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Review

Algae as Nature's Filters: Micro- and Macroalgal Solutions for Nutrient and Contaminant Removal in Aquatic Systems

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Abstract: Algae are emerging not merely as passive nature-based engineered bio-platforms, but as dynamic bio-circular platforms capable of simultaneously removing complex contaminant mixtures while generating vaporizable biomass within integrated water-resource systems. Freshwater and marine micro- and macroalgae possess diverse physiological and biochemical traits that enable them to assimilate excess nitrogen and phosphorus, adsorb and accumulate metals, bind organic pollutants, and immobilize emerging contaminants such as pharmaceuticals, hydrocarbons, and microplastics. This review synthesizes current knowledge on algal remediation across ecosystems, highlighting species-specific mechanisms including nutrient assimilation, biosorption, bioaccumulation, enzymatic biotransformation, extracellular polymeric substance production, and physical interception of suspended particles. Freshwater species such as *Chlorella*, *Scenedesmus*, *Oedogonium*, and *Cladophora* demonstrate high nutrient uptake rates and strong capacity to remove metals and organic contaminants in wastewater treatment and agricultural runoff systems. Marine taxa including *Nannochloropsis*, *Tetraselmis*, *Ulva*, *Gracilaria*, and *Sargassum* exhibit exceptional tolerance to salinity and complex pollutant mixtures, in context-dependent performance variability, making them effective in coastal remediation, aquaculture effluent treatment, and biosorption-based applications. Case studies from municipal wastewater facilities, constructed wetlands, integrated multi-trophic aquaculture, and coastal bioremediation platforms demonstrate high removal efficiencies and the potential for biomass valorization within circular bioeconomy frameworks. Despite these advances, challenges remain related to environmental variability, biological contamination, scalability, regulatory constraints, and the safe management of pollutant-laden biomass. Future progress will depend on advances in strain selection, system engineering, microbial consortia design, digital monitoring, and supportive policy frameworks. Overall, algae represent a robust, adaptable, and ecologically compatible approach to restoring water quality in freshwater and marine ecosystems increasingly affected by anthropogenic pressures.

Keywords: microalgae; macroalgae; phycoremediation; nutrient removal; wastewater contaminants; freshwater and marine ecosystems

1. Introduction

Aquatic environments worldwide are increasingly threatened by the continuous influx of contaminants and excess nutrients originating from agriculture, urbanization, and industrial activities. Runoff is rich in nitrogen and phosphorus from fertilized soils, effluents from wastewater treatment plants, and the discharge of chemical pollutants have intensified eutrophication, biodiversity loss, and ecological imbalance in both freshwater and marine systems [1]. Conventional remediation technologies, although effective in controlled settings, often remain costly, energy-intensive, or insufficient for addressing the complexity and scale of modern pollution. As a result, nature-based solutions are gaining prominence as sustainable, low-impact alternatives for restoring water quality [2,3].

Rather than functioning as engineered bio-platforms, algae should be conceptualized as dynamic, engineerable bio-platforms capable of coupling contaminant removal with resource recovery. Their multifunctionality arises from synergistic interactions among metabolic assimilation, surface-driven sorption processes, microbial consortia, and system-level design configurations. This systems perspective enables algae to address increasingly complex, mixed-contaminant matrices that challenge conventional unit-process treatment technologies [4].

Despite extensive research on algal-based remediation, critical knowledge gaps remain insufficiently addressed. Most existing studies focus on single-contaminant removal under controlled conditions, whereas real-world aquatic systems are characterized by complex mixtures of nutrients, metals, organic pollutants, and emerging contaminants such as microplastics and pharmaceuticals. The synergistic ecotoxicological interactions within these mixed-contaminant matrices, such as the role of microplastics as vectors for metal adsorption and transport, remain poorly resolved. Furthermore, techno-economic constraints associated with large-scale deployment, including harvesting efficiency, biomass management, and system integration into existing treatment infrastructures, are fragmented across the literature. As a result, a consolidated, critical evaluation that integrates mechanistic understanding with system-level design and scalability considerations is urgently needed.

The dual role of algae, as primary producers essential to ecosystem functioning and as biological agents capable of mitigating contamination, positions them as key components of sustainable water management strategies. This review critically synthesizes current knowledge by bridging mechanistic insights with system-level performance, emphasizing mixed-contaminant scenarios and scalability constraints to advance algae-based remediation toward deployable, circular bioeconomy solutions [5].

2. Freshwater Ecosystems

2.1. Contaminants

Freshwater ecosystems are increasingly burdened by a diverse array of contaminants originating from agricultural, urban, and industrial activities [6,7]. Agricultural runoff remains one of the dominant sources of freshwater pollution, delivering high loads of nitrogen and phosphorus from synthetic fertilizers, as well as pesticides, herbicides, and veterinary pharmaceuticals. These inputs accelerate eutrophication, promote harmful algal blooms, and disrupt nutrient cycling, ultimately degrading water quality and reducing biodiversity [1]. In parallel, urban environments contribute contaminants through stormwater runoff, sewage overflows, and effluents from wastewater treatment plants, which often contain microplastics, detergents, personal care products, endocrine-disrupting compounds, and antibiotic residues. Industrial discharges further introduce heavy metals such as cadmium, lead, chromium, and mercury, along with organic solvents, dyes, and persistent organic pollutants that accumulate in sediments and biota [7].

The complexity of freshwater contamination is intensified by the coexistence of multiple pollutant classes, many of which interact synergistically to amplify ecological stress. Excess nutrients stimulate primary productivity beyond ecosystem capacity, while chemical contaminants impair physiological functions in aquatic organisms, alter microbial communities, and compromise ecosystem resilience. Emerging contaminants, including pharmaceuticals, nanomaterials, and microplastics, pose additional challenges due to their persistence, bioaccumulation potential, and limited removal by conventional treatment technologies [8]. In this context, algae offer a promising nature-based solution for mitigating freshwater contamination. Their ability to assimilate nutrients, adsorb metals and organic pollutants, and transform or immobilize contaminants position them as engineered bio-platforms. Understanding the diversity and dynamics of freshwater contaminants is therefore essential for designing algal-based remediation strategies that are both efficient and ecologically compatible [9].

2.2. Algae as Engineered Remediation Platforms

Freshwater ecosystems contain a rich diversity of microalgae and macroalgae that demonstrated removal efficiencies under controlled conditions, capable of removing excess nutrients and chemically diverse contaminant classes spanning inorganic and organic fractions from polluted waters. Their physiological plasticity, rapid growth, and biochemical affinity for dissolved and particulate pollutants allow them to thrive in rivers, lakes, reservoirs, wetlands, and wastewater treatment systems, where they contribute significantly to the mitigation of agricultural, urban, and industrial pollution [10]. Among microalgae, species such as *Chlorella vulgaris*, *Chlorella sorokiniana*, *Auxenochlorella pyrenoidosa*, *Tetradesmus obliquus*, *Scenedesmus quadricauda*, *Desmodesmus communis*, *Ankistrodesmus falcatus*, and *Monoraphidium griffithii* (Chlorophyta) are widely recognized for their capacity to assimilate large quantities of ammonium, nitrate, and phosphate. Their high surface-area-to-volume ratios and efficient nutrient uptake kinetics enable them to reduce nutrient concentrations rapidly, often achieving removal efficiencies above 80–90% under optimized conditions. The cell walls of these species, enriched with polysaccharides and functional groups such as carboxyl, hydroxyl, and amine moieties, also facilitate strong biosorption of heavy metals including cadmium, lead, chromium, and copper. In addition to inorganic pollutants, several freshwater microalgae demonstrate notable affinity for organic contaminants [11,12].

Species like *A. pyrenoidosa* and *A. falcatus* can adsorb or transform pesticides such as atrazine and glyphosate, pharmaceuticals including diclofenac and sulfamethoxazole, and endocrine-disrupting compounds through hydrophobic interactions and enzymatic pathways. Cyanobacteriophyta such as *Limnospira platensis* and *Microcoleus autumnalis* further enhance contaminant removal due to their mucilaginous sheaths and abundant extracellular polymeric substances, which bind metals, dyes, and emerging pollutants such as microplastics and antibiotic residues [13,14].

Freshwater macroalgae, although less extensively studied than their marine counterparts, also exhibit strong remediation potential. Filamentous green algae such as *Cladophora glomerata*, *Cladophora rivularis*, *Ulothrix zonata*, *Oedogonium intermedium*, *Oedogonium capillare*, and *Rhizoclonium hieroglyphicum* (Chlorophyta) are particularly effective in nutrient-rich waters, where their extensive surface area and rapid biomass accumulation allow them to assimilate substantial quantities of nitrogen and phosphorus. Cladophora glomerata is especially notable for its exceptional phosphate uptake capacity and its ability to dominate eutrophic rivers and lakes, contributing to improved water clarity by trapping suspended solids and binding metals through its cellulose-rich cell walls [15–17]. Species of *Oedogonium*, including *O. intermedium* and *O. capillare*, have been successfully integrated into wastewater treatment systems, where they remove nutrients efficiently while producing biomass suitable for biofuel production, composting, or use as a slow-release fertilizer [17]. Freshwater red algae, though less common, also contributes to contaminant removal. Species such as *Batrachospermum gelatinosum* and *Compsopogon caeruleus* (Rhodophyta) accumulate metals and organic pollutants within their mucilaginous matrices, making them particularly effective in low-flow environments or in systems with high sediment loads [18].

The mechanisms underlying the filtration capacity of freshwater algae are diverse and complementary. Nutrient removal occurs primarily through assimilation into cellular biomass, while metals and organic pollutants are removed through biosorption onto cell walls, bioaccumulation into intracellular compartments, and biotransformation via enzymatic pathways [19]. Many species produce extracellular polymeric substances that promote flocculation, enabling the aggregation and sedimentation of suspended solids, microplastics, and colloidal contaminants. Some algae also modulate pH during photosynthesis, enhancing the precipitation of phosphorus or metals and further contributing to water purification [20].

These biological traits have led to the integration of freshwater algae into engineered remediation systems. High-rate algal ponds commonly employ species such as *C. vulgaris*, *T. obliquus*, and *D. communis* for tertiary wastewater treatment. Algal turf scrubbers dominated by *Cladophora glomerata* and *Ulothrix zonata* are used to polish effluents and intercept nutrient-rich runoff [21]. Constructed wetlands incorporating *Oedogonium* and *Rhizoclonium* species enhance nutrient removal while stabilizing sediments [22]. Hybrid algal–bacterial systems further improve contaminant degradation, and photobioreactors allow controlled cultivation of microalgal monocultures for targeted pollutant removal [23]. Across these applications, freshwater algae consistently demonstrate high removal efficiencies for nitrogen, phosphorus, heavy metals, pesticides, pharmaceuticals, dyes, and suspended solids, positioning them as powerful, low-cost, and sustainable tools for restoring water quality in contaminated freshwater environments [24].

However, the majority of these performance data are derived from controlled laboratory systems and may not directly translate to field-scale conditions characterized by fluctuating contaminant loads and environmental variability.

3. Marine Ecosystems

3.1. Contaminants

Marine ecosystems are subject to escalating multi-source contaminant pressures, a complex mixture of contaminants originating from terrestrial runoff, atmospheric deposition, maritime activities, and offshore industrial operations [25]. Coastal zones, estuaries, and open-ocean environments all receive substantial pollutant loads, although their composition and ecological consequences vary with hydrodynamics, proximity to human activities, and biogeochemical conditions. Among the most pervasive contaminants in marine waters are excess nutrients derived from agricultural fertilizers and untreated or partially treated wastewater. Elevated concentrations of nitrate and phosphate stimulate harmful algal blooms, oxygen depletion, and shifts in community structure, ultimately compromising ecosystem resilience. In addition to nutrient enrichment, marine environments accumulate a wide spectrum of chemical pollutants, including heavy metals such as mercury, cadmium, lead, chromium, and arsenic, which enter the ocean through riverine discharge, mining effluents, industrial emissions, and atmospheric transport. These metals persist in seawater and sediments, bioaccumulate in marine organisms, and disrupt physiological processes across multiple trophic levels [26,27].

Organic contaminants represent another major category of marine pollutants. Pesticides, herbicides, and fungicides transported from agricultural landscapes reach coastal waters, where they interfere with photosynthesis, reproduction, and endocrine function in marine biota [27]. Persistent organic pollutants (POPs), including polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), dioxins, and organochlorine pesticides, are of particular concern due to their long environmental half-lives, hydrophobicity, and strong tendency to accumulate in sediments and biological tissues. Pharmaceuticals and personal care products, such as antibiotics, antidepressants, hormones, UV filters, and surfactants, are increasingly detected in marine waters near densely populated regions. Their chronic, low-dose effects on marine organisms remain insufficiently understood but include altered metabolism, oxidative stress, and disruption of microbial communities essential for nutrient cycling [28].

Emerging contaminants, especially microplastics and nano-plastics, have become ubiquitous in marine ecosystems. These particles originate from the fragmentation of larger plastic debris, synthetic textiles, tire wear, and industrial microbeads. Their small size allows them to remain suspended in the water column, accumulate in surface waters, or settle into sediments, where they interact with marine organisms through ingestion, adsorption, and biofouling [29]. Microplastics also act as vectors for hydrophobic pollutants and pathogenic microorganisms, enhancing their transport and bioavailability. Additional emerging contaminants include nanoparticles (e.g., silver, titanium dioxide, zinc oxide), flame retardants, per- and polyfluoroalkyl substances (PFAS), and industrial additives, all of which exhibit persistence and potential toxicity [30].

Marine contamination is further intensified by petroleum hydrocarbons released from oil spills, shipping activities, and offshore extraction. Crude oil and refined petroleum products contain complex mixtures of toxic compounds that impair photosynthesis, respiration, and membrane integrity in marine organisms [31]. Antifouling paints used on ships introduce biocides such as tributyltin (TBT), copper compounds, and synthetic boosters into coastal waters, where they accumulate in sediments and exert long-lasting toxic effects on algae, invertebrates, and fish [32].

The combined presence of nutrients, metals, organic pollutants, plastics, and emerging contaminants creates a multifaceted stress landscape for marine ecosystems. These pollutants interact synergistically, altering food webs, reducing biodiversity, and compromising the ecological functions of primary producers such as microalgae and macroalgae. Understanding the diversity, sources, and ecological impacts of marine contaminants is essential for evaluating the potential of algae as high-performance bio-based remediation agents and for designing effective algal-based remediation strategies in marine environments [33].

3.2. Marine Algae Engineered Remediation Platforms

Marine algae, encompassing a vast diversity of microalgae and macroalgae, perform critical ecosystem and process-level functions in mitigating contamination in coastal and open-ocean environments. Their capacity to assimilate nutrients, adsorb metals, bind organic pollutants, and immobilize particulate contaminants makes them essential high-performance bio-based remediation agents in ecosystems increasingly exposed to anthropogenic stressors [34]. Marine microalgae, including species such as *Nannochloropsis oceanica*, *Microchloropsis gaditana* (Eustigmatophyceae), *Tetraselmis suecica*, *Tetraselmis chui* (Chlorophyta), *Isochrysis galbana* (Haptophyta), *Phaeodactylum tricornutum*, *Skeletonema costatum*, *Thalassiosira pseudonana* (Bacillariophyta), and *Dunaliella salina* (Chlorophyta), exhibit high nutrient uptake rates and strong tolerance to fluctuating salinity and contaminant loads [35]. Their cell walls, composed of polysaccharides, silica (in diatoms), and sulfated exopolymers, provide abundant binding sites for metals such as cadmium, copper, nickel, and chromium. Diatoms like *P. tricornutum* and *T. pseudonana* are particularly effective in adsorbing dissolved metals due to their silica frustules, which possess negatively charged functional groups that attract cationic pollutants [36]. Species such as *T. suecica* and *M. gaditana* also demonstrate strong biosorption of hydrocarbons, pharmaceuticals, and endocrine disruptors, while *D. salina* shows high tolerance to hypersaline, contaminated environments and can accumulate organic pollutants through hydrophobic interactions [37].

Marine macroalgae contribute additional remediation capacity through their large biomass, extensive surface area, and chemically complex cell walls. Brown algae (Phaeophyceae), including *Fucus vesiculosus*, *Fucus serratus*, *Ascophyllum nodo*sum, *Laminaria digitata* (Figure 1), *Laminaria hyperborea*, *Saccharina latissima*, and *Sargassum muticum* (Figure 2), are among the most effective biosorbents due to the presence of alginate, fucoidan, and polyphenols, which bind metals with high affinity [38].

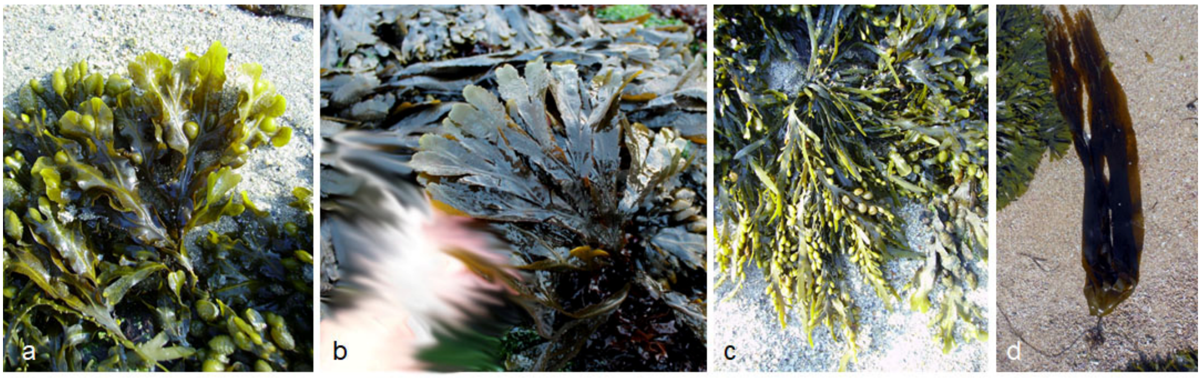

Figure 1. Brown algae—(**a**) *Fucus vesiculosus*, (**b**) *Fucus serratus*, (**c**) *Ascophyllum nodosum*, (**d**) *Laminaria digitata*.

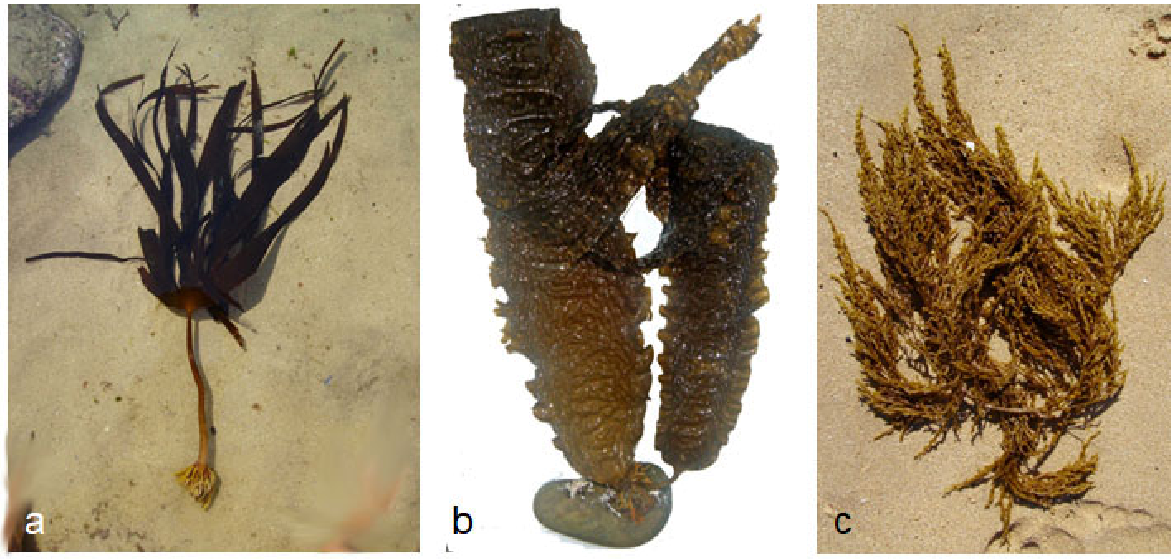

Figure 2. Brown macroalgae—(**a**) *Laminaria hyperborea*, (**b**) *Saccharina latossima*, (**c**) *Sargassum muticum*.

F. vesiculosus and *A. nodosum* are particularly efficient in removing lead, cadmium, and mercury from coastal waters, while *S. muticum* and *Sargassum fusiforme* have demonstrated strong capacity to accumulate arsenic and organic pollutants [39].

Red algae (Rhodophyta) such as *Gracilaria gracilis*, *Gracilaria vermiculophylla*, *Palmaria palmata*, *Gelidium corneum*, and *Porphyra umbilicalis* (Figure 3) contribute to nutrient and contaminant removal through their sulfated galactans (agar and carrageenan), which provide numerous binding sites for metals and dyes. *G. vermiculophylla*, widely distributed in estuarine systems, is particularly effective in assimilating ammonium and phosphate while simultaneously adsorbing copper and zinc [40].

Green macroalgae (Chlorophyta), including *Ulva lactuca*, *Ulva rigida*, *Ulva intestinalis* (Figure 4), *Ulva prolifera*, and *Caulerpa prolifera*, are well known for their rapid growth in nutrient-rich waters and their ability to remove nitrogen and phosphorus at high rates. *U. lactuca* and *U. rigida* are frequently used in integrated multi-trophic aquaculture (IMTA) systems to capture dissolved nutrients from fish farms, while *Caulerpa prolifera* and *Caulerpa taxifolia* can accumulate metals and organic pollutants within their siphonous tissues [41–43].

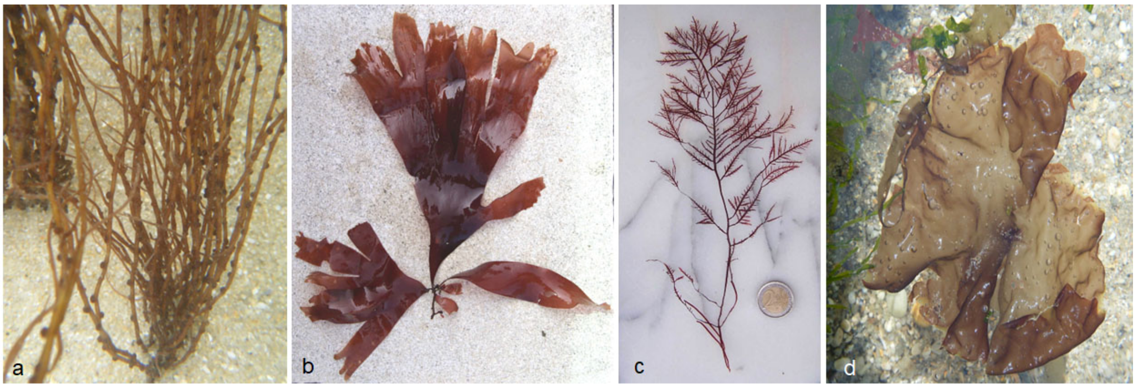

Figure 3. Red macroalgae—(**a**) *Gracilaria gracilis*, (**b**) *Palmaria palmata*, (**c**) *Gelidium corneum*, (**d**) *Porphyra umbilicalis*.

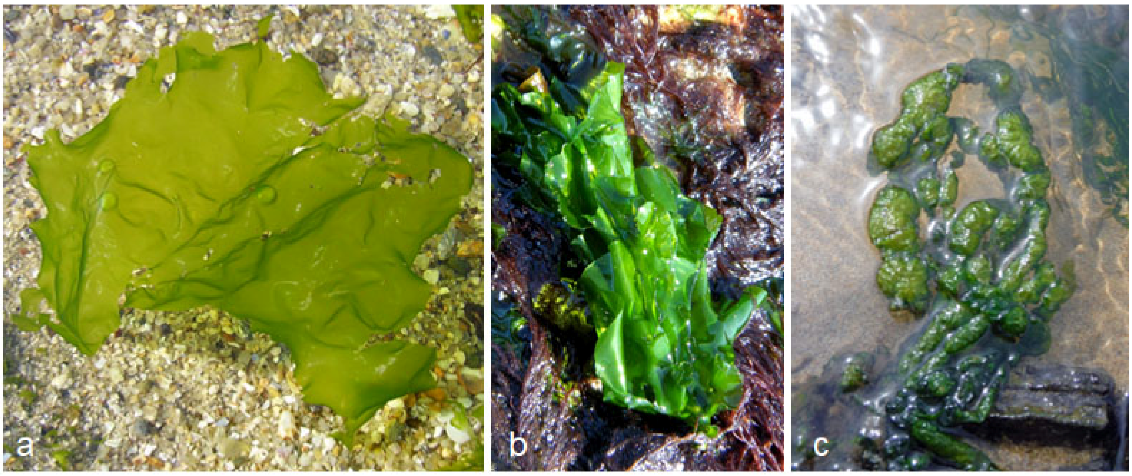

Figure 4. Green Macroalgae—(**a**) *Ulva lactuca*, (**b**) *Ulva rigida*, (**c**) *Ulva intestinalis.*

Marine algae remove contaminants through multiple mechanisms, including assimilation of dissolved nutrients into biomass, biosorption onto cell walls, intracellular bioaccumulation, enzymatic biotransformation of organic pollutants, and the production of extracellular polymeric substances that trap suspended particles, microplastics, and colloids. Many species also influence local pH and redox conditions through photosynthesis, enhancing the precipitation or immobilization of metals. Macroalgae, due to their structural complexity, additionally act as engineered bio-platforms, intercepting particulate matter and providing surfaces for microbial communities that further degrade contaminants [44].

These biological traits have led to the integration of marine algae into engineered remediation systems. Macroalgae such as *U. lactuca*, *G. gracilis*, and *S. latissima* are widely used in IMTA systems to capture nutrients from aquaculture effluents, while Sargassum species are explored for largescale biosorption of metals and organic pollutants [45]. Microalgae like *Nannochloropsis*, *Tetraselmis*, and *Phaeodactylum* are cultivated in photobioreactors and open ponds for tertiary wastewater treatment, hydrocarbon removal, and polishing of desalination brines [46]. Across these applications, marine algae consistently demonstrate high removal efficiency for nitrogen, phosphorus, metals, hydrocarbons, pharmaceuticals, and microplastics, positioning them as powerful, scalable, and ecologically compatible tools for restoring water quality in marine environments increasingly affected by anthropogenic contamination [9].

3.3. Comparative Performance of Freshwater vs. Marine Algae

Freshwater and marine algae exhibit distinct yet complementary capacities for nutrient and contaminant removal, shaped by their evolutionary histories, physiological traits, and environmental contexts. Although both groups function as highly effective engineered bio-platforms, their performance differs in terms of pollutant specificity, tolerance thresholds, uptake mechanisms, and suitability for engineered remediation systems [10].

Freshwater microalgae such as *Chlorella vulgaris*, *Tetradesmus obliquus*, *Desmodesmus communis*, and *Ankistrodesmus falcatus* typically demonstrate exceptionally high assimilation rates for ammonium, nitrate, and phosphate, reflecting their adaptation to nutrient-rich inland waters influenced by agricultural runoff and wastewater discharges. These species often outperform marine microalgae in rapid nutrient uptake due to their high growth rates and flexible metabolic pathways [47]. In contrast, marine microalgae such as *Microchloropsis gaditana*, *Tetraselmis suecica*, *Phaeodactylum tricornutum*, and *Thalassiosira pseudonana* exhibit superior tolerance to salinity fluctuations, metal stress, and organic pollutants, enabling them to thrive in coastal zones where contaminant mixtures are more complex. Their silica-based or sulfated cell walls provide abundant binding sites for metals and hydrophobic compounds, often resulting in higher biosorption capacities than those observed in many freshwater species [48].

Macroalgae show similar ecosystem-driven differences. Freshwater macroalgae such as *Cladophora glomerata*, *Oedogonium intermedium*, and *Ulothrix zonata* excel in nutrient assimilation and suspended solids removal, particularly in rivers and lakes with high turbidity and variable flow regimes. Their filamentous morphology enhances particle trapping and sediment stabilization, making them effective in wastewater polishing and constructed wetlands [49]. Marine macroalgae, especially brown algae such as *Fucus vesiculosus*, *Ascophyllum nodosum*, *Saccharina latissima*, and *Sargassum muticum*, generally outperform freshwater species in metal biosorption due to the presence of alginate, fucoidan, and polyphenolic compounds with strong chelating properties [50]. Red algae such as *Gracilaria vermiculophylla* and *Palmaria palmata* (Figure 4) further contribute to marine bioremediation through their sulfated galactans, which bind metals and dyes with high affinity [51]. Green marine macroalgae like *Ulva lactuca* and *Ulva rigida* combine rapid growth with efficient nutrient uptake, making them particularly suitable for integrated multi-trophic aquaculture systems where they capture dissolved nitrogen and phosphorus from fish farm effluents [42].

Environmental conditions also influence comparative performance. Freshwater algae often experience great variability in nutrient pulses, temperature, and hydraulic retention times, selecting for species capable of rapid physiological adjustment. Marine algae, by contrast, are adapted to higher ionic strength, more stable nutrient gradients, and the presence of hydrophobic pollutants and microplastics, which they can immobilize through adsorption, EPS production, and surface biofilm formation. While freshwater species generally excel in nutrient removal efficiency, marine species tend to show higher tolerance to contaminant mixtures and greater capacity for metal and organic pollutant biosorption [52].

In engineered systems, freshwater algae dominate high-rate algal ponds, photobioreactors, and wastewater polishing units due to their fast growth and ease of cultivation. Marine algae are more frequently used in coastal remediation, aquaculture effluent treatment, and biosorption-based systems targeting metals and persistent organic pollutants [53]. Freshwater and marine algae offer complementary strengths: freshwater species provide rapid nutrient removal and biomass productivity, while marine species deliver superior performance in metal binding, organic pollutant adsorption, and resilience to complex contaminant mixtures. Together, they form a versatile biological toolkit for addressing contamination across diverse aquatic environments [54].

Taken together, freshwater and marine algae exhibit complementary remediation capacities that are strongly context-dependent. Freshwater species generally excel in rapid nutrient assimilation under fluctuating and nutrient-rich conditions, whereas marine species demonstrate greater resilience to salinity, complex contaminant mixtures, and metal stress. A systematic comparison across pollutant classes, environmental conditions, and system configurations is therefore essential to guide species selection and engineering design. This comparative framework provides the necessary foundation for understanding the application case studies discussed in Section 5 and the mechanistic integration outlined in Section 6.

However, the majority of these performance data are derived from controlled laboratory systems and may not directly translate to field-scale conditions characterized by fluctuating contaminant loads and environmental variability.

4. Integrated Mechanistic Pathways in Algal Bio-Platforms

Algae employ a diverse suite of physiological, biochemical, and ecological mechanisms that enable them to remove, transform, or immobilize contaminants in aquatic environments. These mechanisms operate simultaneously and often synergistically, allowing micro- and macroalgae to function as highly efficient high-performance bio-based remediation agents in both freshwater and marine systems. The effectiveness of algal remediation depends on species-specific traits, environmental conditions, and the chemical nature of the pollutants, but several core processes underpin their capacity to mitigate nutrient enrichment, metal contamination, organic pollutants, and emerging contaminants such as microplastics and pharmaceuticals [55].

A primary mechanism is nutrient assimilation, through which algae incorporate dissolved nitrogen and phosphorus into cellular biomass [56]. Microalgae such as *C. vulgaris*, *T. obliquus*, *M. gaditana*, and *T. suecica* rapidly assimilate ammonium, nitrate, and phosphate via high-affinity transporters and efficient metabolic pathways, supporting fast growth and high productivity. Macroalgae, including freshwater species like *C. glomerata* and marine species such as *U. lactuca*, *G. vermiculophylla*, and *S. latissima*, also assimilate large quantities of nutrients through their extensive thalli, contributing to the reduction of eutrophication in nutrient-rich waters. This assimilation not only removes excess nutrients but also generates biomass that can be valorized for bioenergy, fertilizers, and bioproducts, supporting circular bioeconomy approaches [57].

Beyond nutrient uptake, algae play a crucial role in biosorption, a passive process in which contaminants bind to functional groups on the algal cell surface. Cell walls of microalgae and macroalgae contain polysaccharides, proteins, and lipids with carboxyl, hydroxyl, sulfate, phosphate, and amine groups that exhibit strong affinity for metal ions and organic pollutants [58]. Brown macroalgae such as *F. vesiculosus*, *A. nodosum*, and *S. muticum* are particularly effective biosorbents due to their alginate and fucoidan content, which chelate metals including cadmium, lead, copper, and mercury [59]. Red algae like *G. gracilis* and *P. palmata* bind metals and dyes through sulfated galactans, while green algae such as *U. rigida* and *C. prolifera* adsorb metals and hydrophobic contaminants via their cellulose-rich cell walls. Biosorption is rapid, reversible, and effective even at low contaminant concentrations, making it a key mechanism in both natural and engineered systems [60].

Algae also contribute to remediation through bioaccumulation, an active process in which contaminants are transported across the cell membrane and sequestered within intracellular compartments [61]. Microalgae such as *A. pyrenoidosa*, *A. falcatus*, and *P. tricornutum* accumulate metals, pesticides, pharmaceuticals, and hydrocarbons, often transforming them into less toxic forms. Intracellular sequestration may involve binding to metallothionein's, compartmentalization in vacuoles, or incorporation into organic molecules [62]. Some species, including *Dunaliella salina* and *Isochrysis galbana*, exhibit high tolerance to contaminating stress, enabling them to accumulate pollutants without significant impairment of growth or photosynthesis [63].

Another important mechanism is biotransformation, in which algae enzymatically modify contaminants, reducing their toxicity or altering their environmental behavior. Microalgae possess enzymes such as oxidases, reductases, hydrolases, and transferases that can degrade or transform pesticides (e.g., atrazine, diuron), pharmaceuticals (e.g., diclofenac, ibuprofen), and endocrine disruptors [64]. Marine diatoms like *T. pseudonana* and green microalgae such as *Tetraselmis chui* have demonstrated the ability to metabolize hydrocarbons and aromatic compounds, contributing to the natural attenuation of oil-derived pollutants. Biotransformation pathways vary among species and are influenced by nutrient availability, light intensity, and contaminant concentration [65,66].

Algae also produce extracellular polymeric substances (EPS), complex mixtures of polysaccharides, proteins, and lipids, that play a central role in contaminant removal. EPS promotes flocculation, enabling algae to trap suspended solids, colloids, microplastics, and metal-organic complexes [67]. Species such as *S. quadricauda*, *C. sorokiniana*, and marine diatoms produce abundant EPS under stress, enhancing aggregation and sedimentation of pollutants. EPS also provide binding sites for metals and hydrophobic compounds, increasing the overall sorption capacity of algal communities [68].

In addition to biochemical mechanisms, algae influence water chemistry through pH modulation and oxygenation. Photosynthetic activity increases pH and dissolved oxygen, promoting the precipitation of phosphorus and metals as insoluble salts and enhancing aerobic degradation of organic pollutants by associated microbial communities [69]. Macroalgal beds, particularly those formed by *Ulva*, *Gracilaria*, and *Sargassum*, create microhabitats that support diverse microbial assemblages capable of degrading hydrocarbons, pharmaceuticals, and other contaminants, further amplifying remediation capacity [70].

Finally, algae contribute to contaminant removal through physical interception and habitat structuring. Filamentous freshwater macroalgae such as *Oedogonium intermedium* and *Ulothrix zonata* trap suspended solids and microplastics [71], while marine macroalgae with complex thalli, such as *L. digitata* and *S. fusiforme*, intercept particulate matter and provide surfaces for biofilm development. These structural functions enhance sediment stabilization, reduce turbidity, and facilitate the retention and degradation of pollutants [72].

These mechanisms, assimilation, biosorption, bioaccumulation, biotransformation, EPS production, pH modulation, and physical interception, form a robust and multifaceted remediation toolkit [73]. Their combined action demonstrate high efficiency and mechanistic diversity of freshwater and marine algae to mitigate contamination across diverse aquatic environments and underpins their growing use in nature-based and engineered water treatment systems [74].

Algae–Bacteria/Fungi Co-Culture Systems

Algal remediation processes are increasingly understood as multi-organism systems rather than single-species functions. Co-cultivation with bacteria or fungi enhances overall performance through metabolic complementarity. Bacteria contribute to the degradation of organic pollutants and provide CO_2, vitamins, and growth factors that stimulate algal productivity. In return, algae supply oxygen and organic substrates generated via photosynthesis. Fungal–algal systems, including algal-mycelial pellets, improve biomass harvesting efficiency and facilitate flocculation of suspended particles. These synergistic interactions enhance nutrient removal, accelerate contaminant degradation, and improve system stability under variable environmental conditions.

5. Applications and Case Studies

Algae-based remediation systems have been implemented across a wide range of aquatic environments, demonstrating their capacity to remove nutrients, metals, organic pollutants, hydrocarbons, and emerging contaminants under real-world conditions. The diversity of algal species used in these applications reflects the adaptability of both freshwater and marine taxa to different pollution profiles and operational settings [75]. In freshwater systems, microalgae such as *Coelastrum microporum*, *Kirchneriella lunaris* (Chlorophyta), *Euglena gracilis* (Euglenophyta), *Fistulifera pelliculosa* (Bacillariophyta), and *Cryptomonas ovata* (Cryptophyceae) have been successfully cultivated in municipal wastewater treatment facilities, where they contribute to nutrient removal and organic matter reduction [76]. A notable example comes from a pilot plant in Poland, where *E. gracilis* achieved substantial reductions in ammonium and phosphate while simultaneously degrading phenolic compounds present in industrial effluents. Similarly, *C. microporum* has been used in high-rate algal ponds in South Africa to treat brewery wastewater, achieving high removal efficiencies for nitrogen, phosphorus, and chemical oxygen demand while producing biomass suitable for biofertilizer applications [77,78].

Freshwater macroalgae has also been applied in engineered systems, particularly in regions with high nutrient loads [79]. Species such as *Spirogyra varians*, *Hydrodictyon reticulatum* (Chlorophyta), *Nitella flexilis*, and *Chara vulgaris* (Charophyta) have been integrated into constructed wetlands and flow-through channels receiving agricultural drainage [80]. In a case study, *H. reticulatum* demonstrated exceptional capacity to remove nitrate and suspended solids from dairy farm runoff, while *Chara vulgaris* was used in Mediterranean irrigation canals to immobilize metals such as zinc and manganese [81,82]. *S. varians*, with its mucilage-rich filaments, has been shown to trap microplastics and colloidal particles in freshwater reservoirs in India, contributing to improved water clarity and reduced contaminant mobility [83].

Marine systems offer equally compelling examples of algal-based remediation. Marine microalgae such as *Halamphora coffeiformis*, *Chaetoceros muelleri* (Bacillariophyta), *Picochlorum atomus* (Chlorophyta), *Conticribra weissflogii* (Bacillariophyta), and *Diacronema lutheri* (Haptophyta) have been used in coastal wastewater polishing and aquaculture effluent treatment [84]. *Amphora coffeaeformis* was cultivated in open ponds receiving desalination brine, where it removed significant quantities of nitrogen and trace metals while tolerating high salinity and elevated temperatures [85]. *C. muelleri* has been used in shrimp aquaculture systems to reduce ammonia and nitrite concentrations, improving water quality and animal survival rates [86].

Marine macroalgae provides some of the most successful large-scale applications. Species such as *Halimeda opuntia* (Chlorophyta), *Padina pavonica*, *Turbinaria ornata*, *Dictyota dichotoma* (Phaeophyceae), *Gracilariopsis longissima* (Rhodophyta), and *Ulva ohnoi* (Chlorophyta) have been deployed in coastal remediation projects and integrated multi-trophic aquaculture (IMTA) systems. In the Mediterranean, *P. pavonica* has been used to remove copper and chromium from industrial effluents due to its high content of calcified cell wall structures that bind metals efficiently [87]. *T. ornata* has been tested in floating bioremediation platforms designed to intercept nutrient-rich stormwater before it reaches coral reefs, demonstrating high uptake rates for dissolved inorganic nitrogen [88]. *G. longissima* has been cultivated alongside seabass and seabream farms in the Aegean Sea, where it reduced dissolved nitrogen concentrations while producing biomass for agar extraction. Meanwhile, *U. ohnoi* has been integrated into Japanese IMTA systems to capture nutrients from finfish aquaculture, achieving rapid growth and high nitrogen assimilation even under fluctuating salinity conditions [89].

Algae have also been applied in the remediation of hydrocarbons and oil-derived pollutants. Marine diatoms such as *Navicula incerta* and *Cylindrotheca closterium* (Bacillariophyta) have been shown to enhance the biodegradation of petroleum hydrocarbons by supporting hydrocarbons-degrading bacteria in contaminated coastal sediments [90]. Following oil contamination events in the Arabian Gulf, natural blooms of *C. closterium* contributed to the attenuation of dispersed oil droplets, illustrating the ecological relevance of algal-microbial interactions in large-scale pollution events [91].

Finally, algae are increasingly recognized for their role in microplastic capture. Freshwater species such as *Stigeoclonium tenue* (Chlorophyta) and *Zygnema circumcarinatum* (Charophyta) produce extracellular polymeric substances that promote aggregation of microplastic particles, facilitating their sedimentation [92]. Marine macroalgae such as *Sargassopsis decurrens* (Phaeophyceae) and *Codium fragile* (Chlorophyta) have been observed to trap microplastics within their branched thalli in coastal lagoons, reducing particle mobility and enhancing local retention. Pilot studies in Italy and South Korea have demonstrated that macroalgal beds can function as natural microplastic sinks, although the long-term ecological implications of this retention require further investigation [93].

These applications and case studies highlight the versatility of algae as biologically engineered bio-platforms capable of addressing diverse contamination challenges. Their ability to remove nutrients, metals, organic pollutants, hydrocarbons, and microplastics, while generating valuable biomass, positions algae as a cornerstone of sustainable water management and ecological restoration strategies across freshwater and marine environments [9].

Co-culture systems have been successfully applied in wastewater treatment, where algal–bacterial consortia outperform monocultures in removing nitrogen, phosphorus, and organic contaminants. These systems also reduce operational costs by minimizing aeration requirements and improving biomass recovery efficiency. However, maintaining stable community composition and controlling microbial competition remain key challenges.

Inoculation density is a critical operational parameter influencing algal growth dynamics and contaminant removal efficiency. For example, *Chlorococcum sphacosum* demonstrated optimal performance in aquaculture wastewater treatment at an initial concentration of approximately 100 mg/L, achieving ammonia nitrogen and total phosphorus removal rates exceeding 98%. Lower inoculation densities resulted in insufficient biomass for effective nutrient uptake, whereas excessively high densities led to self-shading, reduced light penetration, and diminished photosynthetic efficiency. These findings highlight the importance of optimizing biomass concentration to balance growth kinetics, light availability, and nutrient assimilation capacity.

6. Challenges and Future Directions

Despite the growing evidence supporting algae-based systems as effective tools for nutrient and contaminant removal, several challenges still limit their widespread implementation and long-term reliability [94]. One of the most persistent obstacles is the variability of environmental conditions, which strongly influences algal growth, nutrient uptake rates, and contaminant removal efficiency. Fluctuations in light availability, temperature, salinity, hydraulic retention time, and pollutant concentration can cause significant performance instability, particularly in open systems exposed to seasonal or climatic variability [95]. Freshwater species, like *Dolichospermum circinale* (Cyanobacteriophyta), may experience sudden nutrient pulses or turbidity increases, while marine species must cope with hydrodynamic forces, tidal cycles, and complex contaminant mixtures. These environmental constraints complicate system design and require adaptive management strategies to maintain consistent remediation performance [96].

Another major challenge is the risk of biological contamination and competition. In open ponds, constructed wetlands, and coastal installations, algal cultures may be invaded by unwanted species, grazers, pathogens, or epiphytic organisms that reduce biomass productivity and alter community composition [97]. Maintaining monocultures of sensitive microalgae is particularly difficult, and even robust macroalgal species can be overgrown by epiphytes or displaced by opportunistic taxa. Mixed consortia offer greater ecological stability, but their performance is harder to predict and optimize [98].

The fate of accumulated contaminants represents an additional concern. Algal biomass enriched with metals, organic pollutants, or microplastics must be handled carefully to avoid reintroducing contaminants into the environment. While some biomass can be processed into biochar, fertilizers, or bioenergy feedstocks, the presence of hazardous substances may limit its safe reuse. Developing reliable post-treatment pathways and valorization strategies is therefore essential to ensure that algal remediation systems remain sustainable and do not generate secondary pollution. Importantly, contaminant removal processes should not be considered independently, as interactions among pollutants (e.g., microplastics acting as vectors for metals or hydrophobic organic compounds) can significantly alter bioavailability, uptake pathways, and overall remediation efficiency [99].

From a technological perspective, scaling up algal systems remains challenging. Photobioreactors offer high control and productivity but are costly to build and operate, limiting their use for large-volume wastewater treatment. Open systems such as raceways and algal turf scrubbers are more economical but require large land or coastal areas and are more vulnerable to environmental fluctuations. Integrating algae into existing wastewater treatment infrastructure also requires careful engineering to ensure compatibility with hydraulic flows, nutrient loads, and operational constraints [100].

Regulatory and economic barriers further hinder adoption. In many regions, regulatory frameworks do not yet recognize algae-based systems as approved treatment technologies, slowing their integration into municipal or industrial wastewater management. Economic feasibility depends on biomass valorization, yet markets for algal bioproducts remain unevenly developed. Without clear incentives or policy support, industries may be reluctant to invest in algal remediation despite its environmental benefits [101].

Looking ahead, several promising research directions could significantly enhance the performance and applicability of algal-based remediation. Advances in strain selection, domestication, and metabolic engineering may yield species with improved tolerance to contaminants, higher nutrient uptake rates, or enhanced biosorption capacity [102]. Omics-based approaches can help identify genetic and metabolic traits associated with resilience and remediation efficiency, enabling targeted breeding or genetic modification. The development of synthetic consortia combining algae with bacteria, fungi, or other microorganisms offers another promising avenue, as these multispecies systems can exploit complementary metabolic pathways and improve contaminant degradation [103].

Technological innovation will also play a central role. Hybrid systems that combine photobioreactors with constructed wetlands, membrane technologies, or bio-electrochemical systems may offer improved control and efficiency. Floating algal platforms, offshore macroalgal cultivation structures, and modular treatment units could expand the use of algae in coastal and marine environments. Digital monitoring tools, including remote sensing, automated sensors, and AI-based predictive models, may help optimize system performance under variable environmental conditions [104].

Despite the high biosorption capacity of brown macroalgae such as *Fucus* and *Sargassum*, this process is strongly influenced by environmental and physicochemical parameters. Limiting conditions include pH (optimal typically between 4 and 6 for metal binding), ionic strength (competition with Na^+, Ca^{2+} reduces adsorption efficiency in marine systems), temperature, and the presence of competing ions or organic ligands. Additionally, saturation of functional groups (e.g., carboxyl and sulfate moieties in alginate) imposes an upper limit on metal uptake capacity. Biomass pre-treatment, particle size, and diffusion limitations also affect sorption kinetics. These constraints highlight that biosorption performance observed under laboratory conditions may not directly translate to field-scale systems with complex water chemistry.

Future progress will depend on integrated policy frameworks and circular bioeconomy strategies that recognize the dual value of algae as both remediation agents and biomass resources. Aligning environmental regulations, economic incentives, and industrial applications will be essential to support large-scale deployment. As pressures on freshwater and marine ecosystems intensify, algae-based remediation offers a promising, nature-based pathway toward sustainable water management, provided that scientific, technological, and regulatory challenges are addressed through coordinated research and innovation [105].

A critical limitation across the current literature is the lack of standardized methodologies for quantifying contaminant removal efficiencies. Reported values, often exceeding 80–90%, are frequently derived from heterogeneous experimental conditions, analytical techniques, and reporting formats, limiting cross-study comparability and reproducibility. To enhance scientific robustness and facilitate meta-analyses, future research should align analytical protocols with internationally recognized standards, such as the American Public Health Association (APHA) Standard Methods for the Examination of Water and Wastewater, as well as relevant ISO water quality guidelines. Standardized reporting should include explicit details on initial concentrations, hydraulic retention times, biomass densities, analytical detection limits, and mass balance considerations. Establishing such benchmarking frameworks will be essential to transition algal remediation from experimental systems to reliable, large-scale applications.

6.1. Digital Monitoring and Machine Learning Applications

Recent advancements in machine learning (ML) and remote sensing have enabled real-time monitoring and predictive modeling of algal systems in both natural and engineered environments. ML algorithms can integrate spectral imaging data, environmental parameters, and historical datasets to estimate algal biomass density, detect bloom dynamics, and predict nutrient removal performance. Techniques such as convolutional neural networks (CNNs) and random forest models are increasingly used to analyze satellite imagery and in situ sensor data. However, challenges remain related to data availability, model generalization across ecosystems, and integration with process control systems. Future research should focus on coupling ML-driven monitoring with adaptive control strategies to optimize algal remediation performance under dynamic environmental conditions.

6.2. Technical Barriers in Algal Genetic and Metabolic Engineering

Genetic and metabolic engineering of algae offers promising avenues to enhance contaminant removal and biomass productivity; however, several technical barriers limit practical implementation. Transformation efficiency remains low in many algal species, particularly macroalgae, due to complex cell wall structures and limited availability of stable expression systems. Regulatory challenges associated with genetically modified organisms (GMOs) further restrict environmental deployment. Additionally, metabolic modifications may introduce trade-offs, such as reduced growth rates or decreased environmental robustness. The stability of engineered traits under fluctuating environmental conditions remains uncertain, particularly in open systems. Scaling engineered strains from laboratory to field conditions therefore requires advances in synthetic biology tools, genome editing techniques, and ecological risk assessment frameworks.

6.3. Industrial Conversion Challenges in Algal Biomass Valorization

While algal biomass presents significant opportunities for conversion into biofuels, fertilizers, animal feed, and high-value bioproducts, several industrial bottlenecks remain. Harvesting and dewatering processes are energy-intensive and contribute substantially to operational costs. Conversion pathways such as lipid extraction, anaerobic digestion, or thermochemical processing often require pre-treatment steps that reduce overall process efficiency. Biomass contaminated with heavy metals or organic pollutants further complicates downstream utilization, limiting its suitability for feed or agricultural applications and necessitating additional detoxification steps. Supply chain variability, including inconsistencies in biomass composition due to fluctuating environmental conditions, also challenges process standardization. Economic feasibility ultimately depends on integrated biorefinery approaches that couple remediation with high-value product streams, yet these systems remain at early stages of commercialization.

7. Conclusions

Algae represent one of the most versatile and powerful nature-based solutions available for mitigating nutrient enrichment and chemical contamination in aquatic environments. Across freshwater and marine ecosystems, both microalgae and macroalgae demonstrate a demonstrated removal efficiencies under controlled conditions of excess nitrogen and phosphorus, adsorb and accumulate metals, bind organic pollutants, and immobilize emerging contaminants such as pharmaceuticals, hydrocarbons, and microplastics. Their effectiveness arises from a combination of physiological traits, biochemical pathways, and structural characteristics that enable them to function simultaneously as primary producers and engineered bio-platforms. Species-specific differences, shaped by evolutionary history and environmental adaptation, allow algae to address a wide spectrum of pollution scenarios, from agricultural runoff and municipal wastewater to industrial effluents and coastal aquaculture discharges.

The case studies reviewed in this manuscript highlight the growing maturity of algal-based remediation systems, which are now implemented at scales ranging from laboratory photobioreactors to full-scale high-rate algal ponds, constructed wetlands, integrated multi-trophic aquaculture installations, and coastal bioremediation platforms. These applications consistently demonstrate high removal efficiencies for nutrients and contaminants while generating biomass that can be valorized for bioenergy, fertilizers, feed, and bioproducts. Such dual functionality positions algae as key components of emerging circular bioeconomy strategies aimed at coupling environmental restoration with sustainable resource production.

Despite these advances, several challenges remain, including environmental variability, biological contamination, scalability constraints, regulatory uncertainty, and the need for safe and economically viable pathways for biomass utilization. Addressing these limitations will require coordinated efforts in strain selection, system engineering, microbial consortia design, digital monitoring, and policy development. Future research should focus on enhancing resilience, improving contaminant-specific performance, and integrating algae into hybrid treatment systems that combine biological, physical, and chemical processes.

Overall, algae offer a robust, adaptable, and ecologically compatible approach to restoring water quality in both freshwater and marine environments. As global pressures on aquatic ecosystems intensify, algal-based remediation stands out as a promising and increasingly essential strategy for sustainable environmental management.

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Conflicts of Interest

The author declares no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

References

1. Bamaniya, P.; Vaghela, D.T.; Tandel, V.; et al. Linking Terrestrial and Aquatic Systems: Pollutant Transport, Bioaccumulation Cycles, and Global Food Security. In *Plastic Tides: Tackling Plastic Pollution for Global Food Security*; Abubakr, A., Malik, M., Amin, A., Eds.; Springer: Cham, Switzerland, 2026; pp. 195–228. https://doi.org/10.1007/978-3-032-17411-6_8.
2. Shamshad, J.; Ur Rehman, R. Innovative approaches to sustainable wastewater treatment: A comprehensive exploration of conventional and emerging technologies. *Environ. Sci. Adv.* **2024**, *4*, 189–222. https://doi.org/10.1039/d4va00136b.
3. Ramesh, B.; Saravanan, A.; Senthil Kumar, P.; et al. A review on algae biosorption for the removal of hazardous pollutants from wastewater: Limiting factors, prospects and recommendations. *Environ. Pollut.* **2023**, *327*, 121572. https://doi.org/10.1016/j.envpol.2023.121572.
4. Osathanunkul, M.; Thanaporn, S.; Karapetsi, L.; et al. Diversity of Bioactive Compounds in Microalgae: Key Classes and Functional Applications. *Mar. Drugs* **2025**, *23*, 222. https://doi.org/10.3390/md23060222.
5. Nur, M.M.A.; Mahreni; Murni, S.W.; Setyoningrum, T.M.; et al. Innovative strategies for utilizing microalgae as dual-purpose biofertilizers and phycoremediators in agroecosystems. *Biotechnol. Rep.* **2025**, *45*, e00870. https://doi.org/10.1016/j.btre.2024.e00870.
6. Jolaosho, T.L.; Rasaq, M.F.; Omotoye, E.V.; et al. Microplastics in freshwater and marine ecosystems: Occurrence, characterization, sources, distribution dynamics, fate, transport processes, potential mitigation strategies, and policy interventions. *Ecotoxicol. Environ. Saf.* **2025**, *294*, 118036. https://doi.org/10.1016/j.ecoenv.2025.118036.
7. Müller, A.; Österlund, H.; Marsalek, J.; et al. The pollution conveyed by urban runoff: A review of sources. *Sci. Total Environ.* **2020**, *709*, 136125. https://doi.org/10.1016/j.scitotenv.2019.136125.
8. Singh, C.K.; Sodhi, K.K.; V, N.; et al. Managing the complexity of emerging contaminants in aquatic environments: Exploring their ecotoxicological impacts, detection techniques, and the use of innovative technologies for their remediation. *Discov. Catal.* **2025**, *2*, 9. https://doi.org/10.1007/s44344-025-00013-8.
9. Omokaro, G.O.; Nafula, Z.S.; Iloabuchi, N.E.; et al. Microalgae as biofactories for sustainable applications: Advancing carbon sequestration, bioenergy, and environmental remediation. *Sustain. Chem. Clim. Action* **2025**, *7*, 100098. https://doi.org/10.1016/j.scca.2025.100098.
10. Astuti, S.P.; Hashmi, Z.; Bilad, M.R.; et al. Freshwater microalgae as bioindicators: A review of trait-based advances, ecosystem insights, and biomonitoring innovations. *Environ. Chall.* **2026**, *22*, 101428. https://doi.org/10.1016/j.envc.2026.101428.
11. Pachés, M.; Martínez-Guijarro, R.; González-Camejo, J.; et al. Selecting the most suitable microalgae species to treat the effluent from an anaerobic membrane bioreactor. *Environ. Technol.* **2020**, *41*, 267–276. https://doi.org/10.1080/09593330.2018.1496148.
12. de Oliveira, K.L.; da Silva Oliveira, J.L.; Moraes, E.A.; et al. Cultivation of microalgae *Chlorella vulgaris*, *Monoraphidium* sp. and *Scenedesmus obliquus* in wastewater from the household appliance industry for bioremediation and biofuel production. *3 Biotech* **2024**, *14*, 294. https://doi.org/10.1007/s13205-024-04142-z.
13. Majewska, M.; Harshkova, D.; Pokora, W.; et al. Does diclofenac act like a photosynthetic herbicide on green algae? *Chlamydomonas reinhardtii* synchronous culture-based study with atrazine as reference. *Ecotoxicol. Environ. Saf.* **2021**, *208*, 111630. https://doi.org/10.1016/j.ecoenv.2020.111630.
14. Akmukhanova, N.R.; Seiilbek, S.N.; Zayadan, B.K.; et al. Harnessing Microalgae and Cyanobacteria for Sustainable Pesticide Biodegradation: Advances, Challenges, and Ecological Benefits. *Microorganisms* **2025**, *13*, 2404. https://doi.org/10.3390/microorganisms13102404.
15. Panchal, S.K.; Ghattamaneni, N.K.R.; Magnusson, M.; et al. Freshwater Macroalgae, Oedogonium, Grown in Wastewater Reduce Diet-Induced Metabolic Syndrome in Rats. *Int. J. Mol. Sci.* **2022**, *23*, 13811. https://doi.org/10.3390/ijms232213811.
16. Lawton, R.; de Nys, R.; Paul, N. Selecting Reliable and Robust Freshwater Macroalgae for Biomass Applications. *PLoS ONE* **2013**, *8*, e64168. https://doi.org/10.1371/journal.pone.0064168.

17. Neveux, N.; Magnusson, M.; Mata, L.; et al. The treatment of municipal wastewater by the macroalga Oedogonium sp. and its potential for the production of biocrude. *Algal Res.* **2016**, *13*, 284–292. https://doi.org/10.1016/j.algal.2015.12.010.
18. Guruge, H. Ecological, Morphological and Biochemical Study of Freshwater Red Algae *Batrachospermum* sp. Bachelor’s Thesis, Munster Technological University, Cork, Ireland, 2021. https://doi.org/10.13140/RG.2.2.26663.00166.
19. Barra, L.; Greco, S. The Potential of Microalgae in Phycoremediation. In *Microalgae-Current and Potential Applications*; Aydin, S., Ed.; IntechOpen: London, UK, 2023. https://doi.org/10.5772/intechopen.1003212.
20. Gopalakrishnan, K.; Kashian, D.R. Extracellular polymeric substances in green alga facilitate microplastic deposition. *Chemosphere* **2022**, *286*, 131814. https://doi.org/10.1016/j.chemosphere.2021.131814.
21. Abdel-Raouf, N.; Al-Homaidan, A.A.; Ibraheem, I.B.M. Microalgae and wastewater treatment. *Saudi J. Biol. Sci.* **2012**, *19*, 257–275. https://doi.org/10.1016/j.sjbs.2012.04.005.
22. Fernandez-Fernandez, M.I.; Vega, P.; Jaramillo-Morán, M.A.; et al. Hybrid Constructed Wetland to Improve Organic Matter and Nutrient Removal. *Water* **2020**, *12*, 2023. https://doi.org/10.3390/w12072023.
23. Jayabal, R. Microalgae-bacteria systems in wastewater treatment and biofuel production: Challenges, advances, and future perspectives. *Algal Res.* **2025**, *91*, 104228. https://doi.org/10.1016/j.algal.2025.104228.
24. El-Sheekh, M.M.; El-Kassas, H.Y.; Ali, S.S. Microalgae-based bioremediation of refractory pollutants: An approach towards environmental sustainability. *Microb. Cell Factories* **2025**, *24*, 19. https://doi.org/10.1186/s12934-024-02638-0.
25. Wijesinghe, S.M.K.; Karunarathna, B.G.H.D.; Kumarawansha, W.K.M.G.; et al. Marine pollution: The global challenge of ocean contaminants and mitigation efforts. *Anthr. Coasts* **2026**, *9*, 5. https://doi.org/10.1007/s44218-025-00107-8.
26. Rasmussen, J.A.; Ingleton, T.; Bennett, W.W.; et al. The effects of estuarine outflows on coastal marine ecosystems in New South Wales, Australia. *Mar. Pollut. Bull.* **2024**, *208*, 116915. https://doi.org/10.1016/j.marpolbul.2024.116915.
27. Madesh, S.; Gopi, S.; Sau, A.; et al. Chemical contaminants and environmental stressors induced teratogenic effect in aquatic ecosystem—A comprehensive review. *Toxicol. Rep.* **2024**, *13*, 101819. https://doi.org/10.1016/j.toxrep.2024.101819.
28. Akhtar, A.B.T.; Naseem, S.; Yasar, A.; et al. Persistent Organic Pollutants (POPs): Sources, Types, Impacts, and Their Remediation. In *Environmental Pollution and Remediation*; Prasad, R., Ed.; Springer: Singapore, 2021; pp. 213–246. https://doi.org/10.1007/978-981-15-5499-5_8.
29. Farale, H.; Sreevidhya, K.B.; Bathinapatla, A.; et al. Impact of plastic contaminants on marine ecosystems and advancement in the detection of micro/nano plastics: A review. *J. Hazard. Mater. Adv.* **2025**, *18*, 100736. https://doi.org/10.1016/j.hazadv.2025.100736.
30. Mallek, M.; Barceló, D. Analysis and Risks of Emerging Contaminants and Microplastics in Natural and Treated Waters and Human Health: A Critical Review. *J. Xenobiotics* **2026**, *16*, 93. https://doi.org/10.3390/jox16030093.
31. Mamozai, W.; Hesam, A.M.; Hemma, W.H. Impacts of Crude Oils on Water Quality: A Comprehensive Review. *Eur. J. Theor. Appl. Sci.* **2024**, *2*, 126–138. https://doi.org/10.59324/ejtas.2024.2(1).09.
32. Voulvoulis, N.; Scrimshaw, M.D.; Lester, J.N. Comparative environmental assessment of biocides used in antifouling paints. *Chemosphere* **2002**, *47*, 789–795. https://doi.org/10.1016/S0045-6535(01)00336-8.
33. Sun, S.; Hu, X.; Kang, W.; et al. Combined effects of microplastics and warming enhance algal carbon and nitrogen storage. *Water Res.* **2023**, *233*, 119815. https://doi.org/10.1016/j.watres.2023.119815.
34. Cadar, E.; Popescu, A.; Dragan, A.-M.-L.; et al. Bioactive Compounds of Marine Algae and Their Potential Health and Nutraceutical Applications: A Review. *Mar. Drugs* **2025**, *23*, 152. https://doi.org/10.3390/md23040152.
35. Esteves, M.V.; Marques, D.M.C.; de Almeida, J.D.; et al. Marine Microalgae–Microorganism Co-Cultures: An Insight into *Nannochloropsis* sp. Use and Biotechnological Applications. *Foods* **2025**, *14*, 1522. https://doi.org/10.3390/foods14091522.
36. Srivastava, P.; Singh, S.; Dubey, S. Exploring Role of Bioactive Molecules produced by Diatoms in Heavy Metal Alleviation. *Int. J. Sci. Eng. Technol.* **2025**, *13*. https://doi.org/10.5281/zenodo.17184342.
37. Rojas-Villalta, D.; Rojas-Rodríguez, D.; Villanueva-Ilama, M.; et al. Exploring Extremotolerant and Extremophilic Microalgae: New Frontiers in Sustainable Biotechnological Applications. *Biology* **2024**, *13*, 712. https://doi.org/10.3390/biology13090712.
38. Anisha, G.S.; Padmakumari, S.; Patel, A.K.; et al. Fucoidan from Marine Macroalgae: Biological Actions and Applications in Regenerative Medicine, Drug Delivery Systems and Food Industry. *Bioengineering* **2022**, *9*, 472. https://doi.org/10.3390/bioengineering9090472.
39. Wang, S.; Qiu, Y.; Zhu, F. A comparative review of red, green, and brown seaweed: Bioactive components, health effects, and machine learning approaches. *Food Res. Int.* **2026**, *234*, 118420. https://doi.org/10.1016/j.foodres.2026.118420.
40. Baghel, R.S.; Reddy, C.R.K.; Jha, B. Characterization of agarophytic seaweeds from the biorefinery context. *Bioresour. Technol.* **2014**, *159*, 280–285. https://doi.org/10.1016/j.biortech.2014.02.083.
41. Khan, N.; Sudhakar, K.; Mamat, R. Eco-friendly nutrient from ocean: Exploring *Ulva* seaweed potential as a sustainable food source. *J. Agric. Food Res.* **2024**, *17*, 101239. https://doi.org/10.1016/j.jafr.2024.101239.
42. Wichard, T.; Mapelli-Brahm, P.; Barba, F.J.; et al. Green seaweed *Ulva* spp. bioprocessing: Bioactive molecules, emerging extraction technologies, and industrial applications in the circular bioeconomy. *Bioresour. Technol.* **2026**, *445*, 134066. https://doi.org/10.1016/j.biortech.2026.134066.

43. Theobald, E.J.; Irving, A.D.; Capper, A.; et al. Selection of marine macroalgae for nutrient biofilter and bioproduct trials in the coastal waters of Queensland, Australia. *Aquac. Int.* **2024**, *32*, 9631–9669. https://doi.org/10.1007/s10499-024-01632-y.
44. Yang, X.; Wang, H.; Zhang, L.; et al. Marine algae facilitate transfer of microplastics and associated pollutants into food webs. *Sci. Total Environ.* **2021**, *787*, 147535. https://doi.org/10.1016/j.scitotenv.2021.147535.
45. Narvarte, B.C.V.; Hinaloc, L.A.R.; Gonzaga, S.M.C.; et al. Exploring the suitable extractive species in an IMTA: Inorganic nutrient removal from mariculture effluents by commercially important marine macroalgae. *Bot. Mar.* **2025**, *68*, 403–415. https://doi.org/10.1515/bot-2025-0014.
46. Ansari, F.A.; Hassan, H.; Al-Ouweini, A.S.S.; et al. An Integrated Algal Biorefinery Approach for Wastewater Treatment and Biomass Valorisation. *Sustainability* **2026**, *18*, 2123. https://doi.org/10.3390/su18042123.
47. Okomoda, V.T.; Abdulrahman, A.K.; Khatoon, H.; et al. Performance Characteristics of Ankistrodesmus falcatus in Different Culture Media and Concentration. *Plants* **2021**, *10*, 755. https://doi.org/10.3390/plants10040755.
48. Bautista-Chamizo, E.; Sendra, M.; De Orte, M.R.; et al. Comparative effects of seawater acidification on microalgae: Single and multispecies toxicity tests. *Sci. Total Environ.* **2019**, *649*, 224–232. https://doi.org/10.1016/j.scitotenv.2018.08.225.
49. Wu, J.; Rogers, S.W.; Schaummann, R.; et al. A Comparison of Multiple Macroalgae Cultivation Systems and End-Use Strategies of *Saccharina latissima* and *Gracilaria tikvahiae* Based on Techno-Economic Analysis and Life Cycle Assessment. *Sustainability* **2023**, *15*, 12072. https://doi.org/10.3390/su151512072.
50. Davis, T.A.; Volesky, B.; Mucci, A. A review of the biochemistry of heavy metal biosorption by brown algae. *Water Res.* **2003**, *37*, 4311–4330. https://doi.org/10.1016/S0043-1354(03)00293-8.
51. Mansour, A.T.; Alprol, A.E.; Ashour, M.; et al. Do Red Seaweed Nanoparticles Enhance Bioremediation Capacity of Toxic Dyes from Aqueous Solution? *Gels* **2022**, *8*, 310. https://doi.org/10.3390/gels8050310.
52. La Bella, E.; Occhipinti, P.S.; Puglisi, I.; et al. Comparative Phycoremediation Performance of Three Microalgae Species in Two Different Magnitude of Pollutants in Wastewater from Farmhouse. *Sustainability* **2023**, *15*, 11644. https://doi.org/10.3390/su151511644.
53. Posadas, E.; Alcántara, C.; García-Encina, P.A.; et al. 3—Microalgae cultivation in wastewater. In *Microalgae-Based Biofuels and Bioproducts*; Gonzalez-Fernandez, C., Muñoz, R., Eds.; Woodhead Publishing: Cambridge, UK, 2017; pp. 67–91. https://doi.org/10.1016/B978-0-08-101023-5.00003-0.
54. González Fernández, L.A.; Medellín Castillo, N.A.; Sánchez Polo, M.; et al. Algal-Based Carbonaceous Materials for Environmental Remediation: Advances in Wastewater Treatment, Carbon Sequestration, and Biofuel Applications. *Processes* **2025**, *13*, 556. https://doi.org/10.3390/pr13020556.
55. Alazaiza, M.Y.D.; Albahnasawi, A.; Ahmad, Z.; et al. Potential use of algae for the bioremediation of different types of wastewater and contaminants: Production of bioproducts and biofuel for green circular economy. *J. Environ. Manag.* **2022**, *324*, 116415. https://doi.org/10.1016/j.jenvman.2022.116415.
56. Calijuri, M.L.; Do Couto, E.D.A.; Assemany, P.P.; et al. Microalgae-Based Wastewater Treatment and Biomass Valorization: Insights, Challenges, and Opportunities from 15 Years of Research. *ACS Omega* **2025**, *10*, 49273–49299. https://doi.org/10.1021/acsomega.5c04364.
57. Delran, P.; Barthe, L.; Peydecastaing, J.; et al. Advances in the development of microalgal biorefinery processes: The case of Tetraselmis suecica. *Biotechnol. Adv.* **2026**, *90*, 108900. https://doi.org/10.1016/j.biotechadv.2026.108900.
58. Faruque, M.O.; Uddin, S.; Hossain, M.M.; et al. A comprehensive review on microalgae-driven heavy metals removal from industrial wastewater using living and nonliving microalgae. *J. Hazard. Mater. Adv.* **2024**, *16*, 100492. https://doi.org/10.1016/j.hazadv.2024.100492.
59. Lodeiro, P.; Cordero, B.; Barriada, J.L.; et al. Biosorption of cadmium by biomass of brown marine macroalgae. *Bioresour. Technol.* **2005**, *96*, 1796–1803. https://doi.org/10.1016/j.biortech.2005.01.002.
60. Ferreira, M.; Salgado, J.M.; Fernandes, H.; et al. Potential of Red, Green and Brown Seaweeds as Substrates for Solid State Fermentation to Increase Their Nutritional Value and to Produce Enzymes. *Foods* **2022**, *11*, 3864. https://doi.org/10.3390/foods11233864.
61. Danouche, M.; El Ghachtouli, N.; El Arroussi, H. Phycoremediation mechanisms of heavy metals using living green microalgae: Physicochemical and molecular approaches for enhancing selectivity and removal capacity. *Heliyon* **2021**, *7*, e07609. https://doi.org/10.1016/j.heliyon.2021.e07609.
62. Chugh, M.; Kumar, L.; Shah, M.P.; et al. Bioremediation of heavy metals: An insight into removal mechanisms, recovery of by-products, challenges, and future opportunities. *Energy Nexus* **2022**, *7*, 100129. https://doi.org/10.1016/j.nexus.2022.100129.
63. Folgar, S.; Torres, E.; Pérez-Rama, M.; et al. Dunaliella salina as marine microalga highly tolerant to but a poor remover of cadmium. *J. Hazard. Mater.* **2009**, *165*, 486–493. https://doi.org/10.1016/j.jhazmat.2008.10.010.
64. Narayanan, I.; Rajamanickam, R.; Singh, R.K.; et al. Microalgae-based remediation of pharmaceutical contaminants: Emerging strategies and technological synergies. *Discov. Appl. Sci.* **2025**, *7*, 1288. https://doi.org/10.1007/s42452-025-07226-4.
65. Paniagua-Michel, J.; Banat, I.M. Unravelling Diatoms' Potential for the Bioremediation of Oil Hydrocarbons in Marine Environments. *Clean Technol.* **2024**, *6*, 93–115. https://doi.org/10.3390/cleantechnol6010007.

66. Paterson, S.; Gómez-Cortés, P.; de la Fuente, M.A.; et al. Bioactivity and Digestibility of Microalgae *Tetraselmis* sp. and *Nannochloropsis* sp. as Basis of Their Potential as Novel Functional Foods. *Nutrients* **2023**, *15*, 477. https://doi.org/10.3390/nu15020477.
67. Xiao, R.; Zheng, Y. Overview of microalgal extracellular polymeric substances (EPS) and their applications. *Biotechnol. Adv.* **2016**, *34*, 1225–1244. https://doi.org/10.1016/j.biotechadv.2016.08.004.
68. Minhas, A.K.; Gaur, S.; Sunny, S.; et al. Microalgae-Based Wastewater Treatment Processes for the Bioremediation and Valorization of Biomass: A Review. *Phycology* **2026**, *6*, 18. https://doi.org/10.3390/phycology6010018.
69. Mohsenpour, S.F.; Hennige, S.; Willoughby, N.; et al. Integrating micro-algae into wastewater treatment: A review. *Sci. Total Environ.* **2021**, *752*, 142168. https://doi.org/10.1016/j.scitotenv.2020.142168.
70. Guo, Z.; Wang, L.; Jiang, Z.; et al. Comparison studies of epiphytic microbial communities on four macroalgae and their rocky substrates. *Mar. Pollut. Bull.* **2022**, *176*, 113435. https://doi.org/10.1016/j.marpolbul.2022.113435.
71. Li, X.; Liu, W.; Zhang, J.; et al. Effective removal of microplastics by filamentous algae and its magnetic biochar: Performance and mechanism. *Chemosphere* **2024**, *358*, 142152. https://doi.org/10.1016/j.chemosphere.2024.142152.
72. Garden, C.J.; Smith, A.M. Voyages of seaweeds: The role of macroalgae in sediment transport. *Sediment. Geol.* **2015**, *318*, 1–9. https://doi.org/10.1016/j.sedgeo.2014.11.007.
73. Verma, L.; Ekka, A.; Banjara, R.A.; et al. A Review on Bacterial Exopolysaccharides for Heavy Metal Remediation: Mechanisms, Challenges, and Sustainable Applications. *Water Environ. Res.* **2025**, *97*, e70184. https://doi.org/10.1002/wer.70184.
74. Filote, C.; Roșca, M.; Hlihor, R.M.; et al. Sustainable Application of Biosorption and Bioaccumulation of Persistent Pollutants in Wastewater Treatment: Current Practice. *Processes* **2021**, *9*, 1696. https://doi.org/10.3390/pr9101696.
75. Wang, T.; Patyal, S.; Naushad, M.; et al. Sustainable water remediation with algae-derived adsorbents: From synthesis strategies to adsorption performance and mechanisms. *RSC Adv.* **2026**, *16*, 18770–18800. https://doi.org/10.1039/d5ra09740a.
76. Popa, M.D.; Simionov, I.-A.; Petrea, S.M.; et al. Efficiency of Microalgae Employment in Nutrient Removal (Nitrogen and Phosphorous) from Municipal Wastewater. *Water* **2025**, *17*, 260. https://doi.org/10.3390/w17020260.
77. Nezbrytska, I.; Shamanskyi, S.; Pavliukh, L.; et al. Application of *Euglena gracilis* in wastewater treatment processes. *BioTechnologia* **2022**, *103*, 323–330. https://doi.org/10.5114/bta.2022.120702.
78. Mousavi, S.; Najafpour, G.D.; Mohammadi, M.; et al. Cultivation of newly isolated microalgae *Coelastrum* sp. in wastewater for simultaneous CO_2 fixation, lipid production and wastewater treatment. *Bioprocess Biosyst. Eng.* **2018**, *41*, 519–530. https://doi.org/10.1007/s00449-017-1887-7.
79. Jayasooriya, N.; Gavin, C.; Craggs, R.; et al. Properties of cellulose from four freshwater macroalgae cultivated under high nutrient conditions. *Cellulose* **2026**, *33*, 1927–1943. https://doi.org/10.1007/s10570-026-06974-9.
80. Gordon, B.A.; Lenhart, C.; Peterson, H.; et al. Reduction of nutrient loads from agricultural subsurface drainage water in a small, edge-of-field constructed treatment wetland. *Ecol. Eng.* **2021**, *160*, 106128. https://doi.org/10.1016/j.ecoleng.2020.106128.
81. Volodina, A.; Gerb, M. Findings of Water Net *Hydrodictyon reticulatum* (Hydrodictyaceae, Chlorophyta) in the Curonian Lagoon. *Bot. Lith.* **2013**, *19*. https://doi.org/10.2478/botlit-2013-0006.
82. Van Oosten, M.J.; Maggio, A. Functional biology of halophytes in the phytoremediation of heavy metal contaminated soils. *Environ. Exp. Bot.* **2015**, *111*, 135–146. https://doi.org/10.1016/j.envexpbot.2014.11.010.
83. Salari, Z.; Danafar, F.; Dabaghi, S.; et al. Sustainable synthesis of silver nanoparticles using macroalgae *Spirogyra varians* and analysis of their antibacterial activity. *J. Saudi Chem. Soc.* **2016**, *20*, 459–464. https://doi.org/10.1016/j.jscs.2014.10.004.
84. Minggat, E.; Roseli, W.; Tanaka, Y. Nutrient Absorption and Biomass Production by the Marine Diatom *Chaetoceros muelleri*: Effects of Temperature, Salinity, Photoperiod, and Light Intensity. *J. Ecol. Eng.* **2021**, *22*, 231–240. https://doi.org/10.12911/22998993/129253.
85. Rajaram, M.G.; Nagaraj, S.; Manjunath, M.; et al. Biofuel and Biochemical Analysis of Amphora coffeaeformis RR03, a Novel Marine Diatom, Cultivated in an Open Raceway Pond. *Energies* **2018**, *11*, 1341. https://doi.org/10.3390/en11061341.
86. Reis Batista, I.; Garcia, A.B.; van Dalen, P.; et al. Culturing *Chaetoceros muelleri* using simplified media with different N sources: Effects on production and lipid content. *Eur. J. Phycol.* **2015**, *50*, 92–99. https://doi.org/10.1080/09670262.2014.994137.
87. Leandro, A.; Pereira, L.; Gonçalves, A.M.M. Diverse Applications of Marine Macroalgae. *Mar. Drugs* **2020**, *18*, 17. https://doi.org/10.3390/md18010017.
88. Ramesh, C.H.; Koushik, S.; Shunmugaraj, T.; et al. Bioinvasive Seaweed Genus, Turbinaria in Coral Reefs of Gulf of Mannar. *J. Life Sci. Res.* **2019**, *6*, 1–4.
89. He, Q.; Zhang, J.; Chai, Z.; et al. *Gracilariopsis longissima* as biofilter for an Integrated Multi-Trophic aquaculture (IMTA) system with Sciaenops ocellatus: Bioremediation efficiency and production in a recirculating system. *Indian J. Geo-Mar. Sci.* **2014**, *43*, 528–537.

90. Rajapaksha, Y.; Jayarathne, K.; Nadeesha, D.; et al. Seaweeds for Bioremediation: Removal of Oil From Seawater. 2020. Available online: https://www.researchgate.net/publication/357900791_Seaweeds_for_Bioremediation_Removal_of_Oil_From_Seawater (accessed on 20 May 2026).
91. Al-Thani, R.F.; Yasseen, B.T. Cyanoremediation of Polluted Seawater in the Arabian Gulf: Risks and Benefits to Human Health. *Processes* **2024**, *12*, 2733. https://doi.org/10.3390/pr12122733.
92. Jiang, Y.; Niu, S.; Wu, J. The role of algae in regulating the fate of microplastics: A review for processes, mechanisms, and influencing factors. *Sci. Total Environ.* **2024**, *949*, 175227. https://doi.org/10.1016/j.scitotenv.2024.175227.
93. Ng, K.L.; Suk, K.F.; Cheung, K.W.; et al. Macroalgal morphology mediates microplastic accumulation on thallus and in sediments. *Sci. Total Environ.* **2022**, *825*, 153987. https://doi.org/10.1016/j.scitotenv.2022.153987.
94. Yang, K.; Wang, J.; Zheng, J.; et al. Microalgae-based wastewater treatment: Advances and challenges in membrane harvesting technologies. *Sep. Purif. Technol.* **2025**, *360*, 130805. https://doi.org/10.1016/j.seppur.2024.130805.
95. Amaro, H.M.; Salgado, E.M.; Nunes, O.C.; et al. Microalgae systems—Environmental agents for wastewater treatment and further potential biomass valorisation. *J. Environ. Manag.* **2023**, *337*, 117678. https://doi.org/10.1016/j.jenvman.2023.117678.
96. Mitrovic, S.M.; Oliver, R.L.; Rees, C.; et al. Critical flow velocities for the growth and dominance of *Anabaena circinalis* in some turbid freshwater rivers. *Freshw. Biol.* **2003**, *48*, 164–174. https://doi.org/10.1046/j.1365-2427.2003.00957.x.
97. Plouviez, M.; Copedo, J.; Ingebrigtsen, R.; et al. Chapter 14—Biological contaminants in large-scale microalgae cultures. In *Handbook of Microalgae-Based Processes and Products*, 2nd ed.; Jacob-Lopes, E., Maroneze, M.M., Queiroz, M.I., et al., Eds.; Academic Press: Cambridge, MA, USA, 2026; pp. 271–297. https://doi.org/10.1016/B978-0-443-34082-6.00013-1.
98. Naseema Rasheed, R.; Pourbakhtiar, A.; Mehdizadeh Allaf, M.; et al. Microalgal co-cultivation -recent methods, trends in omic-studies, applications, and future challenges. *Front. Bioeng. Biotechnol.* **2023**, *11*, 1193424. https://doi.org/10.3389/fbioe.2023.1193424.
99. Song, U.; Park, H. Importance of biomass management acts and policies after phytoremediation. *J. Ecol. Environ.* **2017**, *41*, 13. https://doi.org/10.1186/s41610-017-0033-4.
100. Ali, S.S.; Mastropetros, S.G.; Schagerl, M.; et al. Recent advances in wastewater microalgae-based biofuels production: A state-of-the-art review. *Energy Rep.* **2022**, *8*, 13253–13280. https://doi.org/10.1016/j.egyr.2022.09.143.
101. Koko, I.; Ibrahim, E.; Almomani, F.; et al. Breaking the barriers towards large-scale microalgae-based bio-hydrogen production. *Int. J. Hydrogen Energy* **2025**, *193*, 152133. https://doi.org/10.1016/j.ijhydene.2025.152133.
102. Fabris, M.; Abbriano, R.M.; Pernice, M.; et al. Emerging Technologies in Algal Biotechnology: Toward the Establishment of a Sustainable, Algae-Based Bioeconomy. *Front. Plant Sci.* **2020**, *11*, 279. https://doi.org/10.3389/fpls.2020.00279.
103. Zhang, C.; Singh, R.P.; Yadav, P.; et al. Recent advances in biotechnology and bioengineering for efficient microalgal biofuel production. *Fuel Process. Technol.* **2025**, *270*, 108199. https://doi.org/10.1016/j.fuproc.2025.108199.
104. Abonyi, M.N.; Obi, C.C.; Nwabanne, J.T.; et al. Emerging and ecofriendly biological methods for agricultural wastewater treatment. *Environ. Syst. Res.* **2024**, *13*, 45. https://doi.org/10.1186/s40068-024-00373-4.
105. Sarker, N.K.; Kaparaju, P. Microalgal Bioeconomy: A Green Economy Approach Towards Achieving Sustainable Development Goals. *Sustainability* **2024**, *16*, 11218. https://doi.org/10.3390/su162411218.