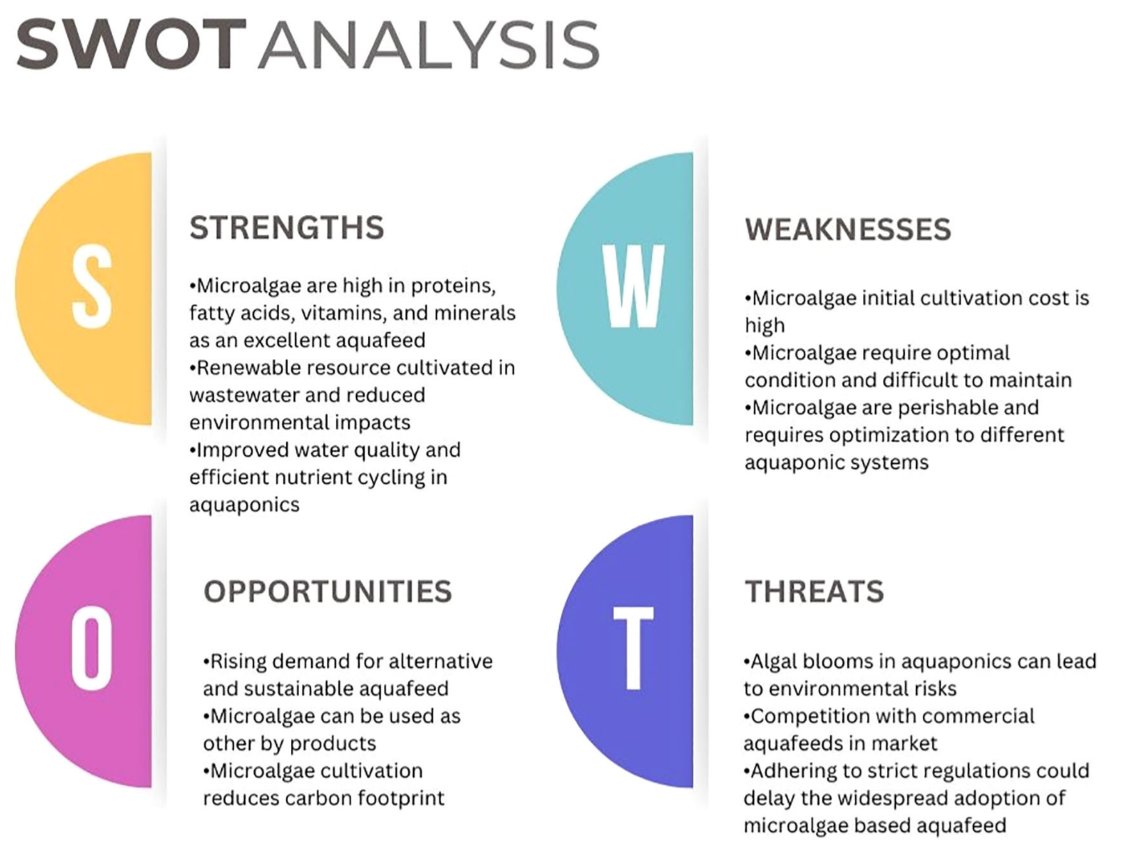

FIGURE 3
SWOT analysis of microalgae-based aquafeed in aquaponic systems.

TABLE 1 Effect of microalgae on fish growth.

Microalgae	Fish species	Effect	Reference
Schizochytrium sp.	Nile tilapia (*Oreochromis niloticus*)	Improved gut health	Souza et al., 2020
Euglena sp.	Atlantic salmon	Immunostimulant	Kiron et al., 2016a, b; Montoya et al., 2017; Yamamoto et al., 2018
Schizochytrium sp.	Atlantic salmon	Enhanced fillet firmness	Kousoulaki et al., 2016
Spirulina sp.	Red tilapia, Koi, Striped jack, Black tiger prawn, and yellow catfish	Enhanced coloration	Ansarifard et al., 2018; Dineshbabu et al., 2019; Liu et al., 2021
2.5% *Phaeodactylum tricornutum*	Gilthead seabream	High fucoxanthin content	Ribeiro et al., 2017
Arthrospira platensis	Freshwater prawns (*Macrobrachium rosenbergii*)	Enhanced growth performance	Radhakrishnan et al., 2016
5% *Schizochytrium* sp. oil	Atlantic salmon (*Salmo salar L.*)	Weight gain	Wei et al., 2021
0.75% *Tetraselmis suecica*	Post larvae pacific white shrimp (*Litopenaeus vannamei*)	30% weight gain	Sharawy et al., 2020
15% *Chlorella* sp.	Nile tilapia (*Oreochromis niloticus*)	30% reduction in FCR (feed conversion ratio)	Fadl et al., 2020
Nannochloropsis gaditana	African catfish and Nile tilapia	Improved weight gain and FCR	Agboola et al., 2019
Spirulina-based fish feed	Mozambique tilapia fingerlings (*Oreochromis mossambicus)*	Improved digestibility	Sharma et al., 2021
Nannochloropsis sp.extruded feed	Gibel carp	Improved digestibility	Shi et al., 2016
Pavlova sp., *Chaetoceros* sp., *Nannochloropsis ocu lata*, and *Isochrysis* sp., in feed,	Seahorses *(Hippocampus reidi)* and Oysters *(Pinctada margaritifera)*	Increased survivability	Martínez-Fernández and Southgate, 2007; Mélo et al., 2016
1-2% *Dunaliella salina* supplemented feed	*Litopenaeus vannamei*	Increased survival rate	Medina-Félix et al., 2014
Tetraselmis suecica live cells	White shrimp (*Fenneropenaeus indicus*	Reduced gut pathogenic bacterial load	Regunathan and Wesley, 2004
Microencapsulated *Chaetoceros* sp.	Pacific white shrimp *(Lito penaeus vannamei)*	Survivability at larval stage increased	Nimrat et al., 2011
Paramylon in *Euglena* sp. cell wall	Atlantic salmon, mussels, red drum, and matrinxa	Immunostimulant	Bianchi et al., 2015; Kiron et al., 2016a, b; Montoya et al., 2017; Yamamoto et al., 2018
6-8% of *Chlorella vulgaris*	Post larvae of *Macrobrachium rosenbergii*	Improved immune response and survivability agiangst *Aeromonas hydrophila* infection	Maliwat et al., 2017
Tetraselmis chuii, Nanno chloropsis gaditana, and *P. tricornutum*	Gilthead seabream *(Sparus. aurata)*	Enhanced defence activity	Cerezuela et al., 2012
Euglena viridis	Rohu fish *(Labeo rohita)*	Increased immunostimulatory effects	Das et al., 2009
Dunaliella salina	*Penaeus monodon*	Increased antioxidant factors and survival rate	Madhumathi and Rengasamy, 2011
Fish diet with *Lactobacillus sakei* and *Navicula* sp.	Pacific red snapper *(Lutjanus peru)*	Improved humoral response	Reyes-Becerril et al., 2013
Feed with *Prunus incisa*	Guppy fish (*Poecilia reticulata)*	Increased survival rate	Nath et al., 2012
10% *A. Platensis* diet	Rainbow trout *(Oncorhynchus mykiss)*	Increased in total proteins level	Yeganeh et al., 2015
5% *Schizochytrium* sp.	Atlantic salmon	Improved fillets quality	Kousoulaki et al., 2016
Schizochytrium limacinum	Atlantic salmon	Improved fillets taste and odour	Katerina et al., 2020

(Continued)

TABLE 1 Continued

Microalgae	Fish species	Effect	Reference
Schizo chytrium sp.	Atlantic salmon	Rich in PUFA (polyunsaturated fatty acids)	Ren et al., 2010
4% defatted-*Spirulina* and 0.4% *Spirulina*-lipid-ex tract	Yellow catfish *(Pelteobagrus fulvidraco)*	Improved skin colour	Liu et al., 2021
7.5% *Spirulina platensis*	Showa koi	Improved pigmentation	Sun et al., 2012

TABLE 2 Effect of microalgae on plant growth.

Microalgae	Plant species	Effect	Reference
Spirulina platensis	*Raphanus sativus*	Enhanced germination rate and seedling vigour	Godlewska et al., 2019
Chlorella vulgaris	*Solanum lycopersicum* L., *Cucumus sativus*	Improved root parameters, increased biomass yield	Bumandalai and Tserennadmid, 2019
Scenedesmus quadricauda, *Chlorella vulgaris*, *Arthrospira* spp.	*Beta vulgaris* L.	Improved root parameters, enhanced biomass and nutritional quality	Barone et al., 2018;
Navicula spp.	*Solanum lycopersicum* L., *Capsicum annuum* L., *Solanum melongena*	Enhanced biomass	Alshehrei et al., 2021
Oscillatoria agardhii	*Triticum* spp.	Drought tolerance	Haggag et al., 2018
Chlorella vulgaris, *Nannochloropsis salina*	*Moringa oleifera*	Salinity tolerance	Al Dayel and El Sherif, 2021
Chlorella vulgaris	*Vigna mungo* L.	Enhanced growth (acts as a biostimulant)	Dineshkumar et al., 2019
Spirulina extract	*Triticum aestivum, Hordeum vulgare*	Enhanced germination and biomass yield	Akgül, 2019
Spirulina platensis extract	*Calotropis procera* Ait	Improved root growth and germination rate	Bahmani Jafarlou et al., 2021
Spirulina platensis extract	*Vigna mungo* L.	Enhanced germination, nutritional content, root growth, biomass and stress tolerance	Thinh, 2021
Spirulina platensis Phycocyanin extract	*Solanum lycopersicum* L.	Increased biomass, nutritional content, and germination	Metwally et al., 2022
Chlorella spp. Cell suspension	*Triticum aestivum, Hordeum vulgare*	Enhanced root development, biomass and germination rate	Odgerel and Tserendulam, 2016
Nostoc commune aqueous extracts	*Oryza sativa* L.	Enhanced root development, biomass and germination rate	Abedi Firoozjaei et al., 2021
Scenedesmus quadricauda and *Chlorella vulagaris* extract	*Beta vulgaris*	Improved seed vigour and root growth	Puglisi et al., 2020
Consortia of *Chlorococcum* spp. *Micractinium* spp. *Scenedesmus* spp. *Chlorella* spp.	*Spinacia oleraceae*	Enhanced biomass, nutritional content and germination rate	Rupawalla et al., 2022
Scenedesmus subspicatus	*Allium cepa* L	Improved root development	Gemin et al., 2022
Chlorella vulgaris biomass with cow dung	*Solanum lycopersicum* L.	Enhanced root growth, leaf phytochemical content, soil, enzyme activity and stress tolerance	Suchithra et al., 2022
Chlorella vulgaris extract	*Lactuca sativa*	Increased crop yield, leaf pigment content, fruits, flowers numbers and nutritional quality	La Bella et al., 2021
Chlorella vulgaris	*Brassica oleracea* var. italica	Enhanced leaf pigments, stress tolerance, enzymatic activity, early flowering	Kusvuran, 2021
Chlorella vulgaris extract	*Latuca sativa* L.	Increased enzymatic activity, early flowering, nutritional quality	Puglisi et al., 2022

(Continued)

TABLE 2 Continued

Microalgae	Plant species	Effect	Reference
Cell lysates of *Chlamydomonas reinhardtii* CC124 *Chlorella* sp. MACC360	*Solanum lycopersicum* L.	Improved crop yield, enzymatic activity, number of fruits, early flowering	Gitau et al., 2022
Polysaccharides extract of *Dunaliella salina* MS002 and MS067 *Phaeodactylum tricornotum* MS023 *Porphyridium* spp.MS081, *Desmodesmus* spp. *Spirulina platensis* MS001	*Solanum lycopersicum* L.	Enhanced nutritional quality and stress tolerance	Rachidi et al., 2021
Extracts of microalgae consortium *Chlorella* spp., *Scenedesmus* spp., *Spirulina* spp., *Synechocystis* spp	*Solanum lycopersicum* L.	Increased biomass, leaf pigment content, nutritional quality	Hans et al., 2020
Chlorella vulgaris	*Cyamopsis tetragonoloba* (L.) Taub.	Early flowering, improved nutritional quality and stress tolerance	Kusvuran and Can, 2020
Polysaccharide extracts of *Chlorella vulgaris, Chlorella Sorokiniana*	*Solanum lycopersicum* L.	Early flowering, increased enzymatic activity and stress tolerance	Farid et al., 2019
Scenedesmus spp.extract, *Arthrospira platensis* cell hydrolysate	*Petunia x hybrida*	Enhanced crop yield, nutritional quality	Plaza et al., 2018
Scenedesmus obliquus Chlorella vulgaris and *Anabaena oryzae* biomass	*Musa* spp.	Improved root growth, leaf phytochemical content, soil quality, stress tolerance	Hamouda and El-Ansary, 2017
Chlorella fusca	*Cucumis sativus Arabidopsis thaliana*	Stress tolerance	Kim et al., 2018; Lee et al., 2020

system productivity and resilience. Moreover, multidisciplinary approaches combining aquaculture, plant science, and microbial ecology are needed to optimise microalgae integration. By addressing these knowledge gaps, aquaponics can evolve into a more self-sustaining, circular food production system capable of meeting future global demands.

Author contributions

RM: Conceptualization, Writing – original draft, Visualization. CS: Data curation, Writing – review & editing. DN: Data curation, Writing – review & editing. RS: Writing – review & editing. ZA: Writing – review & editing. LR: Writing – review & editing. X-LX: Writing – review & editing. M-ZR: Writing – review & editing. AJ: Writing – review & editing, Funding acquisition.

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