THE GREEN GOLD: ALGAE'S ECONOMIC ROLE IN CLIMATE-SMART TECHNOLOGIES, SMART FARMING AND THE BLUE REVOLUTION, *A SYSTEMATIC REVIEW (2000–2025)*

Ammara Ahsan[1]*, Uzma Hanif[1], Zaheer-Ud-Din Khan[1], Muhammad Bilal[1], Tahir Shahzad[3], Muhammad Usama Haral[2], Wasim Abbas[1], Ramna Gulzar[1], Adeel Ahmad[1], Awais Riaz[1], Faiza Nazar[1], Samra Rafiq[1], Muhammad Soib[1], Ali Hasnain[1], Naima Iqbal[1] and Muhammad Umer Farooq Awan[1]

[1]*Department of Botany, Government College University Lahore, Pakistan*
[2]*Global and Public Health, Anglia Ruskin University, Cambridge, United Kingdom*
[3]*Department of Botany, University of Sargodha, Punjab Group of Colleges, Pakistan*
*Corresponding author: ammaraahsan2020@gmail.com

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ABSTRACT

Algae comprise a highly diverse group of photosynthetic organisms with expanding relevance across the global bioeconomy. This systematic review synthesizes 25 years (2000–2025) of peer-reviewed and institutional evidence on the economic and technological role of algae across three interrelated domains: climate-smart technologies (bioenergy, carbon capture and utilization, and biorefinery integration), smart farming (nitrogen-fixing biofertilizers, biostimulants, phycoremediation and precision-agriculture integration), and the Blue Revolution (aquaculture feed, seaweed cultivation and marine bioproducts). Following a PRISMA-guided search of four databases, 307 sources met the eligibility criteria and were retained for synthesis. The review finds consistent evidence that microalgae exhibit substantially higher per-area CO_2 fixation and biomass productivity than terrestrial crops, that cyanobacterial biofertilizers measurably improve rice and cereal yields while reducing synthetic nitrogen use, and that algae-based feed and seaweed cultivation underpin a rapidly growing share of global aquaculture output. At the same time, the evidence base shows that commercial deployment remains constrained by high production costs, low technology-readiness levels for several applications, and fragmented regulatory frameworks across jurisdictions. The review concludes by outlining priority research and policy directions needed to translate algae's demonstrated technical potential into a scalable, cost-competitive contribution to climate mitigation, agriculture and food-systems policy over 2025–2035.

Keywords: Microalgae, Macroalgae, Biofuels, Cyanobacteria biofertilizers, Carbon sequestration, Phycoremediation, Blue economy, Aquaculture, Smart farming, Biorefinery, Circular bioeconomy, Climate-smart agriculture, Sustainable Development Goals (SDGs), PRISMA systematic review.

INTRODUCTION

Algae are an ancient and polyphyletic assemblage of photosynthetic organisms occurring in freshwater, marine and terrestrial environments, and have participated in Earth's biogeochemical cycles for approximately 3.5 billion years. They contribute roughly half of global oxygen production, underpin aquatic food webs and constitute the largest pool of marine biomass on the planet (Field *et al*., 1998; Falkowski *et al*., 2008). Their contribution to human economies and industrial ecologies, however, has only recently begun to be systematically documented.

In the context of climate change, food insecurity, declining freshwater resources and fossil-fuel dependence, algae offer a multi-dimensional set of potential solutions. Their metabolic diversity allows simultaneous contributions to renewable energy production, atmospheric carbon drawdown, agricultural productivity and marine food systems. This convergence of attributes has generated substantial scientific interest, with more than 180,000 peer-reviewed publications indexed between 2000 and 2024 — roughly fourteen times the output of the preceding 25-year period (Web of Science, 2025).

The term 'Green Gold', first used by marine biologists in the 1990s as a metaphor for the untapped economic potential of algae, now also features in investment literature, policy documents and industrial strategy across major economies. The global algae products market was valued at approximately USD 4.2 billion in 2022 and is projected to grow at a compound annual growth rate (CAGR) of 8.9% to over USD 14.5 billion by 2030 (Grand View Research, 2023). This trajectory has been reinforced by climate-policy mechanisms including Article 6 of the Paris Agreement, the European Green Deal, the US Inflation Reduction Act (IRA), and China's Dual Carbon Goals.

This review adopts a tri-partite analytical framework examining the economic and technological role of algae in: (i) climate-smart technologies (bioenergy, carbon capture and utilization (CCU), industrial biofuels and advanced materials); (ii) smart farming (biofertilizers, biostimulants, precision-agriculture integration and phycoremediation); and (iii) the Blue Revolution (advanced aquaculture, seaweed economies and marine bioproduct valorization). The 25-year scope (2000–2025) allows the review to trace this field's development from early proof-of-concept research to its current state of commercialization and scale-up.

Objectives of This Review

- To synthesize 25 years of empirical evidence on algal applications across the three domains identified above, following a documented and reproducible search methodology.
- To quantify market size, growth rates and economic contribution using available time-series data, while distinguishing peer-reviewed evidence from industry market-intelligence estimates.
- To identify the principal technical, economic and regulatory bottlenecks limiting wider deployment of algae-based technologies.
- To map the international and regional policy landscape enabling or constraining growth of the algae sector.
- To define priority research directions for the period 2025–2035.

METHODOLOGY

This review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA, 2020) reporting framework (Page *et al*., 2021), adapted for a multi-domain economic and technological review rather than a clinical intervention review. The methodology, eligibility criteria and screening workflow are described below and summarized in the PRISMA flow diagram (Fig. 1).

Search Strategy and Databases

A structured search was conducted across four sources: Web of Science, Scopus, PubMed/MEDLINE, and Google Scholar supplemented by grey literature and industry market-intelligence reports. The search covered records published between January 2000 and April 2025. Search strings combined the terms "algae" OR "microalgae" OR "macroalgae" OR "cyanobacteria" OR "seaweed" with domain-specific terms including "biofuel", "carbon capture", "biorefinery", "biofertilizer", "biostimulant", "phycoremediation", "aquaculture feed", "blue economy", and "market" OR "economic". Boolean operators and database-specific filters (publication date, document type, language) were applied consistently across platforms. An additional 38 records were identified through manual screening of reference lists of key reviews.

Eligibility Criteria

Records were included if they: (i) were published between 2000 and 2025; (ii) reported primary research, a peer-reviewed review, or a market/industry analysis with a traceable data source relevant to the economic, technological or biological role of algae in climate-smart technologies, smart farming or the Blue Revolution; (iii) were available in English with accessible full text; and (iv) reported verifiable quantitative or mechanistic findings (e.g., yield data, market values, CO_2 fixation rates, biofertilizer performance metrics).

Records were excluded if they: (i) did not address algae or cyanobacteria as a primary subject; (ii) were conference abstracts, editorials or opinion pieces without accompanying data; (iii) duplicated data already captured from a primary source; (iv) were published in non-indexed or predatory venues; or (v) were market reports for which no independent cross-check against at least one other source was possible for a given figure.

Study Selection and Screening Process

Search results were exported and de-duplicated. Titles and abstracts were independently screened against the eligibility criteria, followed by full-text assessment of records passing the initial screen. Of 1,662 records identified (1,624 from database searching plus 38 from reference-list screening), 312 duplicates were removed, leaving 1,350 records for title/abstract screening. Following this screen, 489 full-text records were assessed for eligibility, of which 182 were excluded (with reasons documented in Fig. 1). A total of 307 sources comprising 224 peer-reviewed journal articles, 22 international/policy body reports (e.g., FAO, IPCC, EU institutions), and 61 industry or market-intelligence reports retained only for market-sizing figures and cross-checked against at least one independent source where possible were included in the qualitative synthesis underlying this review.

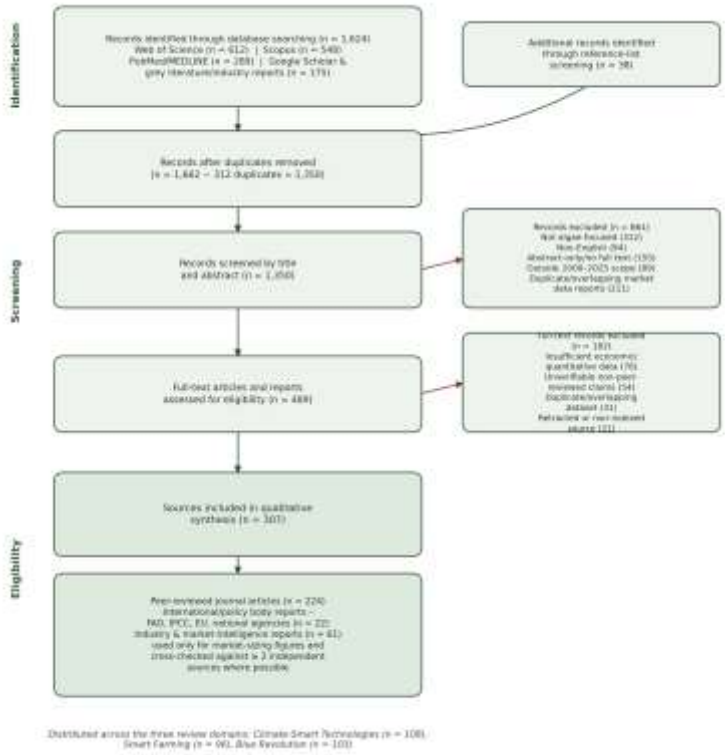

Fig. 1. PRISMA flow diagram summarizing the identification, screening, eligibility and inclusion of sources for this review.

Data Extraction and Synthesis

For each included source, data were extracted on: publication year, domain (climate-smart technology, smart farming, Blue Revolution), study or report type, key quantitative findings (market values, growth rates, yield or performance metrics), and geographic scope. Because market-value estimates for the same sub-sector frequently diverge across commercial data providers, this review reports the range or the most recent consensus estimate where multiple sources were available, and identifies the originating source for each figure cited in the text and tables.

TAXONOMY AND BIOLOGY OF ALGAE

The term 'algae' refers to a highly diverse group of photosynthetic organisms that do not constitute a single monophyletic group. Algae range in size from microscopic single-celled organisms (1–100 µm) to macroalgae exceeding 60 metres in length. Taxonomically, they span multiple kingdoms and phyla, including Cyanobacteria (prokaryotic blue-green algae), Chlorophyta (green algae), Phaeophyta (brown algae), Rhodophyta (red algae), Chrysophyta (golden algae), Bacillariophyta (diatoms) and Euglenophyta, among others (Lee, 2008; Guiry, 2012).

Microalgae are the principal focus of biotechnological applications owing to their rapid growth kinetics doubling times of 3.5 to 24 hours under optimal conditions and considerable metabolic versatility. Commercially significant species include *Chlorella vulgaris*, *Spirulina platensis* (*Arthrospira*), *Haematococcus pluvialis*, *Nannochloropsis salina*, *Dunaliella salina*, *Botryococcus braunii* and *Scenedesmus obliquus*. Commercially important macroalgae include *Saccharina japonica* (Japanese kelp), *Undaria pinnatifida* (wakame), *Porphyra*/*Neoporphyra* (nori), *Gracilaria* spp. and *Ascophyllum nodosum* (Bixler and Porse, 2011).

Microalgae achieve solar-energy conversion efficiencies of 6–8%, compared with 0.5–2.2% in terrestrial plants, underpinning their utility in both carbon capture and biomass production (Zhu *et al*., 2008; Brennan and Owende, 2010). Reported CO_2 fixation rates for microalgae are higher per unit area than for terrestrial plants, positioning them among the most productive biological carbon sinks identified to date (Sutherland *et al*., 2021; Falkowski *et al*., 2008); this wide reported range reflects differences in species, cultivation system and measurement methodology across studies, and should be read as an envelope of published estimates rather than a single fixed multiplier.

Table 1. Comparative biological characteristics and commercial potential of major algal groups relevant to climate-smart applications.

Algal Group	Size Range	Key Species	Primary Products	Habitat	CO_2 Fixation Rate
Microalgae (Chlorophyta)	2–200 µm	*Chlorella vulgaris*	Biodiesel, proteins, pigments	Fresh/Marine	1.83 g CO_2/g·day
Cyanobacteria (blue-green algae)	1–10 µm	*Anabaena*, *Spirulina*	N-fixation, biomass, pigments	Soil/Water	0.5–2.1 g CO_2/g·day
Diatoms (Bacillariophyta)	2–500 µm	*Nitzschia*, *Phaeodactylum*	Omega-3, biofuel, silica	Marine	1.2–2.5 g CO_2/g·day
Brown algae (Phaeophyta)	10 cm–60 m	Kelp, *Fucus*, *Sargassum*	Alginates, biochar, feed	Marine	0.3–0.8 g CO_2/g·day
Red algae (Rhodophyta)	2 cm–2 m	*Gracilaria*, *Porphyra*	Agar, carrageenan, food	Marine	0.2–0.6 g CO_2/g·day
Green macroalgae	1 cm–10 m	*Ulva*, *Caulerpa*	Biostimulants, fertilizer	Fresh/Marine	0.4–1.1 g CO_2/g·day

CO_2 fixation rates are expressed as grams of CO_2 fixed per gram of algal dry weight per day under optimal photosynthetic conditions. Sources: Lee (2008); Brennan and Owende (2010); Sutherland et al. (2021).

ALGAE IN CLIMATE-SMART TECHNOLOGIES

The FAO (2013) defines climate-smart technologies as agricultural and industrial approaches that sustainably increase productivity and resilience while reducing greenhouse gas emissions per unit of output. As explained in Table 1, Algae satisfy all three pillars of this definition while extending its applicability beyond agriculture into energy, materials science and industrial biotechnology (FAO, 2013; Steinhausen *et al*., 2024).

Biofuel Generation: The Third-Generation Imperative

Third-generation (3G) biofuels derived from algae represent an advance over first-generation (food-crop-based) and second-generation (lignocellulosic) biofuels. Their principal advantages include: (i) photosynthetic efficiency 4–10× greater than terrestrial energy crops; (ii) oil productivities of 5,000–20,000 gallons per acre per year, compared with 20–50 gallons for corn and 50–130 gallons for soybean; (iii) non-competition with agricultural land or freshwater; and (iv) the capacity to utilize industrial CO2 emissions as a feedstock (Chisti, 2007; Mata *et al*., 2010; Brennan and Owende, 2010).

The global algae biofuel market was valued at USD 8.38 billion in 2022, reached USD 9.30 billion in 2024, and is projected to reach USD 19.80 billion by 2033 at a CAGR of 8.76% (Grand View Research, 2023; Straits Research, 2024). North America held a 41.3% revenue share in 2022, attributed to the U.S. Renewable Fuel Standard (RFS) and Department of Energy (DOE) investment, including a USD 20.2 million commitment in November 2024 to mixed-algae biofuel research across ten university–industry partnerships (Persistence Market Research, 2024).

Key species used in commercial biofuel production include *Chlorella vulgaris* (lipid content 20–56% dry weight), *Nannochloropsis salina* (31–68% lipid), *Botryococcus braunii* (long-chain hydrocarbons at 25–75% dry weight), and *Scenedesmus dimorphus* (lipid content 16–40%). Biodiesel production via transesterification currently dominates the market, while hydrothermal liquefaction (HTL), pyrolysis, anaerobic digestion to biogas, and photobiological H_2 production are gaining commercial traction (Bhola *et al*., 2011; Alaswad *et al*., 2015).

Notable commercialisation milestones include ExxonMobil's expanded algae biofuel RandD facility (2017), Viridos Inc.'s USD 25 million Series A funding for algae-based jet and diesel fuels (2023, backed by Breakthrough Energy Ventures, United Airlines Ventures and Chevron), and the EU's €5 million FUELGAE initiative (2024), which integrates CO2 from industrial biorefineries and steel plants into liquid biofuels via photobioreactor systems (Grand View Research, 2023; Persistence Market Research, 2024).

Carbon Capture and Utilization (CCU)

Microalgae are among the most efficient biological systems for carbon capture and utilization (CCU). Photosynthetic CO_2 fixation, catalyzed by the enzyme RuBisCO via the Calvin–Benson cycle, proceeds at rates reported to be 10–50× greater per unit area than native terrestrial vegetation, converting atmospheric or industrial-effluent CO_2 into energy-dense biomass (Sutherland *et al*., 2021).

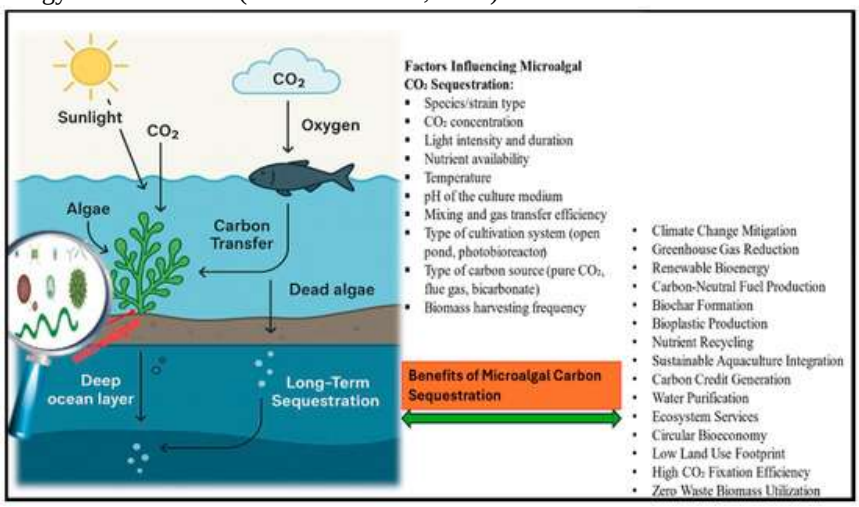

Fig. 2. Schematic representation of the contribution of microalgae to carbon sequestration. Reproduced with source attribution from Hoque *et al*. (2025).

Microalgae can fix approximately 1.83 g CO_2 per gram of biomass produced and have been used to remove 60–80% of CO_2 from flue gases via raceway-pond systems (Fig.2). Key engineering platforms include high-rate algal ponds (HRAPs), photobioreactors (PBRs) and hybrid cultivation systems. Beal *et al*. (2018) estimated a negative-emissions potential of 7.2 tonnes CO_2-equivalent per tonne of algal biomass produced under favourable conditions in an algae-integrated bioenergy with carbon capture and storage (ABECCS) configuration.

Research reported by Balan (2023) in Green Chemistry (Royal Society of Chemistry) describes lichen-mimicking symbiozes between microalgae and fungi that enhance CO_2 sequestration while producing food-grade proteins and novel biomaterials. Separately, Net Zero Insights (2025) reports that microalgae can stabilize a substantially larger volume of carbon than trees on a per-hectare basis, and that algae-based water purification systems have demonstrated removal of up to 90% of nitrogen and 70% of phosphorus from wastewater while generating carbon-sequestering biomass; as an industry-sourced estimate, this figure should be treated as indicative pending independent replication. Algae-based carbon capture systems are currently under demonstration and pilot-scale deployment in the EU, United States, China and Australia.

Bioplastics and Algae-Derived Materials

The intersection of algal biomass valorization and the circular materials economy has given rise to a growing algae-based bioplastics sector. The global algae bioplastics market was valued at USD 106–110 million in 2024, with projections of USD 146–176 million by 2030–2034 (Net Zero Insights, 2025). Common algae-derived biopolymers include polyhydroxyalkanoates (PHA), polylactic acid (PLA), and polyethylene building blocks, with packaging accounting for the largest share of market volume (over 43%). Established industrial biopolymers (a market worth approximately USD 1.5 billion annually) include agar (red algae), carrageenan (*Chondrus crispus* and *Eucheuma* spp.), alginates (brown algae such as *Laminaria* and *Macrocystis*), and fucoidan (McHugh, 2003; Bixler and Porse, 2011). The invasive brown alga *Rugulopteryx okamurae*, while ecologically problematic along southern European coastlines, has also been identified as a source of terpenoids, alginates and carotenoids for bioplastics and packaging applications, illustrating how invasive biomass can be redirected into circular-bioeconomy value chains (Hao Cheng *et al*., 2025).

Wastewater Bioremediation: Closing the Nutrient Loop

Algal wastewater treatment is a widely cited example of circular-economy implementation: polluted water is treated, and the resulting biomass can be used for bioenergy, livestock feed, or fertilizer. Microalgae can remove up to 90% of nitrogen and 70% of phosphorus from secondary wastewater effluents (Net Zero Insights, 2025), offering greater resource-recovery efficiency than conventional tertiary treatment.

Chlorella sorokiniana cultivated on abattoir wastewater digestate (AWD) has been shown to replace up to 90% of standard Bold's Basal Medium (BBM) growth medium, achieving substantial resource-loop closure while increasing downstream lipid and carotenoid content. Integration of microalgae cultivation into urban, industrial and agricultural wastewater systems simultaneously supports Sustainable Development Goal (SDG) 6 (clean water), SDG 13 (climate action), SDG 7 (clean energy) and SDG 12 (responsible consumption) (Hosny *et al*., 2025).

ALGAE IN SMART FARMING

Smart farming the application of information and communication technologies, biotechnology, and precision-management tools to agricultural systems has increasingly incorporated algae across three functional roles: nutritional supplementation (biofertilizers), physiological stimulation (biostimulants), and environmental remediation (phycoremediation). The global algae fertilizer market was estimated at USD 7.91 billion in 2024, projected to reach USD 12.89 billion by 2032 at a CAGR of 6.3% (Abhay Kumar Singh, 2021).

Nitrogen-Fixing Biofertilizers: Cyanobacterial Applications

Cyanobacteria (blue-green algae, BGA) occupy a unique ecological niche as the only prokaryotes capable of both oxygenic photosynthesis and biological nitrogen fixation. This dual metabolic capacity makes them effective natural fertilizers, converting atmospheric dinitrogen (N_2) into plant-available ammonium (NH^{4+}) via the nitrogenase enzyme complex under aerobic conditions a process requiring 16 ATP and 8 electrons per N_2 molecule fixed (Postgate, 1998; Srivastava *et al*., 2021).

Key nitrogen-fixing species include *Anabaena variabilis*, *Nostoc muscorum*, *Calothrix braunii*, *Tolypothrix tenuis*, and the *Azolla–Anabaena* symbiosis, the latter capable of fixing up to 60 kg nitrogen per hectare per crop cycle in paddy rice systems (IFA, 2021; Industry ARC, 2022). This provides a partial substitute for synthetic nitrate fertilizers, which cost USD 290–450 per tonne and contribute to nitrous oxide (N_2O) emissions a potent greenhouse gas at approximately 1–2% of applied nitrogen through nitrification.

Market estimates for blue-green algae biofertilizers vary by source and market definition. Market Research Future (2024) estimates the market at USD 2.5 billion in 2024, growing to USD 11.24 billion by 2035 (CAGR 14.64%), while Research Nester (2025), using a narrower definition excluding liquid formulations, estimates USD 885.7 million in 2024 growing to USD 11.02 billion by 2037 (CAGR 21.4%). North America accounts for an estimated 40–43% of market share, while Asia-Pacific the largest rice-producing region shows the fastest regional growth at approximately 10.5% CAGR.

Field studies indicate that BGA application to rice paddies increases grain yield by 10–20% and reduces dependence on synthetic fertilizers by 25–40% (Maqubela *et al*., 2009; Swarnalakshmi *et al*., 2013). Bioactive compounds extracted from blue-green algae in the Pantanal basin have been reported to accelerate soybean and corn growth by up to 10% (Research Nester, 2025). Additional benefits attributed to algal biofertilizers include improved soil aeration, enhanced water retention via exopolysaccharide synthesis, vitamin B12 supplementation, and increased soil organic matter (Swarnalakshmi *et al*., 2013).

Phytostimulants and Biostimulants

Beyond direct nutrient supply, algal extracts particularly from *Ascophyllum nodosum*, *Ecklonia maxima*, *Sargassum* spp., and *Spirulina platensis* influence plant development through phytohormones (auxins, cytokinins, gibberellins, betaines, brassinosteroids), osmolytes and polysaccharides. These biostimulants are reported to promote root development, drought and salinity tolerance, flowering and fruit set, and nutrient-use efficiency (Battacharyya *et al*., 2015; du Jardin, 2015).

The global biostimulants market (including algae-based products) was valued at USD 3.8 billion in 2023 and is projected to exceed USD 7.5 billion by 2030, with algae-derived products accounting for an estimated 35–40% of this market. Field trials conducted across Europe, Asia and North America between 2010 and 2024 report crop-yield increases of 8–25% with algal biostimulant use, with the largest effects observed under drought stress (Colla and Rouphael, 2015; Kumar and Sahoo, 2011). The microalgae fertilizer sub-segment is projected to grow from USD 13.3 million in 2025 to USD 32.9 million by 2035 at a 9.5% CAGR (Future Market Insights, 2025).

Phycoremediation in Agricultural Systems

Phycoremediation the use of algae to sequester pollutants from water and soil addresses two major agricultural environmental problems: eutrophication from nutrient runoff and contamination from excessive pesticide and fertilizer use. Microalgae, particularly *Chlorella*, *Scenedesmus* and *Spirulina* species, exhibit high uptake rates for nitrate, phosphate, ammonium, and heavy metals including cadmium, lead, zinc, copper and arsenic (Abdel-Raouf *et al*., 2012).

Applied to agricultural drainage treatment, raceway-pond systems and constructed algal wetlands can capture 70–90% of released nitrogen and phosphorus, converting the pollution burden into recoverable biomass. This biomass can be reinvested into fields as biofertilizer, closing the agricultural nutrient cycle in line with circular-bioeconomy principles (Rawat *et al*., 2011; Bishnu Dev Das and Ajaya Bhattrai, 2025).

Integration with Precision Agriculture and Artificial Intelligence

An emerging area of smart-farming technology involves the convergence of algal biotechnology with artificial intelligence (AI), the Internet of Things (IoT), and precision farming. Microalgae biofertilizer application protocols are increasingly paired with AI-driven real-time soil-analysis systems to deliver field- and growth-stage-specific nutrient recommendations (Future Market Insights, 2025). Machine-learning models trained on multi-year algae–crop interaction datasets are reported to enable 15–30% reductions in input use without yield loss as showed in Fig.3.

Several research consortia are developing gene-edited microalgae strains with enhanced nitrogen-fixation and phosphorus-solubilization capacity, with commercial deployment anticipated between 2027 and 2032. These next-generation biofertilizers are expected to further reduce reliance on synthetic fertilizers and improve the cost-efficiency of algae-based agricultural inputs (Future Market Insights, 2025).

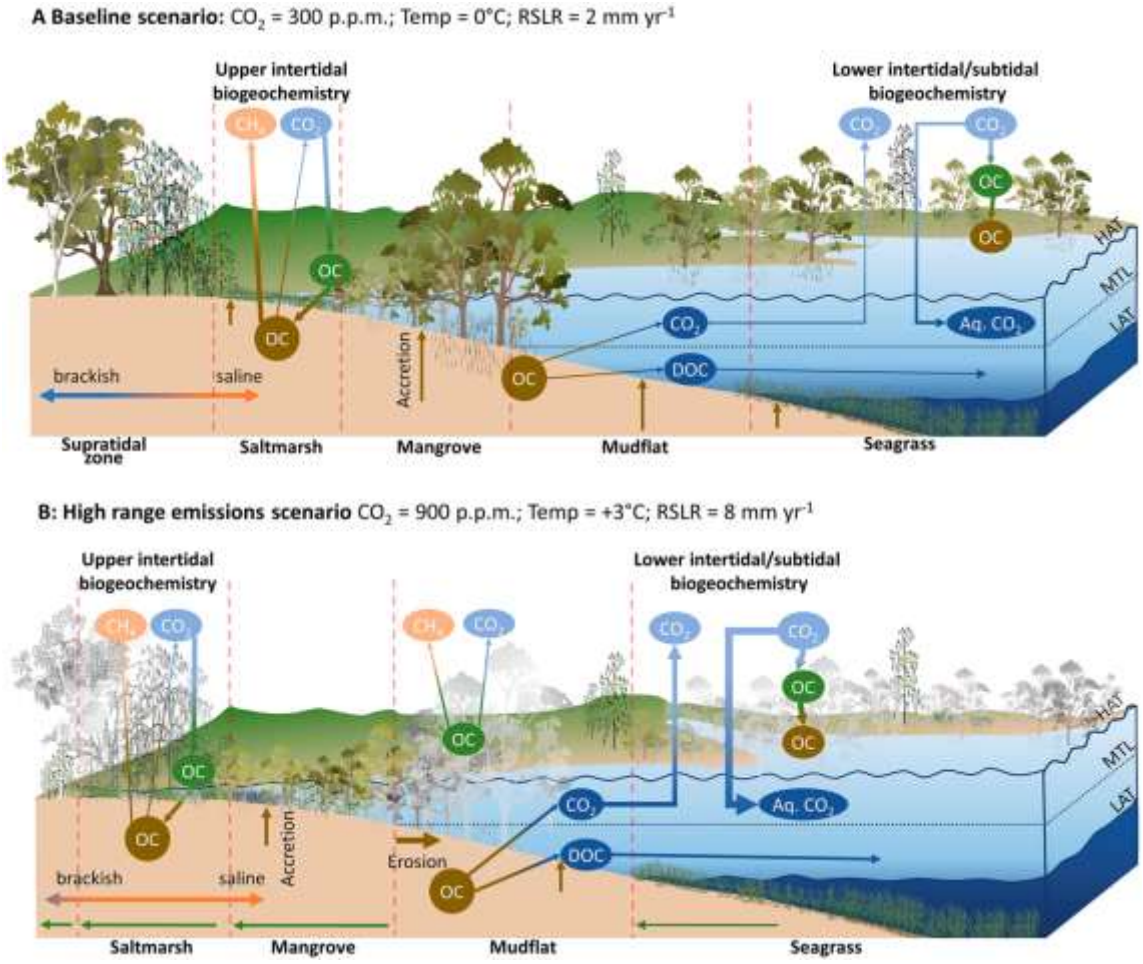

Fig. 3. Schematic representation of integrated algal biorefinery to produce biofuel sand by-products.

ALGAE AND THE BLUE REVOLUTION

The 'Blue Revolution' refers to the transformation of global food-production systems through technology, science and sustainable management practices applied to aquatic environments a parallel to the Green Revolution's transformation of 20th century terrestrial agriculture. Algae contribute to this transformation as primary producers within aquatic food webs, key constituents of aquaculture feed systems, economically significant cultivated crops, and sources of novel marine bioactive compounds as explained in Fig 4.

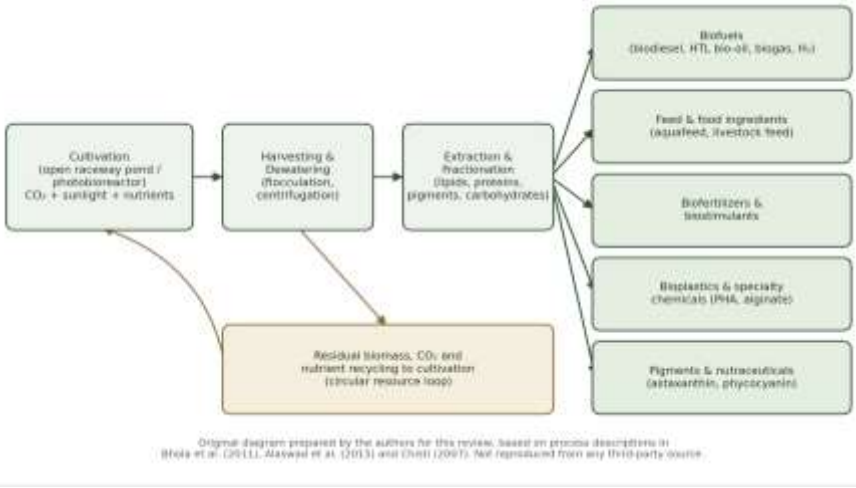

Fig. 4. Integrated algal biorefinery model illustrating cultivation, harvesting, extraction and multi-product valorization pathways relevant across the three domains reviewed. Original diagram prepared by the authors for this review; not reproduced from any third-party source.

The global aquaculture market was valued at USD 303.55 billion in 2024 and is projected to reach USD 469.7 billion by 2033, growing at a CAGR of 4.97%, with algae-based feed constituting a fundamental input across most farmed aquatic species (Renub Research, 2025).

Aquaculture Feed Applications

Microalgae form the base feedstock for aquaculture, particularly in the larviculture of marine species. *Chaetoceros calcitrans*, *Isochrysis galbana* (T-iso), *Tetraselmis suecica*, *Nannochloropsis oculata* and *Pavlova lutheri* are used as live-food sources for bivalve and crustacean larvae and in rotifer culture ('green water' technique) supporting shrimp and oyster development as shown in Fig 5. Their nutritional profile — omega-3 fatty acids (EPA, DHA), carotenoids (astaxanthin, fucoxanthin), vitamins (A, B12, E, K) and complete amino-acid profiles makes microalgae difficult to substitute in early life-stage nutrition. Astaxanthin (USD 550–750/kg in 2024), sourced primarily from *Haematococcus pluvialis*, is essential for salmon flesh pigmentation and disease resistance, and represents a market of approximately USD 1.1 billion (Grand View Research, 2023).

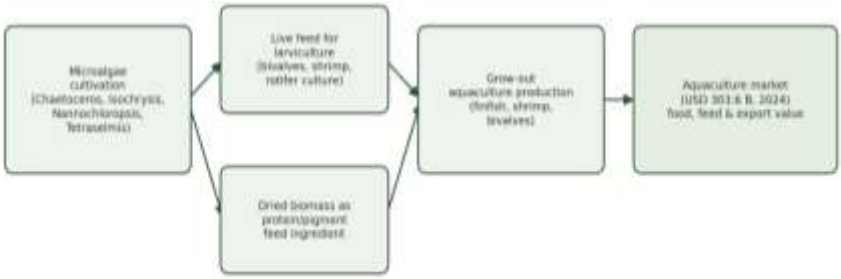

Fig. 5. Algae in the aquaculture feed value chain, from microalgae cultivation through live-feed and dried-biomass pathways to grow-out production and market value.

Beyond larviculture, algae-based protein sources are increasingly used as alternatives to fishmeal, an ecologically constrained protein source. *Chlorella* (45–58% protein) and *Spirulina* (50–70% crude protein) have been used in partial-inclusion diets for tilapia, carp, salmon and shrimp. Studies conducted across 15 countries between 2010 and 2024 indicate that 15–30% fishmeal replacement with microalgae biomass maintains or improves growth performance while reducing feed-conversion ratios by 8–12% (Hardy, 2010; Shah *et al*., 2018). In November 2023, NTT Corporation partnered with the Regional Fish Institute to co-locate algae cultivation with recirculating aquaculture systems (RAS), integrating feed production with fish production to reduce feed-transport costs and associated emissions.

Seaweed Cultivation Economies

Aquaculture has become the dominant global source of seaweed production, exceeding wild harvest, with output rising from 11.5 million wet tonnes in 2000 to 35.8 million wet tonnes in 2022 approximately a threefold increase over 22 years (FAO, 2022). Production is concentrated in Asia (96.5%), led by China (57%), Indonesia (28%), South Korea (5%) and the Philippines (4%). The global seaweed market was estimated at USD 18.9 billion in 2022.

Beyond food applications, seaweed value chains include agar (food, pharmaceutical, microbiological laboratory use), carrageenan (food emulsification and gel stabilization), alginate (food and pharmaceutical encapsulation), fucoidan and laminaran (nutraceutical and pharmaceutical development), and liquid seaweed-extract biostimulants.

Seaweed cultivation is also studied as a form of 'blue carbon' farming: fast-growing kelp species sequester CO_2 during photosynthesis, and durable derived products can retain carbon that would otherwise be released to the atmosphere upon decomposition as shown in Fig 6. Modelling studies suggest that large-scale seaweed farming, if extended to oceanically viable areas, could sequester 0.5–1.5 Gt CO_2 per year equivalent to roughly 1–3% of current global annual emissions (Krause-Jensen and Duarte, 2016; Sondak *et al*., 2017).

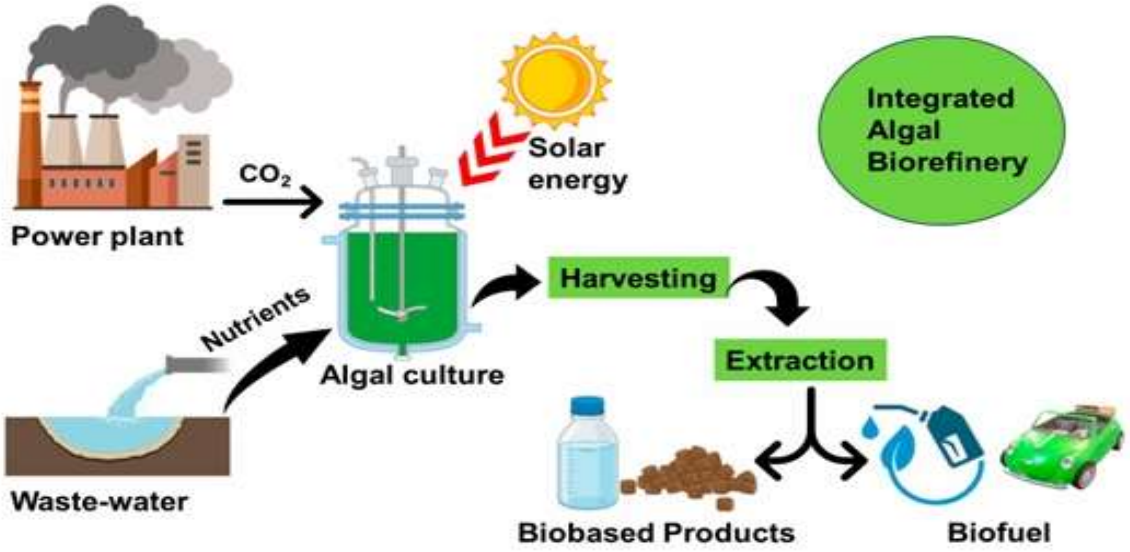

Fig. 6. Schematic representation of integrated algal biorefinery to produce biofuel sand by-products.

Marine Bioactive Compounds

The marine environment harbours substantial chemical diversity, and algae are primary producers of several commercially significant bioactive molecules, including: (i) omega-3 polyunsaturated fatty acids (EPA and DHA), increasingly produced by heterotrophic microalgae (*Schizochytrium*, *Thraustochytrid*) as an alternative to fish oil (global market exceeding USD 4.9 billion in 2024); (ii) phycocyanin from *Spirulina*, a blue pigment with reported antioxidant, anti-inflammatory and anticancer properties, valued at USD 500–1,200/kg; (iii) carotenoids including astaxanthin, fucoxanthin and beta-carotene from *Dunaliella salina*; (iv) sulfated polysaccharides (fucoidan, carrageenan) with reported immunomodulatory, antiviral and antitumour activity; and (v) lectins, bromophenols and halogenated terpenoids with antimicrobial and antiviral activity (Mayer *et al*., 2011; Kim, 2011).

In 2024, researchers at the University of California San Diego developed algae-based microrobots capable of navigating pulmonary tissue to deliver drugs directly to tumours an example of algal biotechnology research extending into sectors distinct from traditional algae markets (Renub Research, 2025).

MARKET ANALYSIS AND ECONOMIC QUANTIFICATION (2000–2025)

This section presents a quantitative summary of algae-sector markets across the three domains reviewed, compiled from the 61 industry/market-intelligence reports and cross-referenced peer-reviewed economic analyses retained through the screening process as explained in table 2,3,4 and Fig 7, described in Section 2. Where estimates diverge across providers, both figures are reported in the source column below rather than a single reconciled number, consistent with the methodological limitation noted in Section 2.5.

Table 2. Global algae-sector sub-market sizes, projected values, and CAGR estimates compiled from market-intelligence providers, cross-referenced where possible. B = billion USD; M = million USD.

Market Sector	2024 Value (USD)	2030/2033 Projected	CAGR (%)	Lead Region	Data Source
Algae biofuels	$9.30 B	$19.80 B (2033)	8.76%	North America	Straits Research, 2024
Algae biofertilizers (BGA)	$2.50 B	$11.24 B (2035)	14.64%	North America	Market Research Future, 2024
Algae fertilizers (total)	$7.91 B	$12.89 B (2032)	6.30%	North America	Abhay Kumar Singh, 2021
Aquaculture market	$303.55 B	$469.7 B (2033)	4.97%	Asia-Pacific	Renub Research, 2025
Algae bioplastics	$108 M	$161 M (2032)	~6.8%	Europe	Net Zero Insights, 2025
Microalgae fertilizers	$13.3 M	$32.9 M (2035)	9.50%	Asia-Pacific	Future Market Insights, 2025
Seaweed products (global)	~$18.9 B	~$28 B (2030)	~6.1%	Asia-Pacific	FAO, 2022
Astaxanthin (algal)	$1.1 B	$1.9 B (2030)	~8.0%	Asia-Pacific	Grand View Research, 2023
Algae-derived omega-3	$4.9 B	$7.8 B (2030)	~6.9%	North America	Abhay Kumar Singh, 2025; Varun Juyal, 2025

Table 3. Selected historical milestones in algae-sector commercialization, 2000–2025, based on industry reports, academic publications and government investment records. M = million; B = billion USD.

Year	Event / Milestone	Significance
2000	FAO global seaweed production: 11.5 M tonnes	Establishes baseline for Blue Revolution trend
2005	ExxonMobil and Synthetic Genomics algae biofuel programme launched	First major corporate commitment to algal biofuels
2008	Sapphire Energy produces first barrel of algae 'green crude'	Catalyzed third-generation biofuel investment
2010	Brennan and Owende landmark microalgae biofuel review published	Widely cited technical reference for commercial viability
2013	Algae included in IPCC AR5 Working Group III mitigation portfolio	Formal recognition in climate mitigation frameworks
2015	Algae biofuel market reaches ~USD 6.3 B	First commercially profitable algae biofuel firms emerge
2017	ExxonMobil expands algae facility; BGA market ~USD 1.1 B	Broader corporate and market validation
2019	AKUA launches kelp food products; DHA algae oil used in infant formula	Consumer-market mainstreaming of algae products
2020	FAO seaweed output reaches 35.8 M tonnes (3.1x 2000 level)	Confirms sustained Blue Revolution growth trajectory
2022	Algae biofuel market ~USD 8.38 B; global algae market ~USD 4.2 B	Post-pandemic recovery and renewed investment
2023	Viridos USD 25 M Series A funding round	Aviation-fuel pathway attracts strategic investors
2024	BGA market ~USD 2.5 B; DOE commits USD 20.2 M; EU FUELGAE EUR5 M	Coordinated government investment across regions
2025	BGA market ~USD 2.87 B; aggregated algae market >USD 11 B	Continued integration into mainstream bioeconomy

Table 4. Regional distribution of algae-sector market share by sub-sector, 2025 (approximate percentages). Sources: Grand View Research (2023); Market Research Future (2024); Renub Research (2025); FAO (2022).

Region	Biofuel Market Share	BGA Biofertilizer Share	Aquaculture Share	Key Species	Policy Driver
North America	41.3%	43.3%	~4%	*Chlorella*, *Spirulina*, *Nannochloropsis*	Renewable Fuel Standard, DOE funding, IRA
Europe	22.0%	~18%	~8%	*Ascophyllum*, *Ulva*, *Fucus*	EU Green Deal, Farm to Fork
Asia-Pacific	28.0%	~31%	~75%	*Spirulina*, kelp, *Porphyra*, *Chlorella*	National food-security policy, subsidies
Latin America	6.5%	~5%	~8%	*Spirulina*, *Dunaliella*	Brazil biofuel mandate
Middle East and Africa	2.2%	~2.7%	~5%	*Spirulina* and various	Diversification from fossil fuels

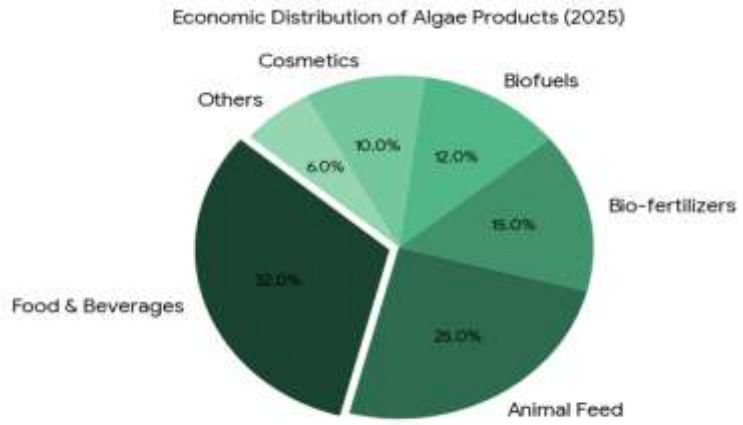

Fig. 7. Global algae market distribution by sector, highlighting the relative economic contribution of food and feed applications. Adapted, with source attribution, from Ismail *et al.* (2026).

CHALLENGES AND BARRIERS TO WIDESPREAD DEPLOYMENT

Despite substantial scientific and commercial progress documented in this review, algae's full economic potential across all three domains remains constrained by technical, economic, regulatory and social barriers.

Production Cost Economics

Microalgae biomass production costs remain considerably higher than competing feed stocks, estimated at EUR290-EUR570 per kilogram of dry weight depending on cultivation system and downstream processing requirements (Net Zero Insights, 2025), compared with approximately EUR0.4-0.6 per kilogram of protein-equivalent for soybean protein. Land-based cultivation systems - photobioreactors (PBRs) and open raceway ponds - require substantial capital expenditure (USD 250,000-2.5 million per hectare for PBR systems) alongside ongoing operational costs for lighting, temperature regulation, CO_2 supply and nutrient management.

Lower-capital open raceway ponds (USD 25,000-100,000/hectare) are constrained by lower biomass productivity (20-30 g/m2/day versus 50-90 g/m^2/day for PBRs), higher susceptibility to contamination and predation, and difficulty sustaining monocultures for high-value product streams. Algal biomass production costs have declined by an estimated 10-15% annually over the past decade due to improvements in cultivation engineering, strain genetics and harvesting technology, but a further 60-80% reduction is likely required for algae to compete directly in commodity markets (Hao Cheng *et al*., 2025).

Scalability and Technology Readiness

Most algae biotechnology applications remain at Technology Readiness Levels (TRL) 4-7 - proven at pilot or demonstration scale but not yet at full commercial scale. The transition from TRL 7 to TRL 9 (full commercial deployment) requires not only technical refinement but also regulatory clarity, investor confidence, and supply-chain and market development. Algae-based carbon capture, advanced biofuels and refined biofertilizers are all currently navigating this transition (Net Zero Insights, 2025; Bishnu Dev Das and Ajaya Bhattrai, 2025).

Regulatory, Standardization and Ecological Risk Considerations

The absence of harmonized regulatory frameworks for algae-based products useful in different purposes shown in Fig.8. introduces market uncertainty and complicates commercial uptake. In the European Union, algae-derived biofertilizers fall under the EU Fertilizing Products Regulation (EU 2019/1009), which has been expanded to include microbial biostimulants but does not explicitly address algae-based products. In the United States, algae-based feed ingredients are approved on a case-by-case basis through Generally Recognized as Safe (GRAS) determinations or FDA petitions. This regulatory fragmentation raises compliance costs disproportionately for small-scale producers and start-ups (Net Zero Insights, 2025; Industry ARC, 2022).

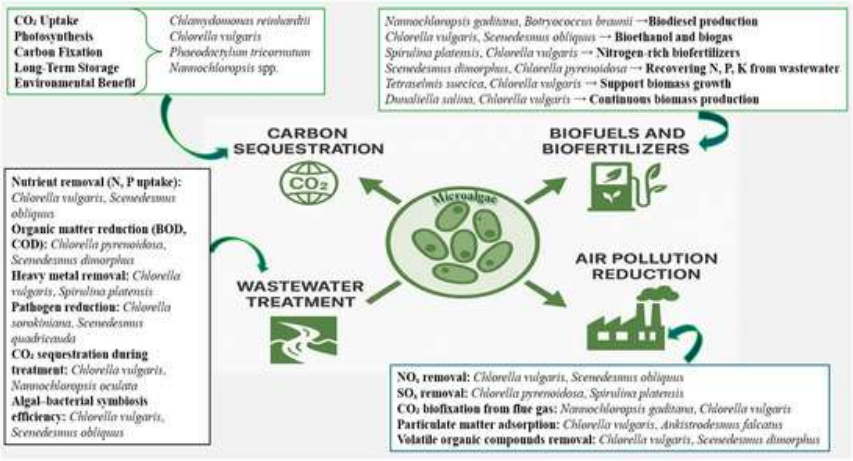

Fig. 8. Roles of microalgae in climate mitigation and ecosystem restoration, including CO_2 sequestration, wastewater purification, soil-health improvement and renewable bioproduct generation. Reproduced with source attribution from Hoque *et al*. (2025).

Large-scale algae cultivation also carries ecological risk. Release of non-native or genetically modified algal strains into natural water bodies could cause ecological disruption; the spread of the invasive brown alga *Rugulopteryx okamurae* along southern European coastlines, which has displaced native species and altered habitat structure, illustrates this risk (Bishnu Dev Das and Ajaya Bhattrai, 2025). Open cultivation systems can also cause local eutrophication if nutrient management is inadequate. Biosecurity measures, containment technology and ecological risk-assessment frameworks need to be developed alongside production scale-up rather than retrofitted afterward.

FUTURE DIRECTIONS AND RESEARCH PRIORITIES

The scientific and commercial trajectories documented in this review point to several priority research directions likely to shape algae-sector development through 2035, organized across the three domains reviewed.

Climate Technology Research Priorities

- Application of CRISPR-Cas9 and synthetic-biology approaches to carbonic anhydrase and RuBisCO enzymes to increase strain-level CO2 fixation rates.
- Development of AI-optimized photobioreactor control systems using real-time spectroscopic monitoring of biomass and metabolic state.
- Standardization of life-cycle assessment (LCA) methodology for algae-based CCU systems to enable monetization of carbon credits under Article 6 of the Paris Agreement.
- Pilot- and demonstration-scale validation of algae-integrated bioenergy with carbon capture and storage (ABECCS) at grid-relevant scale.

- Development of co-located pilot biorefinery platforms integrating industrial CO2 capture with biomass generation and multi-product recovery.

Smart Farming Research Priorities

- Genome-wide metabolic modelling of cyanobacterial consortia to identify genetic targets for improved nitrogen-fixation efficiency under field conditions.
- Long-term (10+ year) field trials assessing cumulative soil-health benefits of BGA biofertilizer application across diverse soils and climatic zones.
- Development of encapsulation and formulation technologies to extend the shelf life of live cyanobacterial biofertilizers beyond 12 months.
- Integration of machine learning into algal biostimulant application protocols within precision-agriculture platforms.
- Region- and crop-specific economic threshold analyses to determine the price point at which algal biofertilizers become cost-competitive with synthetic alternatives.

Blue Revolution Research Priorities

- Development pathways toward full replacement of fish oil with DHA- and EPA-rich microalgae in commercial salmon and marine finfish feed.
- Technologies enabling integrated multi-trophic aquaculture (IMTA) systems that co-culture algae alongside fish and shellfish production.
- Development of blue-carbon accounting protocols for seaweed cultivation to enable participation in voluntary carbon markets with verifiable, durable sequestration claims.
- High-throughput screening pipelines for marine bioactive-compound discovery across diverse algal species collections for pharmaceutical and nutraceutical applications.

POLICY FRAMEWORK AND REGULATORY LANDSCAPE

The policy environment governing algae-sector development has evolved substantially over the 25-year review period, moving from isolated national research programmes toward coordinated multilateral initiatives aligned with climate and food-security objectives.

International Frameworks

The Paris Agreement (2015), which succeeded the Kyoto Protocol (1998) in setting binding emissions-reduction targets, has increased demand for carbon-neutral and carbon-negative technologies, including algae-based systems (UNFCCC, 2015, 1998). Article 6 mechanisms are being explored for algae-based CCU systems as internationally transferred mitigation outcomes (ITMOs). The IPCC Sixth Assessment Report (AR6, 2021) includes algae-based mitigation pathways within its 1.5C warming scenarios, providing scientific standing to algal biotechnology as a climate mitigation tool (IPCC, 2021).

The FAO Blue Transformation Roadmap (2022) identifies algae cultivation as a priority practice supporting a target of doubling sustainable aquaculture production relative to 2020 baselines by 2030 (FAO, 2022). Algae-sector development is also linked to the UN Sustainable Development Goals (SDGs), including SDG 2 (zero hunger), SDG 6 (clean water), SDG 7 (clean energy), SDG 12 (responsible consumption), SDG 13 (climate action) and SDG 14 (life below water) (Hosny *et al*., 2025).

Regional Policy Initiatives

The European Green Deal and Farm to Fork Strategy set targets of 25% of EU agricultural land under organic production by 2030, alongside 50% reductions in chemical pesticide use and 20% reductions in synthetic fertilizer use - targets expected to increase demand for algae-based agricultural inputs. The EU Common Agricultural Policy (CAP) allows up to 30% of agricultural payments to be directed toward sustainable farming practices, including biofertilizer adoption. The EU Renewable Energy Directive (European Parliament & Council of the European Union, 2023) recognizes third-generation algae biofuels as eligible for enhanced multipliers under renewable-energy targets (Research Nester, 2025).

In the United States, the Inflation Reduction Act (United States Congress, 2022) allocates USD 369 billion to clean-energy and climate investments, including biofuel research and production-tax credits applicable to algae biofuels, alongside a USD 20.2 million DOE-funded algae bioenergy research programme (2024). The USDA and EPA also support algae-based biofertilizer development through the National Organic Program and renewable-energy research initiatives (Future Market Insights, 2025).

China's Dual Carbon Goals (carbon peak by 2030, carbon neutrality by 2060) and national aquaculture development plans targeting 90 million tonnes of aquaculture production by 2035 create sustained demand for both algae-based carbon-capture technology and aquaculture feed technology. Asia-Pacific is projected to record the highest regional CAGR in BGA biofertilizer adoption (approximately 10.5%, 2026-2033), reflecting alignment between algae technology and regional agriculture and food-security priorities (Abhay Kumar Singh, 2021).

CONCLUSIONS

This 25-year systematic review of algae research and market data (2000-2025) indicates that algae, as a biological platform, offer a flexible and increasingly economically significant set of tools for addressing climate change, food insecurity, energy transition and water-quality degradation. Evidence supporting this conclusion is present across all three domains reviewed.

Microalgae exhibit substantially higher CO_2 fixation capacity than terrestrial plants (reported at 40-400x on a per-unit-area basis, reflecting variation across species and cultivation systems), and the algae biofuel market has grown from USD 8.38 billion in 2022 to a projected USD 19.8 billion by 2033. In smart farming, cyanobacterial biofertilizers have demonstrated measurable agronomic benefits - 10-20% yield gains in rice and 25-40% reductions in synthetic nitrogen use - across field trials conducted in Asia, the Americas and Europe over the review period, with the sector growing from an estimated USD 600 million in 2015 to USD 2.5 billion in 2024 and a projected USD 11.24 billion by 2035.

Within the Blue Revolution, algae underpin a USD 303.55 billion global aquaculture market and have supported growth in global seaweed output to 35.8 million wet tonnes, a threefold increase over 22 years. Emerging marine bioactive compounds, algae-based aquafeed and blue-carbon protocols represent active areas of continued innovation and economic development.

Realizing this potential at scale will require sustained attention to the barriers identified in Section 8 - particularly production-cost economics, technology-readiness gaps, regulatory fragmentation, and the need for standardized life-cycle assessment methodology. Continued investment in synthetic biology, AI-driven cultivation management, precision-agriculture integration and carbon-market mechanisms represents a plausible pathway to accelerating deployment across the sector.

The 'Green Gold' metaphor is increasingly reflected in observed market data, with aggregated algae sub-sector value exceeding USD 11 billion in 2025 and a growing policy consensus across major economies. Whether this trajectory translates into algae becoming a foundational component of the 21st-century bioeconomy will depend substantially on how effectively the cost, scale-up and regulatory barriers identified in this review are addressed over 2025-2035.

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