

Review

Harnessing Microalgae for Aquatic Ecosystem Restoration: Implementation Strategies, Challenges and Future Perspectives

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Featured Application

Aquatic ecosystem degradation driven by nutrient enrichment, contaminant accumulation, habitat deterioration and other anthropogenic stressors represents a major ecological challenge. Understanding the range of microalgae-based restoration strategies could advance sustainable approaches for alleviating ecological stress, improving ecosystem resilience and supporting nutrient removal, contaminant remediation, carbon sequestration, and ecosystem recovery across freshwater, coastal, and marine environments.

Abstract

Aquatic ecosystems are increasingly impacted by anthropogenic pressures, including nutrient over-enrichment, industrial discharge and physical habitat alteration, resulting from industrialization, urbanization, agricultural intensification and population growth. In recent years, microalgae have been extensively studied in engineered and controlled systems for their potential role in aquatic ecosystem restoration, owing to their capacity to assimilate nutrients, sequester contaminants and interact with microbial consortia, alongside valuable biomass generation. While most of the existing studies are based on ex situ systems, such as high-rate algal ponds, wastewater treatment reactors, algal–bacterial granular sludge, constructed wetlands and aquaculture effluent treatment units, these processes provide mechanistic insights relevant to aquatic ecosystem restoration. Hence, this review critically evaluates the emerging role of microalgae in aquatic ecosystem restoration, mainly through two implementation pathways, namely ex situ engineered systems and in situ applications, based on the current state of the art in microalgae-driven processes, with particular emphasis on nutrient uptake pathways and mechanisms. Furthermore, key challenges and future directions associated with the translational potential of microalgae-based approaches, including field-scale validation, ecological performance assessment, operational stability and regulatory integration, essential for real-world aquatic ecosystem restoration, are discussed. Despite the limitations in direct field-scale restoration, microalgae-based strategies are promising and sustainable platforms for aquatic ecosystem rehabilitation, which align with Sustainable Development Goals 6 and 14.

Keywords: aquatic ecosystem; microalgae; pollutant removal; microalgae–bacteria consortia; sustainability



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1. Introduction

Aquatic ecosystems, including rivers, lakes, wetlands, estuaries, and marine environments, are crucial regulators of biogeochemical cycles and support a wide range of ecosystem services that are fundamental to ecological integrity and human well-being. These aquatic ecosystems contribute to nutrient cycling, carbon (C) sequestration, primary production, and water purification, while supporting fisheries, aquaculture, and freshwater supplies, which govern the regional and global economy [1]. Disruptions to aquatic ecosystem functioning have direct consequences for biodiversity conservation, food security, and water quality management, making their protection and restoration a key objective of contemporary environmental policy and a core target of Sustainable Development Goals (SDGs) 6 and 14. Nevertheless, intensified anthropogenic pressures associated with industrialization, urbanization, agricultural mass production, and rapid population growth over the recent decades have resulted in excessive alterations to the physical, chemical, and biological structures of aquatic ecosystems via chemical pollution, habitat destruction, and climate change (Figure 1). Excessive inputs of nitrogen (N) and phosphorus (P) from agricultural runoff and untreated wastewater discharges lead to eutrophication and increase the frequency of hypoxic events, leading to declines in biodiversity and ecosystem conservation [2]. Meanwhile, the accumulation of inorganic contaminants, including heavy metals (HMs), pharmaceuticals, pesticides, and microplastics in aquatic environments, is an additional persistent stressor, interfering with physiological processes across various ecosystems, while increasing risks to human health through bioaccumulation [3]. Climate-related changes, including elevated temperatures, altered precipitation patterns, and ocean acidification, have been affecting aquatic ecosystems by destabilizing biogeochemical cycles and reducing the resilience of aquatic ecosystems [4,5].

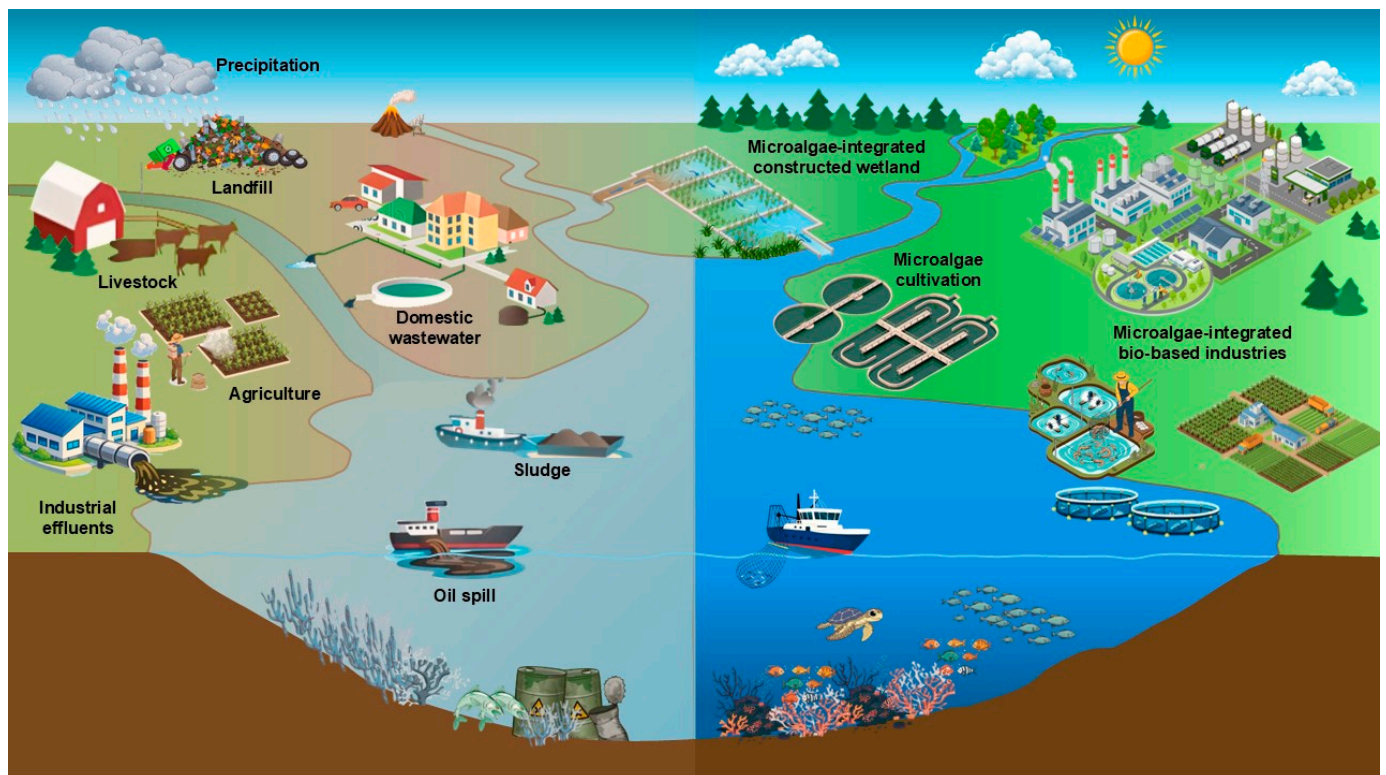


Figure 1. A conceptual schematic representation of the effects on aquatic ecosystems by natural and anthropogenic pollution, and the role of microalgae-based bioremediation in improving water quality and restoring environmental conditions.

These consequences have necessitated aquatic ecosystem restoration, which encompasses interventions aimed at recovering ecological structure, functional processes, and resilience in degraded aquatic environments. Unlike conventional treatment systems primarily focused on pollutant removal or water quality improvement, successful restoration requires sustained recovery of habitat integrity, ecological interactions, biogeochemical functioning, and long-term ecosystem stability [6]. Accordingly, numerous aquatic ecosystem restoration strategies, encompassing physical, chemical, and biological interventions, have been developed and globally implemented. Physical approaches such as dredging, habitat reconstruction, and sediment removal could rapidly modify the structure of aquatic ecosystems, while disrupting benthic processes and requiring repeated applications [7,8]. Similarly, chemical treatments, namely P inactivation and algaecides, reduce nutrient availability over a short period, while introducing secondary environmental risks [9,10]. Although biological methods including biomanipulation through fish stocking or macrophyte reintroduction have demonstrated successful restoration, they are often limited by hydrological constraints, sediment instability, and slow establishment rates [11]. Consequently, many conventional restoration techniques are targeted at discrete consequences of degradation rather than restoring biological processes, which regulate nutrient turnover, redox dynamics, and pollutant removal.

In this regard, microalgae cultivation has emerged as a promising biological tool for supporting aquatic ecosystem restoration due to its ability to directly influence nutrient cycling, oxygen dynamics, contaminant transformation, and microbial interactions [12,13]. As primary producers, microalgae demonstrate high nutrient uptake efficiencies and the capacity for pollutant transformation, thereby reducing eutrophic pressure and suppressing harmful algal blooms that destabilize aquatic food webs [14,15]. Microalgae facilitate attenuation of diverse organic and inorganic contaminants, including HMs, pharmaceuticals and emerging pollutants, through biosorption, bioaccumulation, and biotransformation [16]. The photosynthetic activity of microalgae further enhances the availability of dissolved oxygen (DO) and regulates redox conditions, promoting aerobic microbial degradation and reducing hypoxia-induced ecological stress. Furthermore, microalgal biomass generated through bioremediation processes could be valorized into biofuels, biofertilizers, animal feed, and other valuable bioproducts, which integrate circular bioeconomy principles into aquatic ecosystem restoration (Figure 1).

While extensive research has been conducted on microalgae-based wastewater treatment, phycoremediation and resource recovery systems, the existing literature has predominantly focused on optimizing treatment performance under controlled engineered conditions, with limited focus on the restoration of ecological processes in degraded aquatic ecosystems. Accordingly, the present review aims to address this gap in the literature by evaluating the potential of microalgae as a tool for ecosystem-scale rehabilitation and exploring the integration of microalgae-based bioremediation strategies into aquatic ecosystem restoration frameworks. This review discusses the key microalgae-driven pollutant removal and transformation mechanisms, including nutrient uptake pathways, contaminant attenuation processes and microalgae–microbe interaction dynamics, which are essential for functional performance in aquatic ecosystems. Building on this mechanistic foundation, the review critically evaluates microalgae-based implementation pathways, namely ex situ engineered systems that mitigate external pollutant loading prior to discharge and in situ applications, which directly modulate ecological processes within receiving aquatic environments. Furthermore, the present review discusses the key technical and ecological constraints limiting field-scale deployment of microalgae-based strategies, along with future research directions for scalable and sustainable aquatic ecosystem restoration.

2. Mechanistic Pathways of Microalgal-Based Approaches for Aquatic Ecosystem Restoration

Microalgae contribute to aquatic ecosystem restoration through biological, chemical, and ecological processes operating across spatial and temporal scales by regulating nutrient availability, contaminant fate, sediment stability, and oxygen dynamics [17–19]. These interconnected processes support aquatic ecosystem restoration by improving water quality, restoring habitat conditions, and enhancing ecosystem functionality in degraded aquatic environments. In this regard, the current section critically explores the microalgal-mediated nutrient removal mechanisms and their roles in supporting the aquatic ecosystem restoration.

2.1. Nutrient Assimilation Pathways

Excessive N and P loading from anthropogenic sources is a major driver of eutrophication and ecological degradation in aquatic ecosystems, where pollutant inputs are primarily composed of dissolved inorganic nitrogen (DIN) such as ammonium (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-), as well as dissolved inorganic phosphorus (DIP), predominantly present as orthophosphates (PO_4^{3-} , HPO_4^{2-} , H_2PO_4^-). Furthermore, organic N and P, and particulate organic matter mainly enter aquatic ecosystems through surface runoff, point sources including municipal sewage and industrial wastewater, and sediments [20,21]. When nutrient concentrations exceed ecosystem-specific thresholds associated with eutrophication risk, excessive phytoplankton proliferation and ecological degradation may occur [22]. Due to high nutrient removal efficiencies of ~70–100% for N and ~80–100% for P, microalgae are widely employed as biological agents in aquatic ecosystem restoration, particularly for eutrophication control and improving water quality [23–25].

As illustrated in Figure 2, among DIN forms, NH_4^+ is preferentially assimilated for amino acid synthesis due to lower energy requirements, whereas NO_3^- undergoes sequential reduction to NO_2^- by nitrate reductase (NR) and subsequently to NH_4^+ by nitrite reductase (NiR) prior to the assimilation into cellular metabolism [26,27]. Certain organic N sources, including urea and free amino acids, can also be utilized after transport into the cell and conversion to NH_4^+ [26]. Additionally, microalgae assimilate P through cellular pathways that enable rapid uptake, intracellular storage, and regulated reutilization of P. DIP, primarily as H_2PO_4^- and HPO_4^{2-} , is transported into the cell membrane via phosphate transporters and converted into phosphorylated intermediates required for nucleic acid synthesis, phospholipid biosynthesis, and energy metabolism (Figure 2). P is either utilized in cellular metabolism or stored as intracellular polyphosphate (poly-P) via luxury P uptake, enabling subsequent remobilization under P-limited conditions [28–30].

In ex situ restoration systems designed for eutrophication control, chlorophytes, such as *Chlorella vulgaris*, *Scenedesmus* spp., *Desmodesmus* spp., and *Chlamydomonas reinhardtii* can be widely exploited due to their efficient nutrient assimilation capacities [23,31,32]. Similarly, in marine and brackish aquatic ecosystems, euryhaline microalgae including *Nannochloropsis* sp., *Tetraselmis* sp., *Dunaliella salina*, and *Isochrysis galbana* demonstrate robust assimilation of NO_3^- , NH_4^+ , urea, and orthophosphate under saline and varying nutrient conditions [33–35]. However, microalgal nutrient assimilation mechanisms support ecosystem restoration only when assimilated nutrients are retained within biomass and prevented from rapid re-release through biomass decay. Therefore, biomass harvesting, stable grazing pathways, sediment burial, or long-term biomass retention are essential for sustained nutrient removal. Moreover, sustained nutrient attenuation may suppress eutrophication, improve water transparency, facilitate macrophyte recolonization, and support the recovery of ecological interactions and ecosystem functioning where nutrient enrichment is a dominant driver of degradation.

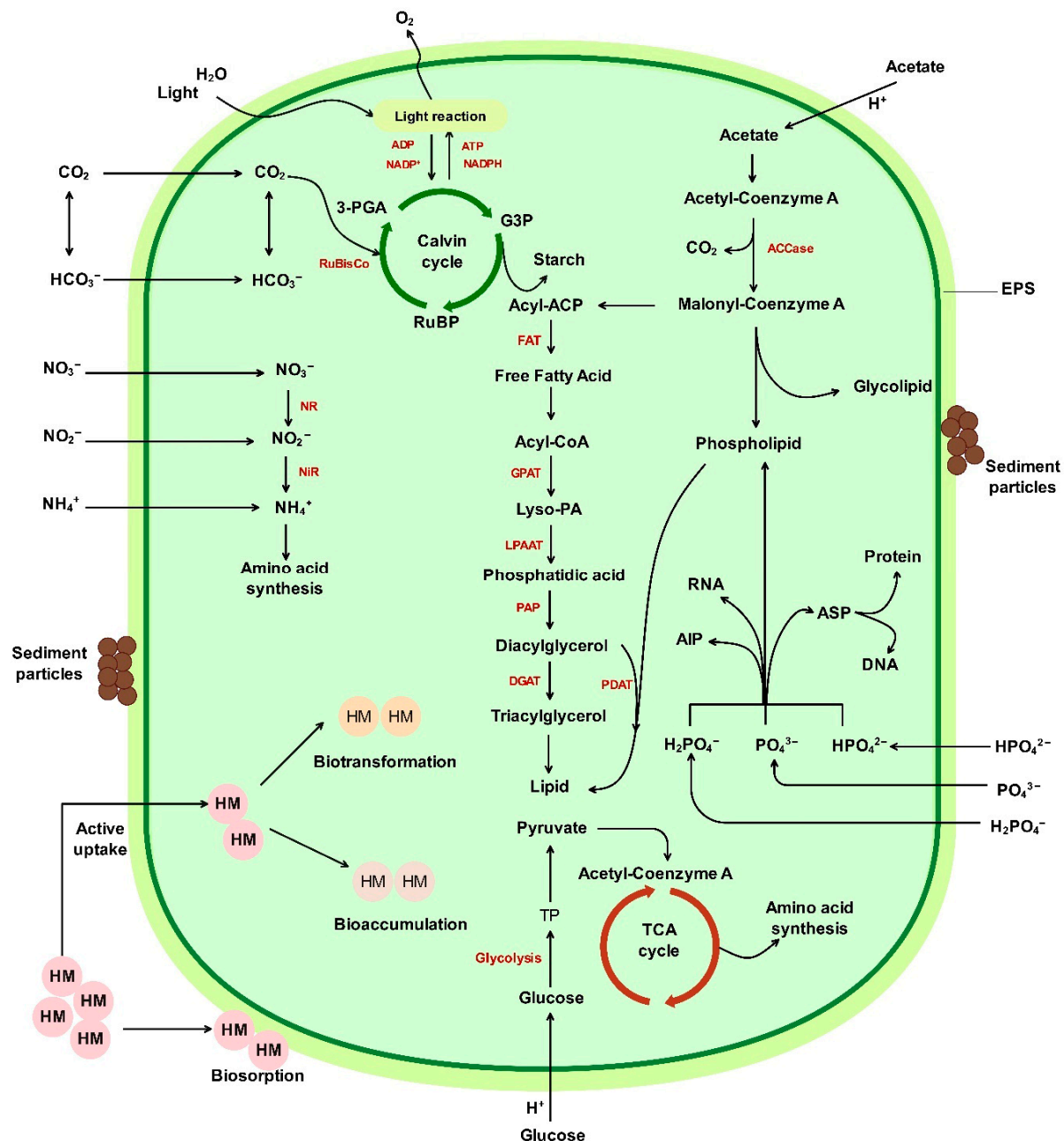


Figure 2. Mechanisms involved in microalgae-based nutrient and heavy metal removal. Abbreviations—RuBisCo: ribulose-1,5-bisphosphate carboxylase/oxygenase, RuBP: ribulose-1,5-bisphosphate, 3-PGA: 3-phosphoglycerate, G3P: glyceraldehyde-3-phosphate, ATP: adenosine triphosphate, ADP: adenosine diphosphate, NADPH: nicotinamide adenine dinucleotide phosphate, NADP⁺: oxidized nicotinamide adenine dinucleotide phosphate, TP: triose phosphate, TCA: tricarboxylic acid, ACCase: acetyl-CoA carboxylase, ACP: acyl carrier protein, FAT: fatty acyl-ACP thioesterase, GPAT: glycerol-3-phosphate acyltransferase, Lyso-PA: lysophosphatidic acid, LPAAT: lysophosphatidic acid acyltransferase, PAP: phosphatidic acid phosphatase, DGAT: diacylglycerol acyltransferase, PDAT: phospholipid/diacylglycerol acyltransferase, AIP: acid-insoluble polyphosphate, ASP: acid-soluble polyphosphate, RNA: ribonucleic acid, DNA: deoxyribonucleic acid, PO₄³⁻: phosphate, H₂PO₄⁻: dihydrogen phosphate, HPO₄²⁻: hydrogen phosphate, NO₃⁻: nitrate, NO₂⁻: nitrite, NH₄⁺: ammonium, NR: nitrate reductase, NiR: nitrite reductase, CO₂: carbon dioxide, HCO₃⁻: bicarbonate, O₂: oxygen, H₂O: water, HM: heavy metal, EPS: extracellular polymeric substances.

2.2. Organic Carbon Attenuation and Detoxification

In polluted aquatic ecosystems, elevated concentrations of organic C (OC), measured as total OC (TOC) and dissolved OC (DOC), are major pollutants that result in excessive microbial oxygen consumption, reducing light penetration through increased turbidity, and enhanced transportation of toxic pollutants [36]. Microalgae attenuate OC through indirect and synergistic mechanisms, where photosynthetic oxygen production stimulates aerobic heterotrophic degradation of labile organic matter, thereby accelerating TOC/DOC reduction. Several microalgal species, such as *C. vulgaris* and *Scenedesmus* sp., exhibit mixotrophic growth, enabling the direct assimilation of OC compounds such as acetate, formate, simple sugars (i.e., glucose), and amino acids via membrane transporters, followed by their incorporation into central C metabolism, as shown in Figure 2 [37,38]. Microalgae facilitate hydrocarbon attenuation through algal–bacterial interactions, where oxygen release supports aerobic hydrocarbon degradation, reducing the organic pollutant toxicity and supporting the recovery of polluted aquatic ecosystems [39].

2.3. Heavy Metal Removal

HMs including cadmium (Cd), mercury (Hg), arsenic (As) and lead (Pb), pose significant risks to aquatic ecosystems due to their persistence, toxicity, and bioaccumulation potential [40]. Microalgae remove HM toxicity through complementary extracellular and intracellular detoxification pathways that reduce metal bioavailability (Figure 2). EPS and cell surface polysaccharides facilitate the bioadsorption and immobilization of HM ions outside the cell, while absorbed metals are subsequently sequestered within cellular compartments or chelated by metal-binding biomolecules, such as metallothioneins and phytochelatins [19,41]. For instance, Waluyo et al. [42] investigated the bioremediation potential of Pb biosorption using the marine microalgae *Nannochloropsis oculata*, with reported removal efficiencies of 28–55%. Similarly, *Chlorella sorokiniana* SU1 and *Picochlorum oklahomensis* were utilized for vanadium (III) treatment, achieving a maximum removal of 25.5 mg L^{−1} after 14 days [43]. Microalgal HM removal predominantly results in metal immobilization and reduced bioavailability, rather than complete transformation into non-toxic forms. Consequently, its long-term restoration potential depends on the stability of immobilized metals and the prevention of subsequent remobilization.

2.4. Removal of Emerging Organic Pollutants

Microalgae have gained significant attention for removal of emerging pollutants including pharmaceuticals, plastics, pesticides, and herbicides, due to their increasing occurrence and ecological risks in aquatic environments. For instance, García-Galán et al. [44] reported that microalgae removed pharmaceuticals through biosorption and bioaccumulation, whereas Hom-Díaz et al. [45] reported that microalgal strains, *C. reinhardtii* and *Dunaliella tertiolecta*, exhibited promising removal performance for antibiotics and antidepressant venlafaxine, with biodegradation identified as the dominant removal mechanism. Microalgae may contribute to plastic and microplastic attenuation through biofilm formation, surface colonization, aggregation, and synergistic interactions with plastisphere microbial communities, thereby enhancing plastic weathering and microbial degradation [46]. However, evidence supporting the complete biodegradation or mineralization of microplastics remains limited and is largely confined to laboratory-scale studies, suggesting that microalgae primarily facilitate indirect degradation rather than complete mineralization.

Moreover, microalgae could remove pesticides and herbicides and use them as N and C sources, depending upon the compositions and chemical structures [19]. Several microalgal species, including *Chlorella*, *Chlamydomonas*, *Scenedesmus*, and *Nostoc* have been reported to achieve removal efficiencies exceeding 90% for different pesticides, primarily through the biodegradation mechanism [47]. In a study by Avila et al. [48], a microalgal consortium bioremediated three active hydrophobic pesticide compounds, namely chlorpyrifos, cypermethrin, and oxadiazon, through combined biodegradation, biosorption and photodegradation mechanisms. The attenuation of emerging contaminants reduces toxicological stress and bioaccumulation risks in aquatic biota, thereby supporting the recovery of microbial and trophic interactions, improving habitat quality, and enhancing ecosystem functioning in polluted aquatic environments.

2.5. Sediment Stabilization and Extracellular Polymeric Substances Secretion

Sediment resuspension and excessive turbidity could impair light penetration, disrupt primary productivity, degrade aquatic habitats, and alter ecosystem functioning. Through biofilm formation and EPS production, microalgae contribute to sediment stabilization, which suppresses sediment resuspension and regulates sediment–water exchanges [49]. Microalgal EPS, composed primarily of polysaccharides, proteins, lipids, and uronic acids, form cohesive matrices that bind sediment particles and enhance resistance to erosion (Figure 2) [50,51]. In shallow aquatic systems, benthic microalgal communities, including diatoms, euglenoids, and cyanobacteria, form microphytobenthic biofilms that stabilize sediment surfaces and reduce erosion. However, the effectiveness of biofilm-mediated stabilization remains highly site-dependent, as hydrodynamic forcing, sediment properties, grazing pressure, and seasonal variability can compromise biofilm persistence and sediment-binding capacity [52]. For example, Ge et al. [50] demonstrated that sediments treated with intact microalgal biofilms composed of diatoms and *Chlorella* exhibited significantly higher resistance to erosion and greater long-term stability than sediments treated with pure EPS.

2.6. Oxygenation, Redox Regulation and Carbon Cycling

Dissolved oxygen (DO) depletion from eutrophication and organic pollution degrades habitat and biodiversity. Microalgal photosynthesis is a key regulator of oxygen availability and redox dynamics in aquatic ecosystems, with implications for biogeochemical cycling and ecosystem recovery [53]. Through photosynthetic activity, microalgae release oxygen into the water column and sediment–water interface, promoting aerobic processes such as nitrification, organic matter mineralization, and oxidative contaminant degradation [54], while shifting redox conditions towards oxidizing states that suppress associated anaerobic pathways [53]. Furthermore, at the sediment surface, oxygen leakage from benthic microalgae establishes microscale redox gradients that limit P release from iron-bound sediment pools and reduce sulfide and methane buildup [17,55], while enhancing oxygenation to facilitate the recolonization of oxygen-sensitive organisms [56,57], which indirectly supports food web recovery and resilience. During nighttime, respiration without photosynthesis (diel cycles) can drive oxygen to critical low ranges [58], and decomposition of accumulated biomass increases oxygen demand, potentially resulting in localized oxygen depletion. Consequently, the ecological outcome of microalgal oxygenation depends on maintaining a positive balance between oxygen generation and oxygen consumption across both diel and seasonal timescales.

Beyond regulating oxygen and redox conditions, microalgae also mediate aquatic C cycling through the assimilation of atmospheric and dissolved carbon dioxide (CO₂) and bicarbonate (HCO₃[−]) into OC via the Calvin–Benson–Bassham cycle, storing it as particulate OC (POC) in biomass [59,60]. Approximately 1 kg of microalgal biomass corresponds to the fixation of ~1.8 kg CO₂ based on stoichiometry [61], which represents gross biological C fixation rather than long-term C sequestration. The extent to which fixed C is ultimately retained within the ecosystem depends on subsequent biomass fate, including harvesting, sediment burial, remineralization, trophic transfer, greenhouse gas emissions, and overall ecosystem carbon balances. In engineered ex situ systems, net climate benefits may further depend on energy requirements associated with cultivation, mixing, harvesting, and downstream processing of biomass, highlighting the importance of life-cycle assessment (LCA) when evaluating overall C outcomes.

Following fixation, microalgal-derived C is partitioned between rapid biological recycling and long-term retention pathways that govern its sequestration potential. Although a substantial fraction of this OC is rapidly remineralized through microbial respiration and trophic transfer, ecosystem restoration may alter C fate by reducing sediment resuspension, enhancing POC retention and promoting biomass recovery pathways that increase C residence times.

These mechanisms demonstrate that the restoration potential of microalgae extends beyond conventional pollutant removal and encompasses the regulation of fundamental biogeochemical and ecological processes governing the functionality of aquatic ecosystems. Through nutrient assimilation, contaminant attenuation, oxygenation, redox regulation, sediment stabilization and C transformation pathways, microalgae could modify the environmental conditions which cause ecosystem degradation and influence the trajectories of ecological recovery. Consequently, microalgae should be considered as multifunctional ecological mediators capable of supporting water quality improvement and ecosystem rehabilitation through interconnected biological, chemical and physical processes. This mechanistic foundation provides the basis for evaluating how microalgal technologies could be integrated into ex situ and in situ restoration frameworks.

3. Implementation of Microalgae-Based Strategies as a Tool for Aquatic Ecosystem Restoration

Aquatic ecosystems are increasingly exposed to anthropogenic pressures including wastewater discharge, nutrient enrichment, habitat destruction, hydrological alteration, and excessive resource exploitation, which significantly result in declining water quality and ecological integrity. In this regard, microalgae-based restoration strategies have gained attention due to their ability to simultaneously remove nutrients and contaminants, improve oxygen dynamics and recover valuable resources from polluted aquatic ecosystems. Microalgae-based strategies for aquatic ecosystem restoration could be performed via engineered ex situ systems, near in situ and in situ pathways for effective pollutant removal. However, the field-level implementation of these strategies occurs predominantly through engineered ex situ systems, which intercept pollutants prior to the receiving water bodies. In contrast, direct in situ restoration applications remain comparatively limited due to challenges associated with hydrological variability, biomass control, ecological uncertainty and long-term system stability. Hence, this section aims to examine microalgae-based engineered ex situ restoration systems and in situ approaches, and their ecological outcomes for effective aquatic ecosystem restoration (Tables 1 and 2).

Table 1. Microalgae-based bioremediation strategies for aquatic ecosystems and their water quality characteristics.

Aquatic System		Key Pollutants/Stressors and Water Characteristics	Microalgae-Based Approach/System Configuration	Study Duration	Scale	Bioremediation Potential	References
River	River Kaduna, Nigeria	Nutrient-rich and heavily polluted freshwater receiving petrochemical, industrial, agricultural, and domestic effluents	Freshwater microalgae biofilm	7 days	Lab-scale	Cd: 70.0%; Pb: 71.0%; Ni: 74.0%; NO ₃ [−] : 42.9%; Cl [−] : 11.5%; SO ₄ ^{2−} : 37.5%; COD: 24.0%; BOD: 33.0%; TSS: 66.7%; TDS: 9.9%	[62]
Lake	Qingling Lake, Yangtze River basin	COD: 3.7–6.8 mg L ^{−1} ; NH ₄ ⁺ -N: 0.6–1.5 mg L ^{−1} ; NO ₃ [−] -N: 0.13–1.0 mg L ^{−1} ; NO ₂ [−] -N: 0.015–0.096 mg L ^{−1} ; TN: 0.4–2.0 mg L ^{−1} ; TP: 0.11–0.33 mg L ^{−1} ; DO: 3–7 mg L ^{−1} ; pH: 7–9.5	Microalgal–bacterial granular sludge	nr (HRT: 12 h)	Lab-scale	Daytime COD: −27.0%; NH ₄ ⁺ -N: 72.1%; NO ₃ [−] -N: 73.2%; NO ₂ [−] -N: 91.5%; TN: 60.5%; TP: 52.8% Nighttime COD: 27.7%; NH ₄ ⁺ -N: 52.7%; NO ₃ [−] -N: 55.8%; NO ₂ [−] -N: 88.4%; TN: 37.9%; TP: 39.9%	[63]

Table 1. Cont.

Aquatic System	Key Pollutants/Stressors and Water Characteristics	Microalgae-Based Approach/System Configuration	Study Duration	Scale	Bioremediation Potential	References	
Lake	Qin Lake, Huangjiahu Campus of Wuhan University of Science and Technology	COD: 13.22 mg L ⁻¹ ; NH ₄ ⁺ -N: 0.46 mg L ⁻¹ ; NO ₃ ⁻ -N: 0.43 mg L ⁻¹ ; NO ₂ ⁻ -N: 0.025 mg L ⁻¹ ; TN: 1.18 mg L ⁻¹ ; PO ₄ ³⁻ -P: 0.075 mg L ⁻¹ ; TP: 0.12 mg L ⁻¹ ; pH: 8.5; Turbidity: ~40.79 NTU	Continuous flow microalgal–bacterial granular sludge	10 days	Lab-scale	Daytime COD: 50.10%; NH ₄ ⁺ -N: 63.52%; NO ₃ ⁻ -N: 43.37%; NO ₂ ⁻ -N: 90.72%; TN: 78.30%; PO ₄ ³⁻ -P: 71.13%; TP: 65.08%; Turbidity: 92.32% Nighttime COD: 61.39%; NH ₄ ⁺ -N: 75.23%; NO ₃ ⁻ -N: 73.57%; NO ₂ ⁻ -N: 93.48%; TN: 80.02%; PO ₄ ³⁻ -P: 74.62%; TP: 70.57%; Turbidity: 89.84%	[64]
	Eutrophic Lake, China	TN: 1.5–5.9 mg L ⁻¹ ; TP: 0.1–1.6 mg L ⁻¹	Indigenous microalgal–bacterial consortium	5 days	Lab-scale	TN: 100%; TP: 67.7%	[65]
n/a	n/a (Wastewater treatment plant, University of Santa Cruz do Sul, Brazil)	TN: 95.0 ± 35.2 mg L ⁻¹ ; Soluble P: 3.5 ± 2.4 mg L ⁻¹ ; NH ₃ : 75.2 ± 41.0 mg L ⁻¹ ; TSS: 12.7 ± 6.2 mg L ⁻¹ ; TDS: 378.1 ± 225.1 mg L ⁻¹ ; Turbidity: 245.5 ± 111.6 NTU; pH: 6.6 ± 0.2 Total coliforms: 1.9 ± 1.9 [ln(x + 1)] UFC mL ⁻¹ ; <i>Escherichia coli</i> : 1.9 ± 1.9 [ln(x + 1)] UFC mL ⁻¹	Microalgae-integrated constructed wetland	10 months (HRT: 7 days)	Field-scale	Soluble P: 67.6%; NH ₄ ⁺ -N: 94.0%; TSS: 100%; COD: 63.7%; Turbidity: 99.7%; Total coliforms: 100%; <i>Escherichia coli</i> : 100%	[66]

Table 1. Cont.

Aquatic System	Key Pollutants/Stressors and Water Characteristics	Microalgae-Based Approach/System Configuration	Study Duration	Scale	Bioremediation Potential	References
nr	COD: 400 mg L ⁻¹ ; TN: 300 mg L ⁻¹ ; NO ₃ ⁻ -N: 106.11 mg L ⁻¹ ; NH ₄ ⁺ -N: 269.6 mg L ⁻¹	Microalgae-integrated constructed wetland	160 days	Lab-scale	COD: 90.26%; TN: 26.80%; NH ₄ ⁺ -N: 62.38%	[67]
n/a	nr (Aquaculture wastewater, Recirculating aquaculture systems facility Lyngdal, Norway)	Cultivation of <i>Isocrysis galbana</i>	14 days	Lab-scale	TN: 0.417 ± 0.084 mg L ⁻¹ ; TP: 0.008 ± 0.003 mg L ⁻¹ ; NH ₄ ⁺ : 0.012 ± 0.004 mg L ⁻¹ ; NO ₂ ⁻ + NO ₃ ⁻ : 0.003 ± 0.002 mg L ⁻¹ ; PO ₄ ³⁻ : 0.002 ± 0.001 mg L ⁻¹ ; SiO ₂ : 1.117 ± 0.333 mg L ⁻¹ ; Si: 0.520 ± 0.154 mg L ⁻¹	[68]
		Cultivation of <i>Phaeodactylum tricornutum</i>			TN: 0.510 ± 0.121 mg L ⁻¹ ; TP: 0.029 ± 0.030 mg L ⁻¹ ; NH ₄ ⁺ : 0.022 ± 0.005 mg L ⁻¹ ; NO ₂ ⁻ + NO ₃ ⁻ : 0.046 ± 0.016 mg L ⁻¹ ; PO ₄ ³⁻ : 0.023 ± 0.020 mg L ⁻¹ ; SiO ₂ : 0.710 ± 0.000 mg L ⁻¹ ; Si: 0.580 ± 0.171 mg L ⁻¹	
		Cultivation of <i>Skeletonema marinoi</i>			TN: 1.367 ± 0.321 mg L ⁻¹ ; TP: 0.022 ± 0.006 mg L ⁻¹ ; NH ₄ ⁺ : 0.060 ± 0.036 mg L ⁻¹ ; NO ₂ ⁻ + NO ₃ ⁻ : 0.640 mg L ⁻¹ ; PO ₄ ³⁻ : 0.003 ± 0.001 mg L ⁻¹ ; SiO ₂ : 0.283 ± 0.075 mg L ⁻¹ ; Si: 0.133 ± 0.035 mg L ⁻¹	

n/a: not applicable; nr: not reported; COD: chemical oxygen demand; BOD: biological oxygen demand; TN: total nitrogen; TP: total phosphorus; TSS: total suspended solids; TDS: total dissolved solids; DO: dissolved oxygen; NH₄⁺-N: ammonium nitrogen; NH₄⁺: ammonium; NH₃: ammonia; NO₃⁻-N: nitrate nitrogen; NO₃⁻: nitrate; NO₂⁻-N: nitrite nitrogen; NO₂⁻: nitrite; PO₄³⁻-P: phosphate phosphorus; PO₄³⁻: phosphate; P: phosphorus; Cl⁻: chloride; SO₄²⁻: sulfate; Cd: cadmium; Pb: lead; Ni: nickel; SiO₂: silicon dioxide; Si: silicon; HRT: hydraulic retention time.

Table 2. Comparative overview of microalgae-based strategies for the potential restoration of different aquatic ecosystems.

Aquatic Ecosystem Type	Major Degradation Pressure	Suitable Microalgae/Consortium	Primary Mechanisms Associated with Restoration	Implementation Mode	Restoration Approach	Potential Scale of Application	Main Restoration Indicator
Lake	- Nutrient enrichment - Eutrophication - Harmful algal blooms	- Indigenous microalgal–bacterial consortium, <i>Chlorella</i> sp. <i>Scenedesmus</i> spp. <i>Desmodesmus</i> spp. <i>Arthrospira platensis</i>	- Nutrient assimilation - Harmful algal bloom suppression - Oxygenation and redox regulation - Carbon fixation	- In situ method - Ex situ system	- Direct inoculation of microalgae - Consortium enrichment	- Lab-scale - Pilot-scale - Field-scale	- TN/TP reduction - Lower chlorophyll-a - Increased Secchi depth - Bloom suppression
River/Stream	- Pollutant loading - Nutrient enrichment - Sedimentation	Indigenous microalgae	- Biosorption - Biotransformation - Nutrient assimilation - EPS-mediated sediment stabilization	Ex situ system	- Biofilm-assisted remediation - Engineered side-stream phycoremediation	Lab-scale	- Reduced contaminant concentration - Reduced suspended solids/turbidity - Improved DO - Habitat recovery
Wetland	- Organic loading - Nutrient enrichment - Habitat degradation	- Indigenous microalgal–bacterial consortium <i>Chlorella</i> sp. <i>Scenedesmus</i> spp. <i>Desmodesmus</i> spp.	- Nutrient assimilation - Organic carbon attenuation - Sediment stabilization	- In-situ method - Ex situ system	- Direct inoculation of microalgae - Consortium enrichment - Engineered phycoremediation	- Lab-scale - Pilot-scale	- COD/BOD reduction - TN/TP reduction - Increased DO - Habitat restoration
Estuary/Coastal aquaculture	- Nutrient enrichment - Salinity fluctuation - Organic loading	<i>Tetraselmis</i> spp. <i>Nannochloropsis</i> spp.	- Nutrient assimilation - Organic carbon attenuation - Biosorption - Carbon fixation	Ex situ system	Engineered phycoremediation	Lab-scale	- Nutrient discharge reduction - COD reduction - Reduced risk of eutrophication - Improved ecological resilience

COD: chemical oxygen demand; BOD: biological oxygen demand; TN: total nitrogen; TP: total phosphorus; DO: dissolved oxygen.

3.1. Ex Situ Restoration Systems

Microalgae-based engineered ex situ systems represent the most widely investigated pathway for aquatic ecosystem restoration, designed to reduce external nutrient and pollutant loading prior to the discharge into the receiving ecosystems. Despite direct biomanipulation of ecological processes within the aquatic ecosystems, ex situ systems operate outside natural water bodies and indirectly support ecological recovery by mitigating external environmental stressors [11]. Consequently, microalgae-based ex situ approaches contribute to indirect restoration, which occurs through the reduction of external pollutant loading and the alleviation of environmental stressors that result in the degradation of aquatic ecosystems. Notably, microalgae-based ex situ restoration systems include microalgal biofilms, microalgae–bacteria consortia, microalgal–bacterial granular sludge (MBGS), high-rate algal ponds (HRAPs) and microalgae-integrated constructed wetlands (CWs), which simultaneously perform pollutant removal with resource recovery and value-added biomass production.

Among these ex situ restoration approaches, microalgae–bacteria integrated systems have gained considerable attention due to the complementary metabolic interactions between both groups of microorganisms. Photosynthetically produced oxygen from microalgae supports aerobic bacterial degradation of organic matter and nitrification, whereas bacterial respiration supplies CO_2 and regenerated nutrients required for algal growth. This metabolic coupling enhances simultaneous nutrient removal, organic matter attenuation and biomass production, while reducing external aeration requirements. For instance, Chen et al. [63] investigated lab-scale MBGS for lake water restoration of Qingling Lake, located near the Yangtze River by evaluating the diurnal variation characteristics of organic matter removal. The study reported that the lake water samples exhibited average daytime removal efficiencies of 72.1%, 73.2%, 91.5%, 60.5% and 52.8% for ammoniacal nitrogen ($\text{NH}_4^+\text{-N}$), nitrate nitrogen ($\text{NO}_3^-\text{-N}$), nitrite nitrogen ($\text{NO}_2^-\text{-N}$), total nitrogen (TN) and total phosphorus (TP), respectively. In contrast, the corresponding nighttime removal efficiencies demonstrated were 52.7% for $\text{NH}_4^+\text{-N}$, 55.8% for $\text{NO}_3^-\text{-N}$, 88.4% for $\text{NO}_2^-\text{-N}$, 37.9% for TN, and 39.9% for TP. High COD removal of 27.7% was observed at nighttime due to the lower DO concentrations and near-neutral pH conditions, which may have enhanced the activity of relevant microorganisms in the MBGS system [63]. Although nutrient removal remained substantial during nighttime, differences in microalgae-based bioremediation performance highlighted the importance of photosynthetic activity in regulating treatment efficiency.

Similarly, Du et al. [64] demonstrated effective removal of COD, nitrogen species, phosphorus and turbidity using a lab-scale continuous-flow tubular-based MBGS for the treatment of natural lake water with loading rate $\sim 0.013 \text{ kg COD kg}^{-1} \text{ MLSS d}^{-1}$. The study showcased average removal efficiencies in the day/night cycles of 50.10/61.39%, 63.52/75.23%, 43.37/73.57%, 90.72/93.48%, 78.30/80.02%, 71.13/74.62%, 65.08/70.57%, and 92.32/89.84% for COD, $\text{NH}_4^+\text{-N}$, $\text{NO}_3^-\text{-N}$, $\text{NO}_2^-\text{-N}$, TN, $\text{PO}_4^{3-}\text{-P}$, TP, and turbidity, respectively, which underscore the feasibility of integrating algal–bacterial systems into restoration-supporting treatment processes. For instance, Wu et al. [65] demonstrated that indigenous microalgae–bacteria consortia enriched from eutrophic lake water located in China exhibited significantly higher algal growth and complete nutrient removal compared with the monocultures of *Chlorella ellipsoidea* FACHB-40 and *Chlorella sorokiniana* FACHB-275 within 5 days under lab-scale conditions, which emphasizes the importance of microbial interactions in determining restoration performance.

In addition, microalgal biofilm systems provide an alternative strategy for aquatic ecosystem restoration by improving biomass retention and facilitating pollutant adsorption and immobilization. For instance, Ugya et al. [62] demonstrated that microalgal biofilms

effectively bioremediated petroleum- and petrochemical-contaminated water from the River Kaduna, Nigeria, under lab-scale conditions, achieving removal efficiencies of 70.0% Cd, 74.0% nickel (Ni), 71.0% Pb, 11.5% chloride, 42.9% NO_3^- and 37.5% sulfate. Additionally, significant reductions in physiochemical parameters, such as alkalinity, total dissolved solids, total suspended solids, COD, BOD, turbidity and conductivity, were observed by 62.5%, 9.9%, 66.7%, 24%, 33%, 71% and 9.8%, respectively. These results showcase the capacity of microalgal biofilm-based pollutant removal systems to simultaneously address multiple contaminants, while reducing pollutant loads entering the aquatic ecosystems.

Constructed wetlands (CWs) integrated with microalgae cultivation represent another promising engineered approach, primarily for freshwater ecosystem restoration, which controls the point-source pollution originating from municipal, agricultural, and industrial effluents. Ferreira et al. [66] reported that the integration of microalgae into field-scale CWs substantially enhanced the bioremediation performance of wastewater collected from the treatment plant of the University of Santa Cruz do Sul, RS, Brazil, with a hydraulic retention time of 7 days, by achieving removal efficiencies of 67.6% for soluble P, 94.0% for $\text{NH}_4^+\text{-N}$, 63.7% for COD, and 42.7% for BOD. Thus, these findings demonstrate the potential of engineered microalgal systems in significantly improving effluent quality prior to discharge into sensitive aquatic ecosystems.

On the other hand, marine microalgae have demonstrated considerable potential for supporting the saline ecosystem restoration through treatment of mariculture wastewater and contaminated coastal waters. Particularly, marine species such as *Isochrysis galbana*, *Phaeodactylum tricornutum*, *Skeletonema marinoi*, and *Tetraselmis* sp. exhibit high tolerance to saline conditions and efficient nutrient assimilation capacities. Kumar et al. [69] showcased effective removal of petroleum hydrocarbons from contaminated seawater using an integrated adsorption-phycoremediation approach with an indigenous *Tetrademus* sp., which simultaneously improved the salinity-related water quality parameters. Similarly, Sacristán de Alva and Luna Pabello [70] investigated the treatment of mariculture wastewater, characterized by 45 mg L^{-1} NO_3^- , 10 mg L^{-1} NO_2^- , 30 mg L^{-1} NH_4^+ , 17 mg L^{-1} orthophosphates, and 270 $\text{mg O}_2 \text{ L}^{-1}$ of dissolved organic matter as COD, by employing *Tetraselmis* sp. cultivation in a 70 L high-rate algal pond (HRAP). The HRAP achieved 1.19 g L^{-1} of dry biomass with $95.5 \pm 0.4\%$ TN, $94.4 \pm 0.5\%$ orthophosphates and $61.4 \pm 3.9\%$ COD removal efficiencies, followed by a 4-cycle semicontinuous cultivation, demonstrating the effectiveness of marine microalgae for nutrient and organic matter removal in mariculture wastewater.

Despite the considerable potential of microalgae-based ex situ approaches, treatment performance varies substantially among studies, due to differences in nutrient loading, hydraulic retention time, salinity, operational configuration, environmental conditions and biomass management strategies. Moreover, most available evidence originates from laboratory-scale, pilot-scale or controlled field systems, which limits the direct extrapolation to ecosystem-scale restoration outcomes. Therefore, the aquatic ecosystem restoration potential of engineered microalgae-based systems should be evaluated using ecological response indicators, such as reductions in eutrophication pressure, improvements in habitat quality, biodiversity recovery and enhanced ecosystem resilience.

3.2. In Situ Restoration Approaches

In situ microalgae-based strategies involve the deliberate biomanipulation of microalgal communities within natural or semi-natural aquatic ecosystems to improve water quality, regulate ecological processes and promote ecosystem recovery. In comparison with engineered ex situ systems, in situ applications remain relatively less common, primarily due to the environmental conditions, hydrodynamics, nutrient loading, graz-

ing pressure and biomass retention, which are difficult to control under natural conditions. Therefore, the literature available for in situ microalgae-based restoration of aquatic ecosystems is largely restricted to site-specific interventions and long-term ecological restoration programs.

One of the most direct in situ approaches is algolization, in which selected microalgal species are introduced into eutrophic systems to alter phytoplankton community structure and improve water quality. For instance, Melikhov et al. [71] demonstrated active in situ restoration of the Tsimlyansk reservoir (Don River) through algolization using *Chlorella vulgaris* to mitigate eutrophication and suppress cyanobacterial blooms. The study reported that the introduction of microalga altered phytoplankton community structure by reducing bloom-forming cyanobacteria such as *Anabaena*, *Microcystis*, *Aphanizomenon*, and *Oscillatoria*, which simultaneously increased DO from 7.5 to 9.2 mg L⁻¹ and reduced COD from 19.4 to 15.0 mg L⁻¹. Moreover, the study highlighted the potential of algolization as an effective in situ strategy for aquatic system restoration, which improves oxygen dynamics, enhances self-purification capacity, and restores ecological balance in eutrophic freshwater ecosystems [71].

In addition to the effective improvements in water bodies quality, in situ restoration may influence food web structure and trophic interactions within the aquatic ecosystems. Taipale et al. [72] demonstrated that restoration measures implemented in the eutrophic Lake Vesijärvi, Finland, including biomanipulation and hypolimnetic aeration, shifted phytoplankton communities by reducing cyanobacterial dominance and promoting nutrient-rich algal taxa such as cryptophytes, chrysophytes, and diatoms. This transition increased the availability of essential sterols and polyunsaturated fatty acids, resulting in increased biomass of the keystone grazer *Daphnia* and improved trophic transfer efficiency [72]. Moreover, the restoration success should be assessed through ecological responses involving food web recovery and ecosystem functioning, alongside the pollutant removal efficiencies.

Nevertheless, limited field-scale evidence reported in the literature reflects the complexity of implementing in situ strategies for aquatic system restoration under natural environmental conditions, in which the hydrological variability, seasonal nutrient loading, internal nutrient release from sediments and complex ecological interactions could significantly influence restoration trajectories and long-term ecosystem stability. Furthermore, introduced or stimulated algal populations may not persist under changing environmental conditions and the long-term stability of observed ecological improvements remains poorly understood. Hence, future research on microalgae-based in situ restoration approaches should prioritize field-scale validation, long-term monitoring and ecosystem-based assessment frameworks, which evaluate biodiversity recovery, habitat rehabilitation, trophic restructuring and ecosystem resilience, alongside conventional water quality indicators.

4. Challenges and Future Perspectives

The field-scale implementation of microalgae-based strategies for aquatic ecosystem restoration remains constrained by technical, ecological, and regulatory challenges, despite the increasing evidence demonstrating their capabilities for effective pollutant removal, resource recovery and simultaneous ecosystem rehabilitation (Section 3). Importantly, a major research gap remains in establishing the feasibility and long-term ecological performance of in situ microalgae-based restoration in natural aquatic ecosystems due to the limited availability of field-scale studies demonstrating successful restoration interventions. As discussed in Section 3.1, ex situ engineered systems have primarily been evaluated at laboratory- and pilot-scales for phycoremediation and pollutant removal, with comparatively limited assessment of their long-term ecological restoration outcomes. Thus, the translation of microalgae-based ex situ and in situ restoration strategies into

field-scale applications remains constrained by environmental heterogeneity, inefficient biomass management, operational complexity and insufficient long-term validation under natural conditions.

Natural aquatic ecosystems exhibit strong spatial and temporal heterogeneity in hydrodynamics, light availability, nutrient loading, and contaminant profiles, which directly influence microalgal growth kinetics, phycoremediation efficiency, photosynthetic activity, and biomass productivity [24,73,74]. Notably, the environmental heterogeneity represents one of the major challenges associated with microalgae-based in situ restoration of aquatic ecosystems, due to unstable treatment performance, limited process controllability, and lack of treatment reproducibility under field conditions. Furthermore, pronounced diurnal fluctuations in nutrient removal driven by light-dependent reactions of photosynthesis and changes in dissolved oxygen, pH, and microbial dynamics have significant impacts on microalgae-based aquatic ecosystem restoration strategies, as summarized in Table 3. While microalgal photosynthesis increases DO concentrations during daytime, nighttime respiration and biomass decomposition may induce localized hypoxia and unintended oxygen supersaturation, particularly in eutrophic or poorly mixed water bodies, thereby adversely affecting aquatic organisms and reducing restoration stability. Hydrological disturbances such as storm events, flooding, rainfall-driven dilution, and sediment resuspension may further reduce biomass retention and compromise the treatment efficiency of microalgae. In biofilm-based systems, physical disturbances may also induce biofilm detachment, resulting in inefficiencies of microalgae-based restoration. Additionally, ecological concerns associated with the introduction of non-native or genetically modified algal strains into the aquatic ecosystems, including harmful algal blooms, invasion risks, alterations in trophic interactions, grazing pressure, food web structure, and potential displacement of indigenous species, affect the sustainable application of microalgae-based aquatic ecosystem restoration [75,76].

Table 3. Challenges and potential solutions associated with microalgae-based aquatic ecosystem restoration.

Challenges	Proposed Mitigation Strategies	References
Environmental variability	• Selection of robust indigenous microalgae strains and consortia • Real-time monitoring • Planning of seasonal operation • Nutrient load reduction at point sources	[63,77]
Diurnal fluctuations in nutrient removal efficiency	• Adaptive operation strategies for day-night cycles • Implementation of process control based on the dissolved oxygen and pH variations	[63]
Presence of toxic substances inhibiting microalgal metabolism	• Upstream pretreatment prior to microalgal remediation	[62,77,78]
Competition from native phytoplankton and harmful cyanobacterial blooms	• Careful selection of microalgal species	[75]
Inefficient biomass retention and harvesting strategies	• Development of advanced biomass retention and harvesting strategies • Use of engineered approaches such as microalgal biofilms, microalgae–bacteria granule sludge and constructed wetlands integrated systems	[79–81]

Table 3. Cont.

Challenges	Proposed Mitigation Strategies	References
Limited understanding of microalgae–bacteria interactions under different stressed conditions	Conduct future research focused on microalgal-bacteria interaction mechanisms	[82]
Lack of standardized and scalable system designs	- Standardization of system configurations - Pilot-to-field scale validation - Develop predictive models	[75]
High capital and operational costs	- Multistage microalgae cultivation - Microalgal biomass valorization	[79–81]
Energy-intensive downstream processing	- Integration of low-energy harvesting strategies - Use of renewable energy - Process optimization	[75]
Ecological risk related to the manipulation of natural microbial communities	- Integration of ecosystem-based management strategies - Long-term ecological monitoring	[77]
Limited institutional coordination and governance barriers	Interdisciplinary collaboration among ecologists, engineers, policymakers, and stakeholders	[9]

Large-scale implementation of ex situ engineered systems for microalgae-based aquatic ecosystem restoration is further constrained by pollutant-specific toxicity effects, where elevated concentrations of HMs, hydrocarbons, and persistent organic pollutants inhibit algal metabolism and biomass productivity [83,84]. Furthermore, excessive N and P loading in influent streams may promote the proliferation of harmful toxin-producing cyanobacteria within microalgae cultivation systems, reducing treatment efficiency and increasing operational risks. Additionally, interactions with microbial pathogens may influence microalgal productivity and system stability by inhibiting algal growth, altering microbial community structure and affecting the performance of microalgae–bacterial consortia, thereby introducing variability in restoration outcomes. In this regard, careful selection and application of robust indigenous microalgae strains and consortia could enhance tolerance to fluctuations in light, temperature, salinity, and nutrient availability of aquatic ecosystems. Furthermore, pretreatment techniques such as sedimentation, adsorption, chemical oxidation, and dilution could be applied to mitigate the inhibitory effects of toxic substances prior to the microalgae-based ex situ restoration of aquatic ecosystems [78,85]. Moreover, real-time monitoring, seasonal operation planning, and basin-scale controlling of nutrient loading are a few strategies that could facilitate the implementation of microalgae for aquatic ecosystem restoration.

In addition, technical constraints and knowledge gaps related to variability in microalgal biomass generation, retention, harvesting and management across diverse aquatic ecosystems remain major barriers to the field-scale implementation of microalgae-based restoration strategies. These challenges are particularly pronounced in in situ applications of microalgae-based restoration strategies, where inefficient biomass recovery may result in biomass decomposition, nutrient re-release, DO depletion and secondary pollution, thereby offsetting the ecological benefits of restoration. For instance, Zhu et al. [86] showcased that the decay of algal material in eutrophic Lake Taihu, China, caused a rapid decrease in DO than in the algae-free controls and led to significant increments in $\text{NH}_4^+\text{-N}$ and

PO_4^{3-} -P. Accordingly, biomass harvesting represents one of the principal engineering bottlenecks limiting the deployment of in situ microalgae-based restoration systems, where low biomass density, spatial heterogeneity, and hydrodynamic disturbances substantially reduce biomass recovery efficiency. Also, the potential generation of metal-contaminated algal biomass further introduces significant downstream challenges related to safe handling, treatment and disposal. Thus, restoration system designs that reduce reliance on suspended cultivation and enable stable biomass capture under open and hydraulically dynamic conditions are critical for sustainable scale-up of microalgae-based aquatic ecosystem restoration.

As discussed in Section 3.1, engineered ex situ systems, including microalgal biofilms, MBGS and microalgae-integrated CWs, demonstrate improved biomass stability and nutrient removal efficiencies in laboratory- and pilot-scale studies. Moreover, the restoration performance of these systems largely relies on microalgae–bacteria interactions, which govern the nutrient uptake, organic matter degradation, and oxygen dynamics in various aquatic ecosystems [62,64,66]. However, the behavior of microalgae–bacteria interactions under varying environmental and operational conditions remains limitedly understood, which hinders the development and optimization of the large-scale restoration of aquatic ecosystems [82]. Hence, future studies must be directed towards the standardization of system configurations for large-scale operations and deeper mechanistic insights into microalgae–bacteria interactions under varying environmental conditions. Moreover, integrating predictive modeling and real-time process control will be essential to enhance system stability, reproducibility, and field-scale applicability of microalgae-based strategies for aquatic ecosystem restoration.

Additionally, operational complexity in microalgae-based strategies for aquatic ecosystem restoration increases substantially under field conditions due to the requirements for infrastructure development, efficient biomass harvesting, influent pretreatment, and energy-intensive downstream processing, resulting in high capital and operational costs. These costs represent key bottlenecks for long-term implementation of microalgae-based strategies, particularly in low- and middle-income regions where progress towards SDGs 6 and 14 is already constrained [27,87,88]. Moreover, the integration of microalgae-based ex situ restoration systems into existing aquatic ecosystem restoration and water management approaches remains limited, as conventional restoration strategies are often not designed to accommodate active biomass production and recovery processes. Therefore, the development and optimization of multistage treatment configurations where different microalgal species are grown in a sequential or stage-dependent manner may improve economic feasibility and process efficiency. Furthermore, microalgal biomass valorization represents a potentially viable approach for valuable bioproduction of biopigments, biofertilizers, biofuels, and animal feed [80,81], which would contribute to the overall cost-effectiveness of the implementation of microalgae-based restoration strategies. For instance, Monlau et al. [89] implemented a three-stage biorefinery process for the recovery of five different bioproducts from *Chlorella protothecoides*, including biodiesel derived from free fatty acids, high-value biomolecules such as sterols, squalene, and carotenoids from defatted biomass, as well as biogas and biofertilizers recovered from defatted and deproteinized microalgal residue. These valorization pathways could be directly employed with the microalgal biomass recovered during aquatic ecosystem restoration, which facilitates enhanced resource recovery, economic sustainability and circular bioeconomy [90].

On the other hand, governance structures, regulatory frameworks, and social acceptance are critical in enhancing the viable implementation of microalgae-based strategies for aquatic ecosystem restoration, particularly at the watershed and regional scales. Furthermore, limited institutional coordination among water authorities, agricultural sectors,

and environmental agencies continues to hinder integrated implementation, as prevailing restoration policies emphasize passive restoration, which focuses on removing external stressors, such as reducing agricultural runoff, restricting deforestation in riparian zones, and limiting human disturbance, to enable natural regeneration and ecological succession. This policy orientation creates structural and regulatory gaps that complicate the adoption of microalgae-based strategies, which require active system operation, biomass management, harvesting, and continuous performance monitoring.

Consequently, successful deployment of microalgae-based ex situ and in situ strategies for aquatic ecosystem restoration will require interdisciplinary collaboration among ecologists, engineers, policymakers, and local stakeholders, supported by adaptive management frameworks, long-term monitoring, and risk-based regulatory oversight. Additionally, updating aquatic restoration guidelines to explicitly incorporate microalgae-based restoration strategies and standardized C accounting for microalgal CO₂ sequestration within emerging Blue Carbon frameworks is essential to enhance policy relevance, regulatory acceptance, and alignment with United Nations (UN) sustainability and climate governance frameworks, including the SDGs and UN Framework Convention on Climate Change-guided climate mitigation pathways [91,92]. Strengthening knowledge dissemination, stakeholder engagement, and community participation will further promote social acceptance and support the integration of microalgae-based technologies into regional water management and aquatic restoration strategies. Collectively, key scientific, technical, and governance priorities are essential to advance microalgae-based strategies for efficient aquatic ecosystem restoration from experimental studies to reliable, scalable and sustainable field-scale applications.

5. Conclusions

Microalgae-based strategies demonstrate strong potential for supporting aquatic ecosystem restoration through nutrient assimilation, contaminant attenuation, sediment stabilization, oxygen regulation and C sequestration. Based on the available literature, microalgae-based aquatic ecosystem restoration could be primarily achieved through engineered ex situ systems, including high-rate algal ponds, algal–bacterial consortia, and constructed wetland integrations, which collectively reduce external pollutant loading to receiving aquatic environments. On the other hand, in situ applications remain comparatively limited and highly site-specific due to hydrological variability, ecological complexity and challenges associated with biomass control and long-term system stability. Consequently, large-scale ecosystem restoration by employing microalgae cultivation under natural environmental conditions remains limitedly studied. Thus, bridging the gap between mechanistic understanding and ecosystem-scale application would require long-term field validation, development of standardized ecological performance indicators and integrated assessment frameworks, which must incorporate biodiversity recovery, habitat quality, trophic structure and ecosystem resilience. Moreover, adaptive regulatory frameworks, interdisciplinary collaboration, and stakeholder engagement are essential to enable active strategies integrating microalgae for aquatic ecosystem restoration. Thus, these research progressions are essential for the transition of microalgae-based approaches from engineered treatment systems towards reliable, scalable aquatic ecosystem restoration, while aligning with SDGs 6 and 14.

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Abbreviations

The following abbreviations are used in this manuscript:

SDG	Sustainable Development Goal
HM	Heavy metal
DIN	Dissolved inorganic nitrogen
DIP	Dissolved inorganic phosphorus
OC	Organic carbon
TOC	Total organic carbon
DOC	Dissolved organic carbon
EPS	Extracellular polymeric substances
DO	Dissolved oxygen
POC	Particulate organic carbon
COD	Chemical oxygen demand
BOD	Biological oxygen demand
HRAP	High-rate algal pond
CW	Constructed wetland
MBGS	Microalgal–bacterial granular sludge
MAB	Microalgae-associated bacteria

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