Review
Aquatic Life Sciences

Multifunctional Roles of Microalgae in Sustainable Aquaculture: Nutrition, Live Feed, Bioremediation, and Carbon Sequestration

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Abstract: As global aquaculture rapidly expands, ensuring ecological and economic sustainability requires a transition toward circular economy solutions. Microalgae have emerged as highly adaptable primary producers capable of addressing both aquaculture nutritional deficits and environmental waste. This systematic review synthesizes 71 peer-reviewed papers published between 2000 to 2025 indexed in PubMed and Google Scholar to evaluate the integration of microalgal biomass across modern aquaculture systems. Quantitatively, microalgae, yield substantial dry cell weight concentrations containing 12–65% proteins, 2–23% lipids, and 5–26% carbohydrates, serving as highly nutritious direct feeds or live prey enrichers that enhance larval growth, survival, and coloration. Currently, their high photosynthetic efficiency drives ecological remediation; 1kg of microalgal biomass sequesters approximately 1.83 kg of CO_2, while their mixotrophic and autotrophic pathways achieve up to 99% removal of hazardous wastewater nutrients like inorganic nitrogen and phosphorus. By evaluating these functional benefits alongside key techno-economic bottlenecks such as species selection methods and harvesting costs this review establishes an integrated frame work for leveraging microalgae to achieve sustainable, eco-friendly global aquaculture.

Introduction

Global aquaculture has expanded dramatically over the past few decades, growing from 20 million tons in 1970 to 88 million tons in 2020, and it is projected to supply 62% of all fish from human consumption by 2030 (1, 2). This rapid intensification is driven by a growing global population's need for nutrient-rich functional foods to improve health and secure food supplies (3). However, the industry's long-term sustainability is severely threatened by its heavy reliance on expensive and ecologically unsustainable commercial aquafeeds (4). Furthermore, aquatic ecosystems face escalating pressure from industrial, agricultural, and municipal pollution which introduces hazardous heavy metals, hydrocarbons, and chemical contaminants into the environment (5). To maintain global food security without competing with traditional agriculture for arable land, the aquaculture sector must transition toward innovative, circular-economy solutions that simultaneously address nutritional shortages and environmental degradation (3).

Microalgae represent a highly adaptable, diverse group of photosynthetic microorganisms ubiquitous in aquatic ecosystems that serve as primary producers and sustainable biomass sources to bridge these industry gaps (6, 7). Utilizing versatile metabolic modes including photoautotrophy, heterotrophy, and mixotrophy microalgae accumulate profound nutritional profiles containing up to 60% protein, 60% carbohydrates, or 70% lipids depending on species and growth conditions (6, 8). Because they consistently yield dry cell weight concentrations of 12-65% protein, 2-23% lipid, and 5-26% carbohydrate, they function as essential direct or indirect feeds for wild fish, larval aquatic organisms, and live prey vectors such as rotifers, Artemia, and Copepods (6, 9). Beyond their primary nutritional value and rich array of bioactive secondary metabolites (such as pigments, PUFAs, and immunostimulants (3, 8), microalgae offer vital ecological services. Their photosynthetic efficiency exceeds that of terrestrial crops by 40-50%, enabling them to reclaim wastewater, mitigate pollution, and drive substantial carbon capture, with 1 kg of microalgal biomass absorbing approximately 1.83 kg of CO_2 (3, 10).

Despite this profound dual potential as both a high value aquafeed alternative and an environmental remediation agent, widespread commercial integration remains constrained. The ultimate economic viability and production effectiveness of microalgae depend heavily on establishing optimized cultivation approaches whether photoautotrophic, heterotrophic, or mixed and developing cost-effective harvesting systems (6, 11). While past

research has documented their widespread applications across the food, pharmaceutical, and biofuel sectors (3, 9), a consolidated evaluation targeting their integrated roles in modern aquaculture is required.

Despite this profound dual potential as both a high value aquafeed alternative and an environmental remediation agent, widespread commercial integration remains constrained. Whilst past literature reviews have documented the isolated applications of microalgae within independent sectors such as standalone biofuel production, basic human nutraceuticals, or generic wastewater treatment (3, 9) prior reviews have overlooked the operational, biological, and technical integration of these roles within a closed loop aquaculture circular economy. Specifically, the field lacks an assessment that bridges real world biological performance (e. g. specific nutritional yields and phycoremediation capacities) with concrete techno-economic realities (CAPEX/OPEX constraints and processing bottlenecks). To bridge this research gap, this systematic review establishes an integrated framework that address how microalgal biomass can simultaneously function as a nutritional feedstock and a bioremediation agent without compromising economic viability.

The specific objectives of this review are to: (i) quantify and map specific microalgal species to their dual roles as larval feed/enrichers and wastewater remediation agents; (ii) evaluate regulatory frameworks governing microalgae in the global food chain; and (iii) synthesize techno-economic data to deliver an optimized structural framework for viable, closed-loop microalgal aquaculture systems.

Methodology

Search Strategy and information Sources

To ensure a comprehensive and reproducible collection of relevant literature, a systematic search was conducted across the PubMed and Google Scholar databases, covering the time frame from 2000 to 2025. The search strategy targeted literature tracking the multifunctional applications of microalgae within aquaculture frameworks following (12). Specific Boolean operators and search strings were deployed, including microalgae role in aquaculture, aquaculture, live feed and aquafeed, phycoremediation, wastewater treatment, carbon sequestration and carbon dioxide fixation of microalgae. To minimize publication bias, reference lists of retrieved review articles were manually screened to identify additional relevant primary studies.

Inclusion and Exclusion Criteria

Studies were screened based on strict, predefined inclusion and exclusion criteria to ensure data integrity and alignment with the review's core objectives. To be included, studies had to: (i) be peer-reviewed, primary research articles or book chapters published in English between 2000 and 2025; (ii) explicitly quantify microalgae dynamics such as nutritional yields and pollutant removal rates within aquaculture systems; and (iii) evaluate at least one primary functional mode, specifically live feed/supplements, phycoremediation or carbon capture. Studies were excluded if they: (i) focused exclusively on terrestrial agricultural applications, wild marine ecosystems without aquaculture context, and standalone biofuel engineering lacking a circular aquaculture component; (ii) consisted of grey literature, conference abstracts and non-peer-reviewed reports; (iii) lacked quantifiable quantitative metrics.

Screening Process and Study Selection (PRISMA Framework)

The study selection process strictly followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (12, 71). The initial database search yielded a total of 1240 records. After removing duplicates (n= 410), the remaining 830 record were screened by title and abstract, resulting in the exclusion of 690 record that did not meet the core topic criteria. The full texts of the remaining 140 articles were thoroughly assessed for eligibility. Out of these, 69 articles were excluded due to missing quantitative data, irrelevance to aquaculture circular economics, and structural baseline deviations. Ultimately, 71 primary papers met all criteria and were synthesized into the final review.

Data Extraction, Synthesis, and Quality Assessment

Data extraction was systematically organized into standardized matrices focusing on technical components, microalgae species, application benefits, and techno-economic implications (CAPEX/OPEX). For each included study, scientific metrics were extracted: microalgae taxonomic classification, nutritional dry weight configurations (protein and lipid percentages), pollutant removal efficiencies (N and P removal percentages), and carbon dioxide fixation capacities.

Concurrently, a qualitative risk-of-bias and quality and quality assessment was conducted on the primary studies, evaluating baseline parameters such as experimental control validity, replication adequacy, and method transparency. Studies exhibiting high methodological ambiguity were omitted. The final data synthesis employed a narrative and tabular synthesis approach, grouping findings into four core thematic quadrants: direct/indirect larval nutrition, greenwater cultivation dynamics, wastewater phycoremediation mechanisms, and techno-economic boundary constraints.

Taxonomic Classification and Global Regulatory Frameworks

Microalgal groups possess unique structural, evolutionary, and biochemical profiles that dictate their suitability for commercial aquaculture. Eukaryotic Chlorophyta (*Chlorella*, *Dunaliella*, and *Haematococcus*) are widely utilized due to their high accumulation of pigments and antioxidants. Conversely, Diatoms (Bacillariophyta) feature distinct silica-based cell walls which, while offering valuable omega-3 fatty acids, introduce mechanical processing limitations that restrict direct whole cell ingestion for certain delicate larval classes. This starkly contrasts with prokaryotic cyanobacteria like *Spirulina*, whose peptidoglycan-based cell walls lack rigid cellulose, providing an easily digestible texture ideal for direct, unprocessed whole-biomass utilization (2).

Despite their profound biological benefits, widespread entry into the global food chain remains

Table 1. Regulatory approvals for microalgae/cyanobacteria in human consumption.

Approval institution/Authority	Approved Species	References
U. S. Food and Drug Administration (FDA) Generally, Recognized as Safe (GRAS Status)	*Arthrospira* sp., *Chlorella* sp., *Dunaliella* sp., *Haematococcus pluvialis*	(13)
European Food safety Authority (EFSA) (Novel Food Regulation EU 2015/2283)	*Aphanizomenon flos-aquae*, *Arthrospira platensis*, *Chlorella vulgaris*, *Tetraselmis chuii*, *Haematococcus pluvialis*	(13)

Table 2. Major classes/genera of microalgae in aquaculture.

Class	Genus	Examples of application
Bacillariophyceae	*Skeletonema*	PL, BL, BP
	Thalassiosira	PL, BL, BP
	Phaeodactylum	PL, BL, BP, ML, BS
	Chaetoceros	PL, BL, BP, BS
	Cylindrotheca	PL
	Bellerochea	BP
	Actinocyclus	BP
	Nitzschia	BS
	Cyclotella	BS
Haptophyceae	*Isochrysis*	PL, BL, BP, ML, BS
	Pseudoisochrysis	BL, BP, ML
	Dicrateria	BP
Chrysophyceae	*Monochrysis* (*Pavlova*)	BL, BP, BS, MR
Prasinophyceae	*Tetraselmis* (*Platymonas*)	PL, BL, BP, AL, BS, MR
	Pyramimonas	BL, BP
	Micromonas	BP
Cryptophyceae	*Chromonas*	BP
	Cryptomonas	BP
	Rhodomonas	BL, BP
Chlorophyceae	*Chlamydomonas*	BL, BP, FZ, MR, BS
	Chlorococcum	BP
	Carteria	BP
	Dunaliella	BL, BP
Xanthophyceae	*Olisthodiscus*	BP
Cyanophyceae	*Spirulina*	PL, BP, BS, MR

Source: (22).
Abbreviations: PL - penaeid shrimp larvae; BL - bivalve mollusk larvae; ML - freshwater prawn larvae; BP - bivalve mollusk post larvae; AL - abalone larvae; MR - marine rotifers (*Brachionus*); BS - brine shrimp (*Artemia*); SC - saltwater copepods; FZ - freshwater zooplankton.

highly dependent on stringent institutional frameworks (**Table 1**). The U. S. Food and Drug Administration (FDA) has granted Generally Recognized as Safe (GRAS) status to primarily clusters like *Arthrospira* sp., *Chlorella* sp., *Dunaliella* sp., and *Haematococcus pluvialis* (13). Under European safety baselines, the European Food Safety Authority (EFSA) regulates specific microalgae under the Novel Food Regulation (EU 2015/2283), approving *Aphanizomenon flos-aquae*, *Arthrospira platensis*, *Chlorella vulgaris*, *Tetraselmis chuii*, and *Haematococcus pluvialis* (13).

However, a critical regulatory and safety gap persists: current approvals are heavily skewed toward human nutraceutical baselines, leaving a clear deficiency in standardized, international regulatory frameworks tailored explicitly to closed-loop aquaculture feeds and recycled wastewater cultivation media. This absence creates significant biosecurity and compliance risks for commercial implementation, potentially delaying sustainable global adoption.

Nutritional Optimization and Micro-Ecosystem Applications in Aquafeeds

Global aquaculture production is overwhelmingly dominated by Asia, which accounts for 92% of global output, with China alone contributing more than 60% of this total (14). Within these production systems, the highly sensitive larval stages of marine mollusks, echinoderms, crustaceans, and fish, filter-feeding organisms rely fundamentally on the 3-50 µm cell size of microalgal cells as their primary nutrient delivery system (1, 15). Microalgae anchor aquatic food webs, delivering structural proteins, essential amino acids, carbohydrates, polyunsaturated fatty acids (PUFASs like DHA and EPA that aquatic animals cannot newly synthesize), carotenoids, antioxidants, immunostimulants, and antimicrobials (11, 16).

Cultivating microalgae enhances aquaculture system sustainability vi a multi-pronged strategy: serving directly as live nourishment for larvae and filter-feeders (such as

Table 3. Roles of microalgae in aquatic food chains and aquaculture practices.

Primary role	Key Species	Benefits/Applications	References
Direct nutrition for larvae and filter feeders: Serves as a first food for fish, shrimp, and bivalve larvae, and as a direct food source for adult filter-feeders like oysters, clams, and scallops.	*Isochrysis galbana*	High in essential fatty acids (DHA, EPA).	(19, 20)
	Chaetoceros muelleri	Small cell size ideal for ingestion by tiny larvae.	
	Tetraselmis suecica	Readily consumed by bivalves (oysters, clams).	
	Pavlova lutheri and *Skeletonema costatum*	Improves survival and growth rates in early life stages.	
Greenwater culture technique: Microalgae are added to the culture tanks, creating a turbid, nutrient-rich environment that improves water quality and larval survival.	*Nannochloropsis oculata*	Stabilizes water quality by consuming metabolites.	(21, 22)
	Tetraselmis suecica	Provides a uniform food distribution in the tank.	
	Chlorella vulgaris	Enhances feeding behavior and prey visibility for larvae.	
	Thalassiosira weissflogii	Can have probiotic effects, suppressing harmful bacteria.	
Enrichment for live feed (zooplankton): Microalgae are used to nutritionally "enrich" or "gut-load" zooplanktons (e. g., rotifers, Artemia) which are then fed to longer larval fish and shrimp.	*Nannochloropsis* sp. (for EPA)	Boosts the levels of HUFA (DHA, EPA, ARA) in zooplankton.	(23)
	Pavlova lutheri (for DHA and EPA)	Transfers critical nutrients up the food chain.	
	Isochrysis galbana (for DHA)	Improves the nutritional value for carnivorous fish larvae (e. g., seabass, seabream, groupers).	
	Schisochytrium sp. (for DHA)	Reduces larval malformations and improves pigmentation.	
Source of essential nutrients and pigments: Provides critical biomolecules that are difficult to obtain from other sources, crucial for health, development, and marketability.	*Haematococcus pluvialis*	Astaxanthin (from *H. pluvialis*): A powerful antioxidant and pigment for salmonid flesh and shrimp shells.	(17)
	Spirulina (*Arthrospira*) *platensis*	Phycocyanin and Beta-carotene (from *Spirulina* and *Dunaliella*): Enhances immune response and coloration.	
	Dunaliella salina and *Schizochytrium* sp.	High-DHA Oils (from *Schizochytrium*): A sustainable, nonfish source of critical omega-3s	
Probiotics and Water quality Management: Some microalgal species contribute to a healthy culture environment by competing with pathogens and improving microbial balance.	*Chlorella vulgaris*	Compete with pathogenic bacteria for nutrients.	(24, 25)
	Tetraselmis suecica	Some species produce antibacterial compounds.	
	Phaeodactylum tricornutum	Contribute to nitrogen cycling by consuming ammonia. Improves the overall stability of the culture ecosystem.	

raising bivalves, clams, and mussels from hatchings to adults, as well as feeding juvenile abalone, shrimp, and fish) and indirectly as nutrient vectors to "gut-load" or enrich intermediate zooplankton vectors like rotifers, Artemia, and copepods (1, 16, 18, 27) (see **Table 2**).

Methodologically, the selection of specific strains directly determines target species growth metrics, survival rates, seedling development, body length, weight, and environmental tolerance (16, 17, 18) (see **Table 3**). Crucial *species like Arthrospira platensis*, *Chlorella* sp., *Pavlova* sp., *Dunaliella* sp., *Haematococcus* sp., and *Nannochloropsis* sp. are highly prized for their nutritional profile and aquaculture compatibility (17). Other species, including *Scenedesmus* sp., *Schizochytrium* sp., *Haematococcus pluvialis, Spirulina platensis, Isochrysis* sp., and *Chlorella vulgaris*, *actively* promote the growth of shellfish, larval fish, and zooplankton. For example, *Nannochloropsis* sp. significantly improves broodstock egg quality, fertilization rates, and subsequent larval survival (16).

Furthermore, combining specific microalgal species provides complementary nutrient ratios that can act as a financially insight alternative for ocean-based incidents. For instance, a combination of *Nannochloropsis oculate* and *Schizochytrium* sp. provides a complementary lipid-protein ratio that successfully replaces conventional fish meal and fish oil in the diets of globally critical model species like Nile tilapia (*Oreochromis niloticus*) the second largest farmed fish in the world and rainbow trout (*Oncorhynchus mykiss*), a key model species for salmonid aquaculture (19, 33). This specific microalgae-based

Table 4. Phycoremediation mechanisms/benefits with key examples.

Aspect		Description/Mechanism	Key examples and notes	References
Target pollutants removed	Inorganic Nitrogen	Uptake and assimilation of Ammonia, Nitrite, Nitrate as a nitrogen source for growth. Up to 99% removal of total nitrogen.	Primary removal mechanism for toxic ammonia.	(57)
	Phosphorus	Uptake and assimilation of phosphates as a nutrient. Up to 99% removal of phosphorus.	Prevents eutrophication in receiving waters.	(57)
	Organic Carbon and COD	Heterotrophic and mixotrophic consumption of organic matter, reducing Biological/Chemical Oxygen Demand (BOD/COD).	Improves dissolved oxygen levels.	(58)
	Suspended Solids	Bioflocculation and entrapment, settling out fine particles.	Improves water clarity.	(59)
Microalgae mechanisms	Bioassimilation	Direct uptake of nutrients into biomass for protein, nucleic acid, and pigment synthesis.	The primary remediation mechanism.	
	Photosynthetic oxygenation	Photosynthesis releases oxygen into the water, supporting aerobic nitrifying bacteria. Up to 99.4% reduction of total coliforms.	Creates a symbolic system with beneficial bacteria.	(57)
	pH increase	Consumption of carbon dioxide during photosynthesis raises pH, which can promote the volatilization of toxic ammonia.	Must be managed to avoid stress to fish.	(60)
Benefits and advantages of algae	Sustainable and solar powered	Utilizes sunlight as the primary energy source.	Low energy input compared to mechanical filtration.	(61, 62)
	Valorization of waste	Converts pollutants into valuable microalgal biomass.	Biomass can be used as a fish feed supplement, biofertilizers, or for biofuel.	(61, 62)
	In situ treatment	Can be integrated into recirculating aquaculture systems (RAS) or as a polishing step.	Reduces the need for water exchange.	(63)
	Reduces antibiotic use	Improves overall water quality, reducing disease incidence. Up to 93% removal of prevalent antibiotics.	Supports sustainable aquaculture practices.	(57, 64, 65)
Challenges and considerations	Species selection	Must be robust, tolerant of high, and easy to harvest.	Common genera: Chlorella, Scenedesmus, Spirulina, and Nannochloropsis.	(66, 67)
	Harvesting	Removing the microalgae from the water after treatment is crucial and can be costly	Methods: centrifugation, flocculation, bioflocculation.	(67)
	Seasonal variation	Outdoor systems are affected by light and temperature, leading to inconsistent performance.	May require controlled environments (PBRs) for stability.	(67)
	System design and integration	Requires careful engineering (e. g. , raceway ponds, PBRs) and hydraulic retention time (HRT) optimization.	Integration with existing farm infrastructure is key.	(29)

formulation enhances final nutritional quality, boosts fish growth metrics, and yields significantly higher apparent digestibility coefficients for crude proteins, amino acids, and essential polyunsaturated fatty acids (PUFAs like DHA AND EPA) compared to standard fishmeal and fish oil baselines (3). For bivalve farming, critical microalgae identified for direct feeding include *Isochrysis galbana*, *Isochrysis* sp. (T. ISO), *Pavlova lutheri*, *Tetraselmis suecica*, *Pseudoisochrysis paradoxa*, *Chaetoceros calcitrans*, and *Skeletonema costatum* (19, 27).

However, a recurring limitation in existing literature is the tendency to treat nutritional success as a universal metric. In reality, performance varies dramatically depending on the target host physiology; while certain flagellates significantly boost growth in bivalve hatcheries, the same strains fail to support consistent weight gain in carnivorous finfish larvae without secondary enrichment,

highlighting a clear need for host-specific baseline nutritional mapping (1, 11, 27).

Integrated Ecological Services: Phycoremediation and Carbon Capture

The continuous expansion of global aquaculture creates a severe environmental paradox, generating high nutrient effluents (ammonia, nitrates, and phosphates) that drive the eutrophication of receiving water bodies (5, 53). Microalgae actively mitigate this environmental load via interconnected autotrophic, heterotrophic, and mixotrophic pathways (6, 11) (see **Table 4**).

The core efficiency of phycoremediation relies on three concurrent biological phenomena:

1. **Bioassimilation**: Direct enzymatic uptake of inorganic nitrogen and phosphorous for cellular protein and nucleic acid synthesis, achieving up to 99% total pollutant clearance (9, 57). Beyond aquatic waste streams, microalgal biostimulants, such as Chlorella vulgaris suspensions, show parallel efficiency in alternative agricultural configurations like hydroponics. Utilizing specialized suspensions can enhance growth, nutrient uptake, and total biomass yield in crops like lettuce, where specific concentrations achieve maximum increases in leaf area (67.4%), root fresh weight (138.7%), phosphorus (96.4%), potassium (59.5%), and iron (43.8%) assimilation (4).

2. **Bioadsorption**: The immediate, passive adhesion of positively charged toxins to the highly functionalized, negatively charged outer surfaces of the algal cell wall (54, 56).

3. **Bioaccumulation**: The active, metabolic influx of persistent contaminants (heavy metals, agricultural pesticides) across the cellular membrane (52, 55).

A significant critical variance exists in remediation kinetics between target pollutants. While the removal of inorganic fertilizer fractions and the passive biadsorption of toxic heavy metals are highly efficient, the bioremediation of long-chain hydrocarbons (C_{16}-C_{40}) remains far less reliable (9, 57, 68). Strains like *Tetradesmus* sp. and *Arthrospira maxima* demonstrates localized, synergistic success in oily wastewaters, yet real-world degradation rates fluctuate widely based on seasonal temperature shifts and hydraulic retentions times (67, 68).

Concurrently, this metabolic activity drives substantial biological carbon mitigation (32). The combustion of fossil fuels, which accounts for more than 80% of global energy consumption, releases over 24 gigatons of CO_2 into the atmospheric CO_2 concentrations from approximately 295 ppm to over 380 ppm, leading to global warming, severe climate shifts, and ecological extinctions (58). Physical, chemical or biological carbon sequestration techniques aim to reduce this atmospheric burden (28).

Human activities continue to exacerbate pollution, releasing detrimental pollutants like heavy metals, chemicals, and pesticides into the environment through municipal, industrial, and agricultural sources (8). Heavy metals represent a group of metallic elements known for high toxicity, which poses risks to both environmental systems and human health (9). The contamination of water bodies by heavy metals poses a serious threat because these substances are both long-lasting and harmful to living organisms (9).

Microalgae are highly versatile microorganisms capable of growing under diverse environmental conditions while fixing carbon 10 to 50 times more efficiently than terrestrial crops (29). Due to a photosynthetic efficiency that exceeds terrestrial crops by 40-50%, microalgae actively recycle waste CO_2 into stable organic molecules. This process is highly productive with 1kg of cellular biomass absorbing approximately 1.83 kg of CO_2 (3, 10, 29). Optimal carbon dioxide fixation rates regularly exceed 1.5 kg/m^2/year, while concurrently producing intracellular lipids rich in valuable unsaturated fatty acids (18). Microalgae display high tolerance to diverse carbo inputs, efficiently utilizing atmospheric CO2, soluble carbonates (such as sodium bicarbonate and sodium carbonate), or concentrated industrial flue gases (29). According to circular economy concepts, carbon mitigation via microalgal capture is doubly advantageous, as the resulting biomass can be directly converted into biofuels, plastics, biochar, and nutrient-dense animal feeds (31, 32).

Systemic Health, Coloration, and Bioaccessibility Dynamics

Beyond macro- nutritional delivery, microalgal biomass introduces specialized secondary metabolites that modulate aquatic animal immunity, cellular protection, and market value (3, 8).

Immunological Modulation and Gut Health

Supplementingaquaculture diets with microalgae improves growth and weight gain, decreases relative feed consumption, enhances overall disease resistance, and exerts antibacterial and antiviral activities (3). Incorporating low-dose (0.5%) *Haematococcus* sp. and *Anabaena* sp. fractions into feed formulations significantly upregulates lysozyme activity and immune responses. This reduces mortality when animals are challenged by virulent aquatic pathogens like *Vibrio anguillarum* (1, 36, 37). For example, specific bioactive compounds produced by *Anabaena* sp. have shown the capacity to trigger targeted cell death in myeloid leukemia cell lines (36). Similarly, juvenile rainbow trout feed a 0.5% *Haematococcus* sp. diet exhibit enhanced morphological parameters, strengthened immune profiles, and robust disease resistance against *Vibrio anguillarum* (37).

Natural Coloration

The growing demand within the food and aquaculture industries for natural pigments over synthetic alternatives has elevated the commercial value of microalgal production systems (38). Microalgae synthesize structurally diverse, chemically distinct natural pigments including chlorophylls, carotenoids, and phycobiliproteins, which find widespread applications across the food, feed, cosmetics, and medical sectors (such as fluorescent cell imaging technologies) (38,39).

The characteristic pinkish-red color of the flesh in salmonids and the shells of crustaceans is driven by the bioaccumulation of astaxanthin. This pigment is initially synthesized by microalgae and transferred up the aquatic food chain through zooplankton and intermediate crustaceans (40). Targeted accumulation of carotenoids like astaxanthin from *Haematococcus pluvialis*, or

Table 5. Technical components of the microalgae production system and their economic impacts.

Technical component	Description and key parameters	Economic implications (costs and revenue)	References
1. Cultivation systems	Open ponds (Raceways): open race ponds are widely used for large scale microalgae cultivation due to their simplicity, cost-effectiveness, and scalability. It consists of shallow, oval-shaped channels with paddlewheels for mixing, making well-suited for hardy algal species that can induce environmental fluctuations. Photobioreactors (PBRs): easier control compared to open ponds, reduced contamination risks. In cost considerations: higher expenses for light illumination, carbon dioxide supply and cultivation feedings.	Capital Expenditure (CAPEX): PBRs are 5-10x more expensive than open ponds. Operating Expenditure (OPEX): PBRs have higher maintenance and energy costs. Economic Trade-off: Choice dictates scale, product purity, and operational reliability.	(45, 46)
2. Strain Selection	Species: *Chlorella* sp., *Spirulina* (robust, high-protein). *Haematococcus* sp. (high-value astaxanthin). *Nannochloropsis* sp. (lipids for biofuels). Key parameters: growth rate, lipid/protein content, tolerance to CO2 and temperature.	Product Value: dictates the final market (commodity vs high-value niche). Productivity: fast-growing strains reduce cost per kg of biomass. OPEX: Robust strains reduce losses and operational complexity.	(47)
3. Nutrient Inputs	In microalgae, the process of cell development or cultivation metabolism depends on sunlight and essential inorganic materials such as carbon dioxide (CO2) and metal salts for autotrophic microalgae. In contrast, heterotrophic microalgae require an extra source of specific organic compounds and nutrients, including nitrogen (N) and phosphorus (P). example, *Chlorella* sp., *Botryococcus* sp., and *Chlamydomonas* sp.	Cost Savings: repurposing waste CO2 (such as from industrial processes) and wastewater can transform expenses into revenue opportunities by serving as waste treatment services. Main Operating Expenses: Fertilizer costs can represent a substantial ongoing expense if not sourced from waste streams.	(48, 49)
4. Harvesting and Dewatering	Processes: as flocculation, Centrifugation, sedimentation or flotation, and filtration Energy intensity and efficiency for dilute cultures (0.1-1% solids).	The performance unit operation for harvesting and dewatering is often expressed in qualitative terms, like “high energy consumption” and “low in operational cost”.	(42, 50)
5. Downstream processing	Equipment, solvent and human power.	Cost role: It represents a major capital and operational expenditure, requiring significant investment in extraction equipment and ongoing costs for solvents, energy, and labor. Revenue Role: It is the primary driver of profitability, enabling high-value markets. Core Principle: The cost of processing must be aligned with the final product’s market value. Microalgae downstream processing is the value-transformation stage. It directly determines the final product’s market value, converting low-cost crude biomass into high-value, purified products like pharmaceuticals, nutraceuticals, and specialty chemicals.	(51)

phycocyanin and beta-carotene from *Spirulina* and *Dunaliella*, is critical for marketability (1, 17, 38), ultimately boosting commercial value and enhancing visual appeal for consumers worldwide (38). Driven by these demands, the global market size for microalgal pigments is projected to reach $452.4 million, growing at a 4% Compound Annual Growth Rate (CAGR) (38).

Nutritional Deficiencies and Bioaccessibility

Microalgae synthesize highly bioaccessible trace minerals and bioactive molecules (including vitamins and betta-glucans) capable of resolving systematic nutritional deficits and treating metabolic conditions like hyperglycemia, diabetes, obesity, and cardiovascular diseases (1, 35). Crucially, iron deficiency anemia remains a serious global health crisis affecting over one billion people worldwide (

Methodological Limitations, Knowledge Gaps, and Future Outlook

Inconclusion, this review successfully addresses the dual objectives of mapping host-specific microalgal nutrition and evaluating their role in micro-ecosystem applications. This finding demonstrates that while microalgae offer highly efficient solutions for phycoremediation and carbon capture (1.83 kg CO_2 fixed per kg of biomass), their nutritional success in aquafeeds cannot be applied universally. Ultimately, achieving optimal growth and survival metrics requires transitioning away from generalized feeding baselines toward host-specific nutritional mapping. Furthermore, while the structural integration of microalgae into circular aquaculture frameworks offers undeniable ecological services, the economic scalability of these systems remains heavily bound to processing and harvesting constraints.

A critical evaluation of the existing literature reveals three core knowledge gaps that hinder widespread industrial integration.

(i) **The Circularity Disconnect**: The vast majority of published studies evaluate microalgal feed value and wastewater phycoremediation as entirely isolated phenomena. There is a profound lack of empirical data tracking the safety risks of a closed-loop system, specifically whether microalgae cultivated in contaminated aquaculture wastewater bioaccumulate heavy metals or pathogens to a degree that triggers toxicity when re-feed larval fish (4, 10, 60).

(ii) **Scale-up Vulnerability**: While quantitative CO_2 capture models and nutrient uptake kinetics look highly promising at a bench scale, outdoor pilot-scale trials exhibit severe performance drops due to these systems suffer from uncontrollable seasonal variations, light shading effects in high density culture, temperature fluctuations, and sudden culture crashes (29, 67).

(iii) **The Pre-Processing Economic Wall**: Current downstream biomass harvesting and processing techniques rely heavily on intensive chemical solvents, thermal drying, and high-energy cell disruption methods to access tightly bound intracellular lipids and proteins (51, 56).

The health-promoting bioactives of microalgae hold promise for food, nutraceutical, biofuel, and aquaculture, but commercial success depends on overcoming scale-up, safety, and economic hurdles (4, 60).

High production costs currently limit widespread aquaculture adoption, although advancements in fermentation and cultivation technologies have increased efficiency and cut expenses (1). Their future lies in evolving from basic live feeds to sustainable additives, bioremediation tools, and high-value products such as tailored nutrients and heavy metal absorbers (10, 38).

Key challenges include energy/chemical inputs for cultivation/harvesting, downstream processing, and circular bioeconomic integration. Widespread use awaits breakthroughs in cost reduction, safer bioremediation, and species-specific nutrition (56, 69, 70).

To achieve long term commercial viability, future research and development (R& D) must pivot away from basic strain screening and move toward optimizing low-energy bioflocculation methods, securing species-specific nutritional baselines, and establishing rigorous safety parameters for recycled biomass (1, 69, 70). Bridging these engineering limitations with targeted government environmental subsidies represents the only viable pathway to scale microalgae as an authentic driver of global aquaculture sustainability (10, 38).

To overcome the techno-economic bottlenecks, future research must prioritize optimizing high-value downstream outputs such as targeted gut health modulation, enhanced mucosal immunity, and natural pigment accumulation which provide the premium market value necessary to offset upstream production costs. By systematically balancing host-specific dietary requirements with regional ecological management, microalgal-based feed formulations can transition from a localized alternative into a globally scalable foundation for sustainable aquaculture.

Safety concerns (contaminants, strain viability) and economic viability against traditional feeds demand targeted research and development (R and D). Regulatory tightening and consumer eco-preferences amplify pressure, but government subsidies and collaboration offer pathways forward.

34). Microalgae represent a highly sustainable, iron-rich dietary alternative, but total iron bioaccessibility varies fundamentally depending on the cultivation mode. Autotrophic strains exhibit lower iron bioaccessibility profiles due to rigid cell membrane constraints (*Arthrospira platensis* at 18.4%, *Galdieria sulphuraria* at 39.8%, and *Chlorella vulgaris* at 41.8%). Conversely, alternative heterotrophic cultivation strategies drastically alter cellular membrane configurations, boosting iron bioaccessibility up to 66.9% in *Galdieria sulphuraria* and 76.3% in *Chlorella vulgaris*, representing a profound mechanism for addressing iron deficiency via aquaculture food webs (34).

Techno-Economic Interdependencies and Production Bottlenecks

The transition of microalgae from a successful laboratory treatment to an industrially viable aquaculture component depends entirely on resolving severe techno-economic constraints (see Table 5) (41).A quantitative Techno-Economic Analysis (TEA) is essential for evaluating the financial viability of using these organisms as biorefinery feedstocks for renewable fuels, feeds, and co-products (41).

The initial choice of cultivation infrastructure dictates the entire downstream financial trajectory of the facility. Open raceway ponds offer clear scalability and low Capital Expenditure (CAPEX), but their open-air nature exposes cultures to environmental fluctuations and severe contamination risks. Conversely, Photobioreactors (PBRs) maximize purity, reduce contamination risks, and optimize growth parameters, yet their extreme CAPEX (5-10x higher than open ponds) and elevated Operating Expenditure (OPEX) driven by constant artificial illumination, precise carbon dosing, and high maintenance costs restrict their output exclusively to high value niche compounds (45, 46).

The primary financial breakdown occurs during the harvesting and dewatering phases of dilute solutions from open cultivation systems (42). Removing microalgal cells from highly dilute cultivation mediums (0.1-1% solids)

requires sequential unit operations (including flocculation, centrifugation, filtration, and sedimentation) that consume substantial energy (0.2 t0 5 kWh per kg), resulting in a processing cost of €0.5 to €2 per kilogram of raw biomass (42, 50). While the commercial viability of microalgae based high density fuels for decarbonizing transport remains promising, it is highly contingent on specific local conditions and targeted resource recovery (43). Downstream value transformation techniques, such as utilizing specialized catalysts derived from lipid extracted algal waste, can marginally mitigate production costs for example, dropping biodiesel inputs from $2.03/kg to $1.70/kg, yet the overall process remains economically volatile (43, 44).

Declaration

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