Diankristanti and Ng *Blue Biotechnology* (2024) 1:10
https://doi.org/10.1186/s44315-024-00010-w

Blue Biotechnology

REVIEW

Open Access

Marine microalgae for bioremediation and waste-to-worth valorization: recent progress and future prospects

Priskila Adjani Diankristanti[1] and I-Son Ng[1*]

Abstract

In the quest for sustainable environmental solutions, marine microalgae emerge as powerful allies in bioremediation and biomass valorization endeavors. This review navigates through various facets of marine microalgae utilization, starting with isolation, screening, and identification techniques, which lay the foundation for understanding strain diversity and capabilities. Delving deeper, bioremediation mechanisms performed by marine microalgae are elucidated, showcasing the natural capacity to cleanse polluted environments via biosorption, bioaccumulation, and biodegradation. Furthermore, the waste-to-worth valorization of marine microalgae is explored, with comprehensive discussions on conversions into biofuels, bioplastics, high-value products, and animal feed. As one way forward, emerging advancements in genetic engineering to enhance pollutant removal capacities are presented alongside the development of microalgae consortia and integrated waste treatment processes. This multidimensional approach highlights the ultimate potential of marine microalgae in bioremediation and biomass valorization, laying the groundwork for a sustainable future achieved by working with nature, hand-in-hand.

Keywords Marine microalgae, Bioremediation, Valorization, Wastewater, Pollutant removal, Sustainable

Introduction

The health of our planet relies heavily on the well-being of both aquatic and terrestrial ecosystems, which serve as life support systems and provide a vast array of resources. Despite the essential contributions of nature to human existence, targets for halting the degradation of land and oceans have not yet been met [1]. Our oceans, already burdened by the presence of around 5.25 trillion microplastics particles [2], are further threatened by an estimated numbers of 2.4 million tons oil spills entering water bodies annually [3]. At the same time, Earth has lost one-third of arable land in the past 40 years due to pollution and soil contamination [4], and the remaining two thirds are at risk of unsustainable agricultural practices, deforestation, and urbanization [5]. Moreover, industrial facilities, such as smelters, battery manufacturing plants, and mines, often release heavy metals and toxic chemicals which not only contaminate water bodies but also seep into the soil, posing a serious threat on the life on land and below water [6].

The tide of ecological damages can be stemmed by advancements in marine biotechnology, particularly through bioremediation– the process of using living organisms, mostly microorganisms and plants, to degrade, decompose, and detoxify environmental pollutants [7]. Among the most promising bioremediation agents are marine microalgae, performing natural purification with an excellent salinity and pollutant tolerance [8]. Marine microalgae are naturally adapted to thrive in high salinity, exposed to a constant influx of nutrients

---

*Correspondence:
I-Son Ng
yswu@mail.ncku.edu.tw
[1] Department of Chemical Engineering, National Cheng Kung University, Tainan 701, Taiwan

from upwelling zones and a broad spectrum of pollutants in the surrounding seawater. In contrast to freshwater microalgae, utilizing marine microalgae for bioremediation eliminates the need for complex and energy-intensive desalination processes [9]. Furthermore, marine microalgae demonstrate remarkable versatility in nutrient removal from wastewater under various trophic cultivation modes, even in high-stress conditions such as low light, limited inorganic carbon (CO_2), and anoxic environments [10–12].

A new wave in bioremediation using marine microalgae is pushing the boundaries by focusing on retrieving additional value from harvested biomass and intracellular metabolites, not only offsetting carbon emissions and cultivation costs but also creating valuable products [13]. However, cultivating microalgae in wastewater raises a significant concern: potential presence of contaminants or toxins in the resulting biomass [14]. Despite limitations for food and feed applications, wastewater-cultured microalgae present an opportunity for biofuel production. High lipid content, reaching up to 37% in *Dunaliella tertiolecta* [15] and 46% in *Nannochloropsis* sp. [16], is ideal for biodiesel production via transesterification [12]. This approach offers a double benefit of creating a valuable end product and avoiding the risk associated with contaminated biomass for human or animal consumption. Additionally, anaerobic digestion remains a viable closed-loop valorization option, generating methane for energy production and nutrient-rich digestate for fertilizer [17]. Simultaneous utilization of pollutants and production of carbon–neutral energy ultimately align with Sustainable Development Goal 7 (Affordable and Clean Energy).

First and foremost, we ask: “How can humanity collaborate in harmony with marine microalgae for environmental restoration?” This review begins with an overview of isolation techniques and strain diversity to delve into the question, followed by bioremediation mechanisms and waste-to-worth valorization. As the urgency for sustainability intensifies, emerging advancements are showcased as an all-inclusive plan to foster circular bioeconomy, ensuring a greener future for years to come.

Isolation and screening techniques

Successful application of marine microalgae in bioremediation hinges on isolating strains with potent pollutant removal capabilities. Traditional methods involve DNA extraction, purification, amplification, sequencing, and taxonomic identification, which are time-consuming and require specialized equipment. Jahn et al. pioneered a new approach combining plate isolation with direct PCR (dPCR) to amplify a specific gene region, followed by electropherogram analysis to confirm single-species cultures. This cascade was shown to eliminate the need for DNA cloning, thereby reducing processing time to about three weeks [18]. Although dPCR may exclude some flagellates, combining it with single-cell Raman spectroscopy (SCRS) may capture a broader spectrum of strains [19]. As another strategy, microfluidic devices offer a high-throughput solution for screening and isolating diverse strains through automatic isolation. By cultivating single cells, seamless screening can be carried out with minimal sample volumes [20].

Despite the ease, downstream analysis remains crucial for identifying strains with desired bioremediation traits. One example of analysis technique is flow cytometry, which facilitates rapid screening of large cell populations with relevant bioremediation traits based on size and specific markers [21, 22]. Next-generation sequencing (NGS) and metagenomics provide deeper insights into genetic makeup and functionalities linked to bioremediation by revealing the entire genome, thus allowing precise analysis of pollutant reduction, nutrient removal, and coliform inhibition [23, 24]. Following identification, enrichment cultures and selective media further isolate and confirm desired traits, such as growth rate, pollutant tolerance, and biocompatibility, ultimately to ensure efficient and effective climate repair.

Strain diversity of marine microalgae

Vast diversity of marine microalgae offers a wide range of pollutant removal capacity [25], as summarized in Table 1. While fast-growing strains with high tolerance to pollutants are generally preferred, careful selection of strains is crucial, as different microalgae excel at removing specific types of pollutants, be it nutrients in wastewater [26], hydrocarbons [27], pharmaceuticals [28], and dyes [29].

Green microalga

Ezenweani and Kadiri studied the performance of *Nannochloropsis oculata* and *Porphyridium cruentum* in petroleum fuel fractions, and reported that *N. oculata* biomass increased in the presence of hydrocarbons, while *P. cruentum* growth was inhibited [27]. Another green microalga, *Scenedesmus obliquus*, can withstand high doses of sulfamethazine, sulfamethoxazole [33], and doxylamine [34], and achieve up to 62% removal of pharmaceutical contaminants. In wastewater remediation, *Scenedesmus* sp. and *Desmodesmus* sp. utilized nitrogen and phosphorus for growth, attaining biomass as high as 0.4 g/L with 91.2% and 66.2% removal of total nitrogen and phosphorus, respectively [26].

Intriguingly, Gowthami et al. investigated *Picochlorum maculatum* for the biodegradation of low-density polyethylene (LDPE) to address the so-called “white

Table 1 Strain diversity and pollutant removal capability

Strains	Pollutant	Removal	Cultivation strategy	Remarks	Ref
Desmodesmus sp.	10.8 mg/L N 0.9 mg/L P	66.2% N 75% P	Indoor 1 L PBR 8 days	Final biomass yield of 0.42 g/L	[26]
Nannochloropsis oculata	Water soluble fraction of petroleum	84.6% kerosene 65.5% diesel 70.8% gasoline	Indoor 500 mL flask 14 days	Final biomass yield of 0.69 g/L	[27]
Navicula sp.	10 mg/L carbamazepine	87.3% carbamazepine	Indoor 250 mL flask 72 h	EC_{50}[a] of 0.18 mg/L	[30]
Navicula sp.	~800 ng/L triclosan	98.8% triclosan	Indoor 100 mL flask 72 h	EC_{50}[a] of 0.17 mg/L	[31]
Phaeodactylum tricornutum	1 mg/L chromium	76%	Indoor 250 mL flask 3 days	Final OD_{600} of 0.48	[32]
Scenedesmus obliquus	0.25 mg/L sulfamethazine	62.3%	Indoor 250 mL flask 14 days	EC_{50}[a] of 1.23 mg/L	[33]
Scenedesmus obliquus	1 mg/L doxylamine	63%	Indoor 250 mL flask 7 days	Addition of 2 g/L bicarbonate to enhance removal	[34]
Scenedesmus sp.	10.8 mg/L N 0.9 mg/L P	91.2% N 78.7% P	Indoor 1 L PBR 8 days	Final biomass yield of 0.34 g/L	[26]
Thalassiosira pseudonana	1.27 mg/L copper	46.3%	Outdoor 10 L tank 96 h	Elevated CO_2 at 1000 µatm to reduce toxicity	[35]

[a] EC_{50} is defined as inhibition concentration where the response is reduced by half

pollution". While the study reported weight loss and changes in LDPE properties, the observed 20% weight loss over 45 days suggested a very slow degradation rate [36], which might be due to the significant difference in polarity between the hydrophilic cell surface of Chlorophyta and hydrophobic LDPE [37].

Diatoms

Diatoms are noteworthy for their unique properties, such as rigid silica frustules and specialized transporters. The first complete genome sequence of *Diplonema papillatum* reveals a central role in polysaccharide degradation by utilizing carbohydrate-active (CAZyme families) enzymes, suggesting applications in mitigating eutrophication events [38]. Additionally, studies on two benthic oleaginous diatoms, *Phaeodactylum tricornutum* and *Navicula pelliculosa*, have shown potential in pharmaceuticals [30, 31, 39, 40] and heavy metal removal [32, 41], although growth inhibition remained a challenge. *Thalassiosira pseudonana*, another diatom strain, adapts to higher CO_2 by employing a unique copper uptake mechanism: reducing copper accumulation to alleviate copper toxicity [35]. This highlights such a complex interplay in the event of ocean acidification, as it may lead to decreased metal interactions in marine organisms, although specific effects depend on the organism, metal type, and timescale of exposure.

Cyanobacteria

Cyanobacteria, also referred to as blue-green algae, are known for nitrogen fixation and nutrient cycling in polluted environments. Beyond nutrient assimilation, *Synechococcus* sp. and *Aphanocapsa* sp. show promise in removing chromium and lead [42], while *Microcystis aeruginosa* tackles zinc and cadmium [43]. Interestingly, habitat influences heavy metal uptake, as observed in *Nostoc* sp. isolated from limestone and freshwater. Ghorbani et al. revealed that *Nostoc* sp. N27P72 isolated from limestones have higher stress tolerance and higher uptake capacity of heavy metal ions compared to *Nostoc* sp. FB71 isolated from freshwater [44].

As environmental contamination grows, exploring microalgae diversity becomes increasingly significant. Continued efforts in isolating novel strains, conducting whole-genome studies, and exploring heavy metal cross-tolerance are essential in pushing microalgae-based bioremediation forward [45].

Bioremediation mechanism

Marine microalgae, poised to revolutionize environmental decontamination, utilize a diverse array of bioremediation mechanisms, broadly categorized into three: biosorption, bioaccumulation, and biodegradation [46]. Each of these mechanisms shown in Fig. 1 is discussed in detail throughout this section.

Biosorption

Biosorption involves the passive binding of various pollutants, including heavy metals, organic compounds, and dyes, to the surface of microalgae, which is rich in carbohydrates and proteins. Functional groups (i.e., carboxyls, amines, phosphates) on the cell wall and extracellular polymeric substances (EPS) interact with pollutants via mechanisms including electrostatic interactions, chelation, and complex formation. Notably, even after microalgae are rendered inactive through death or autoclaving, EPS remains intact in quantities comparable to living cells or isolated EPS, underscoring the crucial role of cell-associated polymeric substances. Several studies have confirmed the persistence of EPS in the removal of ibuprofen [39], dichromate [32], and dye [47] by *Phaeodactylum tricornutum*. Nonetheless, it is important to acknowledge that pollutants interact with EPS differently, possibly influencing the efficiency and mechanisms of biosorption.

As microalgae bind pollutants, available sites for further adsorption decrease, leading to a decline in removal efficiency, especially with a high initial concentration of pollutants or the presence of competing ions in the medium. For instance, the presence of copper in a mixed solution can affect the adsorption capacity of *Chlorella vulgaris* and *Scenedesmus obliquus* for cadmium [48, 49]. Some strategies are explored to enhance biosorption such as cultivation in higher pH range of 7.5 to 9.5 [50], elevating phosphorus content in medium [51], harvesting biomass at stationary phase

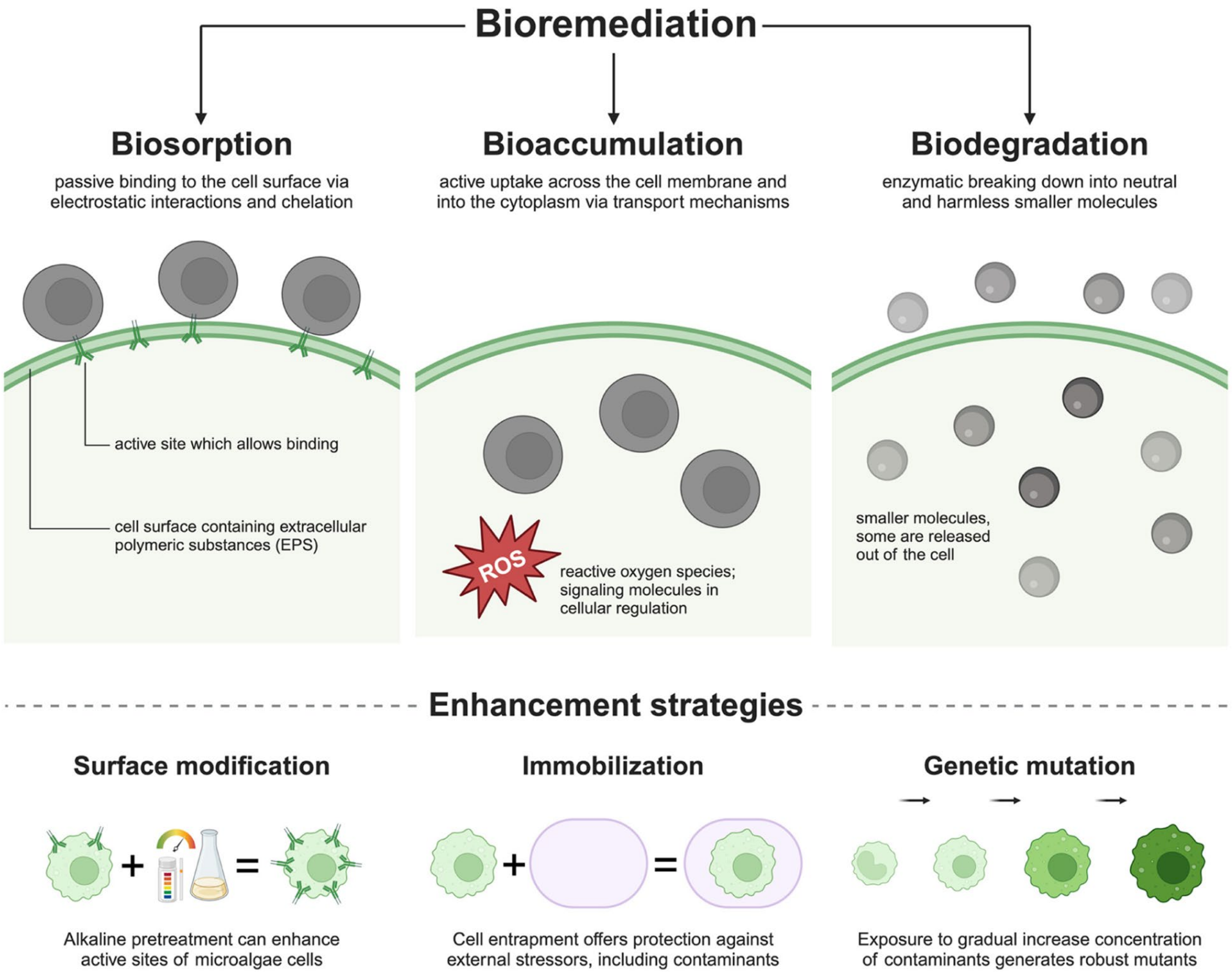

Fig. 1 Bioremediation mechanism by marine microalgae, encompassing biosorption, bioaccumulation, and biodegradation

[52], and employing alkaline pretreatment on microalgae biomass [53].

Bioaccumulation

Bioaccumulation refers to the uptake of pollutants across the cell membrane and into the cytoplasm through specific transport mechanisms, mainly facilitated transmembrane diffusion and energy-dependent active uptake [54]. This uptake can induce stress in microalgae and subsequently trigger alterations in metabolic pathways and antioxidative defenses. For example, *Dunaliella salina* upregulates arsenic transporters when exposed to arsenic and performs detoxification by converting it into less harmful organoarsenicals [55].

A key consequence of bioaccumulation is the generation of intracellular reactive oxygen species (ROS) that acts as signaling molecules in regulating cellular function and metabolism. However, ROS levels increase with higher concentrations of pollutants, potentially overwhelming the antioxidant defenses within microalgae cells [56, 57]. Studies have shown increased ROS content in *Chlorella vulgaris* with increasing concentrations of perfluorooctane sulfonate, triflumizol, and nonylphenol [58]. To counteract damages from excessive ROS, microalgae upregulate the production of superoxide dismutase, catalases, and glutathione to scavenge ROS and maintain photosynthetic capacity [57, 58].

Complications arise when multiple pollutants are present, and competition for uptake is inescapable. For instance, microalgae may prioritize binding nanoparticles over metal ions due to the abundance, but high nanoparticle concentrations can trigger cell wall thickening and further reduce cellular metal uptake [59]. To address challenges posed by ROS and optimize bioaccumulation efficiency, immobilization can be employed for increased density, improved contact, and enhanced resilience. Numerous attempts have been made to maximize bioaccumulation by immobilized microalgae, such as optimizing bead size [60], formulating nutrient-rich media [61], and selecting appropriate entrapment matrices [62]. Achieving selective uptake of target pollutants while minimizing unwanted elements are ongoing research areas with significant promise for enhancing the bioaccumulation efficiency and sustainability.

Biodegradation

Biodegradation involves enzymes acting as biological catalysts in breaking down contaminants into specific molecules, including organic compounds, sugars, or CO_2, in order to neutralize harmful effects without introducing toxic residues into the food chain (Fig. 1). Certain microalgae species exhibit selective biodegradation capabilities, targeting specific contaminants while leaving beneficial components in the water unharmed. For example, *Nannochloropsis oculata* performed up to 94% polycyclic aromatic hydrocarbons (PAHs) removal by employing oxidoreductase [63]. In pharmaceuticals, *Chlorella vulgaris* and *Phaeodactylum tricornutum* demonstrated remarkable efficiency in iohexol and sulfadimethoxine biodegradation, respectively, and attained final removal rates of 40–59% [64, 65]. Recently, a newly isolated marine microalgae, *Rhodomonas* sp. JZB-2, was reported for the capacity to remove 30 mg/L para-xylene within 6 days [66].

The complexity of contaminants contributes to the slow pace of biodegradation in marine microalgae, as they may need to produce or adapt existing enzymes to break down complex molecules, limiting applicability in situations requiring rapid remediation. One approach to address this challenge is Adaptive Laboratory Evolution (ALE), which involves exposing microalgae to gradual increase of a specific contaminant over multiple generations. Li et al. successfully leveraged ALE to address time-sensitive bioremediation needs by generating *Isochrysis galbana* mutants capable of degrading high-level phenol at 300 mg/L within 10 days [67]. However, it is important to consider that ALE-derived strains may require further evaluation for adaptation to seawater environments typically used in marine microalgae bioremediation applications with different salinity and nutrient levels.

Waste-to-worth valorization

Waste-to-worth is a perspective of envisioning marine microalgae beyond the mere capture of nutrient buildup in water bodies and waste streams [68], to convert the nutrient-rich biomass into valuable products and promote circular bioeconomy (Fig. 2). This section explores the various applications of microalgae-derived biomass as a means of valorization.

Biofuels

The integration of microalgae cultivation with wastewater treatment presents a comprehensive approach to biofuel production, often referred to as the "waste-to-biofuels" concept. Marine microalgae, cultivated directly in wastewater streams, efficiently consume excess nitrogen and phosphorus for growth [13, 26, 69], then subsequently yield valuable lipids suitable for biofuel feedstock (Table 2). Cicci et al. reported that *Scenedesmus dimorphus* and *Arthrospira platensis* can produce lipid content as high as 48% when grown in modulated olive mill wastewater and cattle digestate [70]. However, one primary challenge lies in extracting these valuable lipids for biofuel production without compromising the bioremediation capacity of microalgae. For instance, maximizing lipid content for biofuels through nutrient depletion

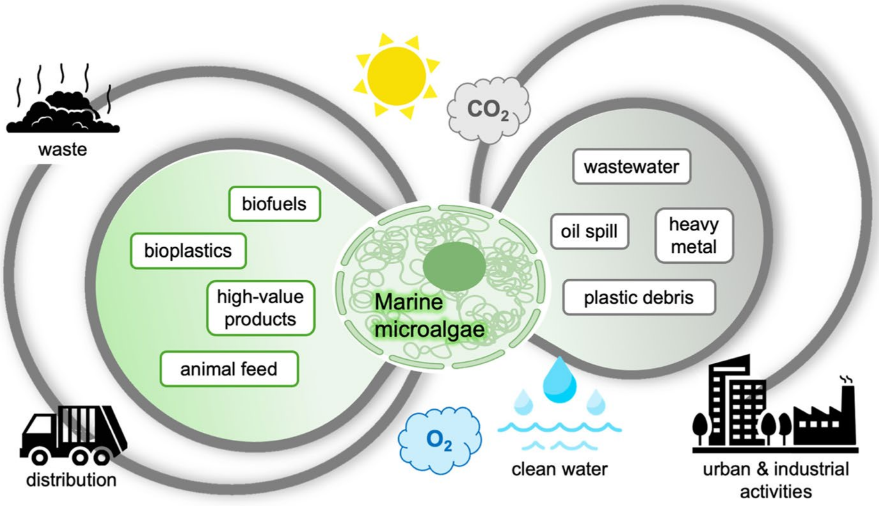

Fig. 2 Marine microalgae as the center of waste-to-worth perspective and circular bioeconomy, linking wastewater, oil spill, plastic debris, and heavy metal generated from urban and industrial activities to valuable products such as biofuels, bioplastics, high-value products, and animal feed

Table 2 Waste-to-worth valorization by specific microalgae strain

Strain	Pollutant	Target product	Yield	Strategy	Ref
Cyanobacteria consortium (*Nostoc*, *Phormidium*, *Geitlerinema*)	Wastewater, anaerobic digestion	Phycocyanin, biomethane	0.02 g/L PC, 200 mL biomethane/g volatile solid	Integration of pigment extraction and biogas production from residual biomass	[72]
Chaetoceros gracilis	Aquaculture wastewater, nano silica	Carotenoid	2.04 mg total carotenoid/g dry cell weight	Addition of nano silica as catalysts to promote nutrient uptake and cell growth	[73]
Cyanobacterium aponinum	Industrial wastewater	Phycocyanin (PC)	1.23 g/L biomass, 0.5 g/L PC	Cultivation at elevated salinity and temperature	[74]
Oscillatoria sp.	Industrial wastewater	Biomethane	97 mL/g total solid	Cultivated at diluted waste stream and seawater	[75]
Scenedesmus dimorphus	Olive mill wastewater, cattle digestate	Biofuel	48% lipid content	Fine-tuning wastewater and digestate as cultivation medium	[70]
Spirulina platensis	Palm oil mill effluent	Phycocyanin, biofuel	1.16 g/L biomass, 0.17 g/L PC	Formulation of appropriate waste stream concentration	[76]
Synechocystis sp.	Secondary urban wastewater	Phycobiliprotein (PCB), PHB, lipid	1.43 g/L biomass, 7.4–4.8–44.7% PCB-PHB-lipid	Semi-continuous cultivation using hydraulic retention time (HRT) to modulate starvation period	[77]
Synechococcus leopoliensis	Aquaculture wastewater, biogas digestate	PHB	6 g/L biomass, 0.9% PHB	Varying starvation regime in open system	[78]
Synechococcus sp.	Heavy metal (lead)	Phycocyanin	0.8 g/L biomass, 40% PC	Supplementation of nitrogen source (nitrate and ammonia)	[79]

in *P. tricornutum* and *N. pelliculosa* can lead to reduced overall biomass, hindering overall nutrient removal and heavy metal detoxification [32]. To address this challenge, attempts are directed toward two-stage cultivation system (TSCS), where growth and production stages are separated [71]. TSCS allows for efficient bioremediation during the first stage in a nutrient-rich environment, followed by transfer to a nutrient-depleted environment in the second stage to trigger increased lipid production for biofuel generation.

Reintegrating the remaining biomass, still rich in nutrients and residual lipids, back into the wastewater treatment process is a promising strategy for enhancing bioremediation efficiency. Another attempt was done by Arashiro et al. where higher energy recovery was achieved by combining pigment extraction and biogas production from residual biomass [72]. This integrated approach has the potential to improve overall bioremediation efficiency and reduce processing costs by minimizing waste generation.

Bioplastics

Bioplastics, specifically derived from marine microalgae, offer a sustainable alternative to traditional plastics. Numerous strains, particularly cyanobacteria such as *Anabaena* sp. [80], *Synechocystis* sp. [77], and *Synechococcus* sp. [78], are able to accumulate polyhydroxybutanoates (PHB) when cultivated in wastewater, with PHB content ranging from 2.4% to 7.4% dry cell weight (Table 2). Furthermore, the biomass itself can serve as a resource for developing starch-based bioplastics [81], or as reinforcing agent to enhance the properties of existing bioplastics through blending. Previous studies have demonstrated success in blending microalgae biomass with avocado-based starch [82] and chitosan [83], resulting in bioplastics with improved mechanical strength, thermal stability, and biodegradability.

However, efficiently integrating different waste streams, especially in large-scale processes, remains a challenge in the microalgae cultivation for bioplastics production. An innovative three-stage system utilizing large outdoor tanks (PBRs), each with a capacity of 11,700 L (3,100 gallons), demonstrated effective bioplastics production from cyanobacteria using agricultural runoff as the nutrient source. The first tank focused on selecting and growing cyanobacteria, achieving a high removal efficiency of 95% and 99% for total nitrogen and phosphorus, respectively. Inorganic carbon was introduced in a feast-famine regime to the second tank to promote cyanobacteria growth, followed by continuous inorganic carbon supply in the final tank to enhance bioplastics production [84]. Ultimately, ensuring waste compatibility with microalgae growth and optimizing nutrient extraction are crucial for driving waste-to-bioplastics initiatives forward.

High-value products

Microalgae possess the remarkable ability to convert waste streams into a diverse array of high-value products with applications in pharmaceuticals, food additives, and cosmetics. One notable example is C-phycocyanin, a vibrant blue pigment protein (phycobiliprotein) which can accumulate to more than 15–20% of the total dry weight in cyanobacteria such as *Spirulina* sp. [85], *Synechococcus* sp. [79], and *Cyanobacterium aponinum* [74]. Another noteworthy valuable chemical is carotenoid, which has been produced through the valorization of aquaculture wastewater using *Chaetoceros gracilis*. Interestingly, nano silica was added in the culture medium as a catalyst to trigger utilization of excess nutrients in the wastewater, thus promoting growth and biomass accumulation [73].

Additionally, microalgae serve as valuable sources of essential fatty acids (EFAs), particularly long-chain polyunsaturated fatty acids (PUFAs) namely gamma-linolenic acid, arachidonic acid, eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA) [75]. Studies have demonstrated that cultivating microalgae in waste streams, such as palm oil mill effluent and fish waste hydrolysate, can yield higher concentrations of high-value compounds compared to conventional media [76, 86]. For example, increased production of arachidonic acid has been observed in *Porphyridium purpureum* under stress conditions when cultivated in a mixotrophic mode supplemented with organic carbon sources [75].

Nonetheless, a significant challenge in the bioremediation process lies in the downstream purification of these compounds from the complex mixtures present in waste streams, not to mention the essential encapsulation stage. Emerging non-destructive and selective extraction techniques, say osmotic shock and enzymatic extraction, enable the recovery of high-value products while facilitating the reuse of microalgae for subsequent bioremediation cycles [87]. This closed-loop system enhances sustainability and economic viability by maximizing the utility of microalgal biomass for the waste-to-worth concept.

Animal feed

Microalgae biomass represents a nutrient-rich source of protein, vitamins, and minerals in animal feed production, particularly beneficial for aquaculture. *Spirulina* and *Chlorella* are renowned for their high protein content, ranging from 50–70% of dry weight, along with essential fatty acids (EFAs), antioxidants, and micronutrients crucial for livestock and fish health. However, a critical challenge arises regarding potential toxin accumulation through bioaccumulation pathways. Research on *Dunaliella salina*, for instance, revealed high levels of arsenic accumulation in contaminated environments [55]. Similarly, concerns about phenanthrene accumulation in *Nannochloropsis oculata* during bioremediation underscore the importance of careful strain selection and monitoring for animal feed applications [63]. Conversely, recent study on Nile tilapia (*Oreochromis niloticus*) shows promise for *Nannochloropsis oculata* as a dietary supplement to mitigate environmental pollutant effects. Incorporating *N. oculata* into tilapia diets reduced mercury bioaccumulation, improved blood cell health, and mitigated organ damage [88], illustrating the dual benefits of microalgae in nutrition and environmental protection.

Strain selection for animal feed must prioritize high digestibility and minimal toxin accumulation. For example, *Scenedesmus* sp. DDVG I demonstrated 62% digestibility, potentially lowering toxin absorption risks due to reduced undigested material [89]. Addressing the challenge of toxin accumulation involves ongoing research into developing and selecting strains less prone to heavy metal and organic pollutant accumulation. Moreover, implementing proper pre-treatment and post-treatment processes, such as washing, enzymatic treatment, or fermentation, can reduce or eliminate toxins before utilizing biomass as feed. To ensure safety and quality, edible products should come from "safe" wastewater streams, such as those from the food, dairy, beverage, and brewery industries. Another possibility lies in combining microalgae cultivation with aquaculture systems, where microalgae serve as live feed for fish or shellfish, providing nutrients while simultaneously removing excess nutrients from the water [90]. This closed-loop system reduces reliance on external feed sources and improves water quality within the aquaculture unit.

Emerging advancements and future perspectives

Synthetic biology and genetic engineering

Ongoing research dives even deeper into the natural ability of marine microalgae, exploring possibilities of genetic engineering to enhance pollutant removal capabilities and the subsequent waste-to-worth concept, or to manipulate microalgal metabolism and introduce novel power. For instance, bacterial PHB biosynthesis pathway from *Ralstonia eutropha* H16 has been introduced into the cytosolic compartment of the diatom *Phaeodactylum tricornutum*, which enabled PHB accumulation of 10.6% dry weight in a granule-like form within the cell cytosol [91]. As another advancement in bioplastics, Moog et al. engineered a microalgae-based system for degrading PET, a common plastic found in marine environments, via heterologous overexpression of PETase from *Ideonella sakaiensis* into *Phaeodactylum tricornutum*. Functional PETase was successfully produced, allowing for the degradation of both PET and PETG plastics, even at moderate temperatures (21 °C) in saltwater, on a par with real-world ocean conditions [92]. Understanding the underlying mechanism of pollutant removal at omics scale is essential to reveal novel target genes. For example, research has shown that ferroptosis is a key mechanism of Bisphenol A detoxification [93], which can be explored further by introducing it to desired hosts and explore wider possibilities of strain diversity. Another gene worth exploring is sulfate transporter gene encoding SULTR2, reported to increase chromium accumulation in *Chlamydomonas reinhardtii* [94].

CRISPR technology, stands for Clustered Regularly Interspaced Short Palindromic Repeats, serves as the foundation of developing genetic toolbox for marine microalgae. While it has been well established in freshwater green algae *Chlamydomonas reinhardtii*, progress in marine microalgae is maturing, as implemented in *Nannochloropsis oceanica* [95], *Phaeodactylum tricornutum* [96], *Chaetoceros muelleri* [97], and diverse strains of cyanobacteria [98]. Breakthrough in in silico sgRNA design tools [99] and anti-CRISPR proteins [100, 101] are also employed to mitigate cytotoxicity and improve Cas9 expression. Further optimization strategies, including fine-tuning expression levels of heterologous genes, enhancing the efficiency of gene delivery methods, and precise mutagenesis without off-targets, are vital for maximizing the application genetic engineering in marine microalgae.

Development of microalgae consortia for complex scenario

Real-world bioremediation often faces the challenge of complex environmental scenarios with multiple pollutants, where axenic cultures may not suffice. Microalgae consortia, composed of multiple microalgae strains and even bacteria, offer advantages over single-strain cultures, including reduced environmental risk, higher biomass yields, and improved nutrient removal, with some consortia achieving over 70% nitrogen removal [102].

Metagenomics analysis, a powerful tool for studying microbial communities, can identify beneficial interactions between different microalgae and bacteria for bioremediation. For example, bacteria can act as "vitamin prototrophs" and provide essential vitamins to vitamin-auxotrophic microalgae in order to enhance productivity [103]. In a co-culture system, *Pelagibaca bermudensis* was reported to promote the growth of *Tetraselmis striata*, resulting in a 3.6-fold increase in biomass even under fluctuating temperature, light, and salinity conditions [104]. *P. bermudensis* secretes metabolic products that serve as growth substrates for *T. striata*, thereby enhancing growth and mitigating inhibitory effects from other bacterial metabolites.

Further optimization strategies, such as nitrate limitation or adjusting light and nutrient conditions, can enhance the effectiveness of these consortia. Developing robust microalgae-bacteria consortia tailored to specific environmental conditions and pollutants represents a significant leap forward in bioremediation, serving as a versatile tool to tackle complex environmental challenges and promote sustainable waste-to-worth valorization.

Integration of microalgae cultivation with external processes

Moving beyond standalone applications, integrating microalgae cultivation with existing bioremediation processes is foreseen to enhance overall system efficiency, specifically by capitalizing on the unique capabilities of microalgae to optimize treatment effectiveness. Combining microalgae cultivation with constructed wetlands for wastewater treatment allows microalgae to act as biofilters, which reduce nutrient load, enhance efficiency, and minimize downstream processing [105]. Additionally, microalgae can serve as a pre-treatment step in removing organic pollutants and particulates before the membrane filtration stage, thus extending membrane lifespan and improving filtration efficiency [106].

Microalgae-based biohybrid micro/nano-robots (MNRs) represent a groundbreaking approach to bioremediation (Fig. 3) by combining living microalgae with engineered components, such as magnetic nanoparticles or light-sensitive materials, to enhance targeted contaminant removal and treatment efficiency [107]. Another cutting-edge application is biophotovoltaics (BPVs), which utilize photosynthetic microorganisms to generate electricity for powering wastewater treatment processes. Okedi et al. demonstrated that *Synechococcus elongatus* sp. PCC7942 can absorb nutrients from wastewater while producing an electric current. This research highlighted the relationship between cell shape and electron transfer rates, with wider and longer cells showing better electron transfer, although this varies throughout the growth phase [108]. In future projections of ocean carbon storage, microalgae act as microbial carbon pumps, mediating the carbon reservoir through refractory dissolved organic carbon and contributing to negative carbon emissions in the ocean [109].

Conclusion

Utilization of marine microalgae presents a promising avenue for addressing environmental challenges while simultaneously unlocking valuable resources, such as biofuels, bioplastics, high-value compounds, and animal feed. However, realizing the full potential requires ongoing research and innovation. Future studies should focus on optimizing genetic engineering techniques, understanding long-term effects, and maximizing efficacy in specific contaminant removal processes. Additionally, developing robust, commercial-scale microalgae-based bioremediation facilities, and applying artificial intelligence for database analysis are essential for widespread

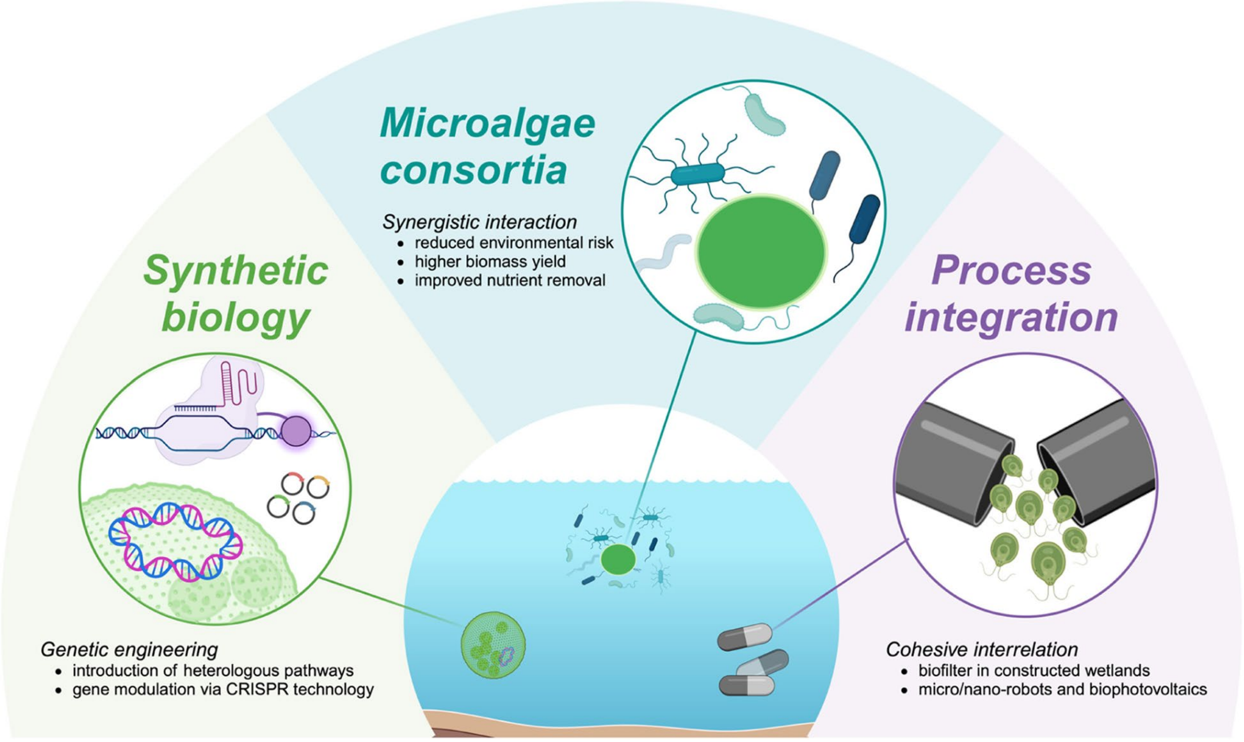

Fig. 3 Cutting-edge advancement in bioremediation performed by marine microalgae, including synthetic biology, consortia development, and process integration

implementation. Continued efforts and collaboration will undoubtedly lead to innovative solutions, leveraging the unique capabilities of marine microalgae to mitigate environmental pollution and foster a greener, more resilient planet.

Acknowledgements
The authors are grateful for the financial support from the Ministry of Science and Technology (MOST 111-2221-E-006-012-MY3) and National Science and Technology Council (NSTC 113-2218-E-006-014) in Taiwan.

Authors' contributions
Priskila Adjani Diankristanti: writing original draft and conceptualization, prepared all tables and figures. I-Son Ng: conceptualization, resources, supervision, writing-original draft, writing-review, and editing.

Funding
This work was funded by the Ministry of Science and Technology (MOST 111–2221-E-006–012-MY3) and National Science and Technology Council (NSTC 113-2218-E-006-014) in Taiwan.

Availability of data and materials
All the figures are prepared by the authors, unnecessary for the permission of reproduced images.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
This article does not involve human subjects, including tests on live vertebrates and/or higher invertebrates.

Consent for publication
The authors declare that they fully understand the manuscript content and they have agreed to submit it to "Blue Biotechnology".

Competing interests
The authors declare no competing interests.

Received: 10 June 2024 Accepted: 5 August 2024

References

1. United Nations Environment Programme. Pivotal fourth session of negotiations on a global plastics treaty opens in Ottawa. 2024. https://www.unep.org/news-and-stories/press-release/pivotal-fourth-session-negotiations-global-plastics-treaty-opens. Accessed on 29 April 2024.
2. Laura Parker, National Geographic. Ocean trash: 5.25 trillion pieces and counting, but big questions remain. 2023. https://education.nationalgeographic.org/resource/ocean-trash-525-trillion-pieces-and-counting-big-questions-remain/#. Accessed 29 Apr 2024.
3. Effendi H, Mursalin M, Hariyadi S. Rapid water quality assessment as a quick response of oil spill incident in coastal area of Karawang. Indonesia Front Environ Sci. 2022;10:757412.
4. Food and Agriculture Organization of the United Nations. Evaluation at FAO: Learning from FAO projects on land and soils. 2023. https://www.fao.org/evaluation/highlights/detail/soils/en#:~:text=FAO%20estimates%20that%20nearly%20one,health%20and%20mitigating%20climate%20change. Accessed 29 Apr 2024.
5. Federico Maggi, The University of Sydney. Two thirds of farmland at risk of pesticide pollution. 2021. https://www.sydney.edu.au/news-opinion/news/2021/03/30/two-thirds-of-farmland-at-risk-of-pesticide-pollution.html. Accessed 29 Apr 2024.
6. Liu YR, Van der Heijden MG, Riedo J, Sanz-Lazaro C, Eldridge DJ, Bastida F, et al. Soil contamination in nearby natural areas mirrors that in urban greenspaces worldwide. Nat Commun. 2023;14(1):1706.
7. Rempel A, Gutkoski JP, Nazari MT, Biolchi GN, Cavanhi VAF, Treichel H, et al. Current advances in microalgae-based bioremediation and other technologies for emerging contaminants treatment. Sci Total Environ. 2021;772:144918.
8. Zafar AM, Javed MA, Hassan AA, Mehmood K, Sahle-Demessie E. Recent updates on ions and nutrients uptake by halotolerant freshwater and marine microalgae in conditions of high salinity. J Water Proc Eng. 2021;44:102382.
9. Patel AK, Tseng YS, Singhania RR, Chen CW, Chang JS, Di Dong C. Novel application of microalgae platform for biodesalination process: a review. Bioresour Technol. 2021;337:125343.
10. Rizwan M, Mujtaba G, Memon SA, Lee K. Influence of salinity and nitrogen in dark on *Dunaliella tertiolecta*'s lipid and carbohydrate productivity. Biofuels. 2022;13(4):475–81.
11. Young JN, Schmidt K. It's what's inside that matters: physiological adaptations of high-latitude marine microalgae to environmental change. New Phytol. 2020;227(5):1307–18.
12. Chakravarty S, Mallick N. Carbon dioxide mitigation and biodiesel production by a marine microalga under mixotrophic mode by using transesterification by-product crude glycerol: a synergy of biofuels and waste valorization. Environ Technol Innov. 2022;27:102441.
13. Kumar N, Banerjee C, Chang JS, Shukla P. Valorization of wastewater through microalgae as a prospect for generation of biofuel and high-value products. J Clean Prod. 2022;362:132114.
14. Markou G, Wang L, Ye J, Unc A. Using agro-industrial wastes for the cultivation of microalgae and duckweeds: Contamination risks and biomass safety concerns. Biotechnol Adv. 2018;36(4):1238–54.
15. Patel A, Gami B, Patel P, Patel B. Biodiesel production from microalgae *Dunaliella tertiolecta*: A study on economic feasibility on large-scale cultivation systems. Biomass Convers Biorefin. 2023;13(2):1071–85.
16. Wu J, Chen C, Wu H, Li T, Chen X, Wu H, et al. Enhancement in lipid productivity of the marine microalga *Nannochloropsis* sp. SCSIO-45217 through phosphate adjustment strategies. J Appl Phycol. 2023;35(3):1023–35.
17. Kannah RY, Kavitha S, Karthikeyan OP, Rene ER, Kumar G, Banu JR. A review on anaerobic digestion of energy and cost effective microalgae pretreatment for biogas production. Bioresour Technol. 2021;332:125055.
18. Jahn MT, Schmidt K, Mock T. A novel cost effective and high-throughput isolation and identification method for marine microalgae. Plant Methods. 2014;10:1–10.
19. Pinto R, Vilarinho R, Carvalho AP, Moreira JA, Guimarães L, Oliva-Teles L. Raman spectroscopy applied to diatoms (microalgae, Bacillariophyta): Prospective use in the environmental diagnosis of freshwater ecosystems. Water Res. 2021;198:117102.
20. Wang J, Wang G, Chen M, Wang Y, Ding G, Zhang Y, et al. An integrated microfluidic chip for treatment and detection of microalgae cells. Algal Res. 2019;42:101593.
21. Chebotaryova SP, Zakharova OV, Baranchikov PA, Kolesnikov EA, Gusev AA. Assessment of the potential of using microalgae from the genus *Desmodesmus* for the bioremediation of water polluted with TiO_2 nanoparticles. Nanobiotechnol Rep. 2023;18(3):352–61.
22. Urrutia C, Yañez-Mansilla E, Jeison D. Bioremoval of heavy metals from metal mine tailings water using microalgae biomass. Algal Res. 2019;43:101659.
23. Gunjal A, Gupta S, Nweze JE, Nweze JA. Chapter 4: Metagenomics in bioremediation: Recent advances, challenges, and perspectives. In: Kumar V, Bilal M, Shahi SK, Garg VK, editors. Metagenomics to Bioremediation. Academic Press: Elsevier; 2023. p. 81–102.
24. Chowdhury BR, Das S, Bardhan S, Lahiri D. Chapter 8: Omics approaches for microalgal applications in wastewater treatment. In: Kumar V, Bilal M, Ferreira LFR, Iqbal HMN, editors. Genomics Approach to Bioremediation: Principles, Tools, and Emerging Technologies. John Wiley & Sons, Inc; 2023. p. 143–156.
25. WoRMS Editorial Board. World Register of Marine Species. 2024. https://www.marinespecies.org/aphia.php?p=taxlist. Accessed 20 May 2024.

26. Kashem AHM, Das P, AbdulQuadir M, Khan S, Thaher MI, Alghasal G, et al. Microalgal bioremediation of brackish aquaculture wastewater. Sci Total Environ. 2023;873:162384.
27. Ezenweani RS, Kadiri MO. Evaluating the productivity and bioremediation potential of two tropical marine algae in petroleum hydrocarbon polluted tropical marine water. Int J Phytoremediation. 2024;26(7):1099–116.
28. Santos MDJO, de Souza CO, Marcelino HR. Blue technology for a sustainable pharmaceutical industry: microalgae for bioremediation and pharmaceutical production. Algal Res. 2023;69:102931.
29. Radwan EK, Abdel-Aty AM, El-Wakeel ST, Abdel Ghafar HH. Bioremediation of potentially toxic metal and reactive dye-contaminated water by pristine and modified *Chlorella vulgaris*. Environ Sci Pollut Res. 2020;27:21777–89.
30. Ding T, Li W, Li J. Influence of multi-walled carbon nanotubes on the toxicity and removal of carbamazepine in diatom *Navicula* sp. Sci Total Environ. 2019;697:134104.
31. Ding T, Lin K, Yang M, Bao L, Li J, Yang B, et al. Biodegradation of triclosan in diatom *Navicula* sp.: Kinetics, transformation products, toxicity evaluation and the effects of pH and potassium permanganate. J Hazard Mater. 2018;344:200–9.
32. Hedayatkhah A, Cretoiu MS, Emtiazi G, Stal LJ, Bolhuis H. Bioremediation of chromium contaminated water by diatoms with concomitant lipid accumulation for biofuel production. J Environ Manage. 2018;227:313–20.
33. Xiong JQ, Govindwar S, Kurade MB, Paeng KJ, Roh HS, Khan MA, et al. Toxicity of sulfamethazine and sulfamethoxazole and their removal by a green microalga, *Scenedesmus obliquus*. Chemosphere. 2019;218:551–8.
34. Xiong JQ, Cui P, Ru S. Biodegradation of doxylamine from wastewater by a green microalga, *Scenedesmus obliquus*. Front Microbiol. 2020;11:584020.
35. Xu D, Huang S, Fan X, Zhang X, Wang Y, Wang W, et al. Elevated CO_2 reduces copper accumulation and toxicity in the diatom *Thalassiosira pseudonana*. Front Microbiol. 2023;13:1113388.
36. Gowthami A, Marjuk MS, Raju P, Devi KN, Santhanam P, Kumar SD, et al. Biodegradation efficacy of selected marine microalgae against Low-Density Polyethylene (LDPE): an environment friendly green approach. Mar Pollut Bull. 2023;190:114889.
37. Chia WY, Tang DYY, Khoo KS, Lup ANK, Chew KW. Nature's fight against plastic pollution: Algae for plastic biodegradation and bioplastics production. Environ Sci Ecotechnol. 2020;4:100065.
38. Valach M, Moreira S, Petitjean C, Benz C, Butenko A, Flegontova O, et al. Recent expansion of metabolic versatility in *Diplonema papillatum*, the model species of a highly speciose group of marine eukaryotes. BMC Biol. 2023;21(1):99.
39. Santaeufemia S, Torres E, Abalde J. Biosorption of ibuprofen from aqueous solution using living and dead biomass of the microalga *Phaeodactylum tricornutum*. J Appl Phycol. 2018;30:471–82.
40. Chang X, He Y, Song L, Ding J, Ren S, Lv M, et al. Methylparaben toxicity and its removal by microalgae *Chlorella vulgaris* and *Phaeodactylum tricornutum*. J Hazard Mater. 2023;454:131528.
41. Ma J, Zhou B, Chen F, Pan K. How marine diatoms cope with metal challenge: Insights from the morphotype-dependent metal tolerance in *Phaeodactylum tricornutum*. Ecotoxicol Environ Saf. 2021;208:111715.
42. de Souza PO, Sinhor V, Crizel MG, Pires N, Sanches Filho PJ, Picoloto RS, et al. Bioremediation of chromium and lead in wastewater from chemistry laboratories promotes by cyanobacteria. Bioresour Technol Rep. 2022;19:101161.
43. Deng J, Fu D, Hu W, Lu X, Wu Y, Bryan H. Physiological responses and accumulation ability of *Microcystis aeruginosa* to zinc and cadmium: implications for bioremediation of heavy metal pollution. Bioresour Technol. 2020;303:122963.
44. Ghorbani E, Nowruzi B, Nezhadali M, Hekmat A. Metal removal capability of two cyanobacterial species in autotrophic and mixotrophic mode of nutrition. BMC Microbiol. 2022;22(1):58.
45. Cui J, Xie Y, Sun T, Chen L, Zhang W. Deciphering and engineering photosynthetic cyanobacteria for heavy metal bioremediation. Sci Total Environ. 2021;761:144111.
46. Dubey S, Chen CW, Haldar D, Tambat VS, Kumar P, Tiwari A, et al. Advancement in algal bioremediation for organic, inorganic, and emerging pollutants. Environ Pollut. 2023;317:120840.
47. Santaeufemia S, Abalde J, Torres E. Efficient removal of dyes from seawater using as biosorbent the dead and living biomass of the microalga *Phaeodactylum tricornutum*: Equilibrium and kinetics studies. J Appl Phycol. 2021;33:3071–90.
48. Hockaday J, Harvey A, Velasquez-Orta S. A comparative analysis of the adsorption kinetics of Cu^{2+} and Cd^{2+} by the microalgae *Chlorella vulgaris* and *Scenedesmus obliquus*. Algal Res. 2022;64:102710.
49. Gu S, Lan CQ. Biosorption of heavy metal ions by green *alga Neochloris oleoabundans*: effects of metal ion properties and cell wall structure. J Hazard Mater. 2021;418:126336.
50. Gu S, Lan CQ. Effects of culture pH on cell surface properties and biosorption of Pb (II), Cd (II), Zn (II) of green alga *Neochloris oleoabundans*. Chem Eng J. 2023;468:143579.
51. Li Y, Song S, Xia L, Yin H, Meza JVG, Ju W. Enhanced Pb (II) removal by algal-based biosorbent cultivated in high-phosphorus cultures. Chem Eng J. 2019;361:167–79.
52. Li Y, Xia L, Huang R, Xia C, Song S. Algal biomass from the stable growth phase as a potential biosorbent for Pb (II) removal from water. RSC Adv. 2017;7(55):34600–8.
53. Martínez-Macias MDR, Nateras-Ramírez O, López-Cervantes J, Sánchez-Machado DI, Corona-Martínez DO, Sánchez-Duarte RG, et al. Effect of pretreatment on Cd (II) and Pb (II) biosorption by Nannochloropsis oculata microalgae biomass. J Appl Phycol. 2024;36:1339–52.
54. Saini N, Dhull P, Pal M, Manzoor I, Rao R, Mushtaq B, et al. Algal membrane photo-bioreactors for efficient removal of emerging contaminants and resource recovery: current advances and future outlook. J Environ Chem Eng. 2024;12(3):112669.
55. Xi Y, Han B, Meng Z, Li Y, Zeng X, Kong F, et al. Arsenic uptake and biotransformation mechanisms in *Dunaliella salina*: Insights into physiological and molecular responses. Algal Res. 2024;80:103539.
56. Zhang Y, Sun D, Gao W, Zhang X, Ye W, Zhang Z. The metabolic mechanisms of Cd-induced hormesis in photosynthetic microalgae, Chromochloris zofingiensis. Sci Total Environ. 2024;912:168966.
57. Kumar N, Shukla P. Microalgal multiomics-based approaches in bioremediation of hazardous contaminants. Environ Res. 2024;247:118135.
58. Vale F, Sousa CA, Sousa H, Santos L, Simões M. Impact of parabens on microalgae bioremediation of wastewaters: a mechanistic study. Chem Eng J. 2022;442:136374.
59. Li H, Lin L, Liu H, Deng X, Wang L, Kuang Y, et al. Simultaneous exposure to nanoplastics and cadmium mitigates microalgae cellular toxicity: Insights from molecular simulation and metabolomics. Environ Int. 2024;186:108633.
60. Lee H, Jeong D, Im S, Jang A. Optimization of alginate bead size immobilized with *Chlorella vulgaris* and *Chlamydomonas reinhardtii* for nutrient removal. Bioresour Technol. 2020;302:122891.
61. Huang R, Huo G, Song S, Li Y, Xia L, Gaillard JF. Immobilization of mercury using high-phosphate culture-modified microalgae. Environ Pollut. 2019;254:112966.
62. Han M, Zhang C, Li F, Ho SH. Data-driven analysis on immobilized microalgae system: New upgrading trends for microalgal wastewater treatment. Sci Total Environ. 2022;852:158514.
63. Marques IM, Oliveira ACV, de Oliveira OMC, Sales EA, Moreira ÍTA. A photobioreactor using *Nannochloropsis oculata* marine microalgae for removal of polycyclic aromatic hydrocarbons and sorption of metals in produced water. Chemosphere. 2021;281:130775.
64. Akao PK, Mamane H, Kaplan A, Gozlan I, Yehoshua Y, Kinel-Tahan Y, Avisar D. Iohexol removal and degradation-product formation via biodegradation by the microalga *Chlorella vulgaris*. Algal Res. 2020;51:102050.
65. Li B, Wu D, Li Y, Shi Y, Wang C, Sun J, et al. Metabolic mechanism of sulfadimethoxine biodegradation by *Chlorella* sp. L38 and Phaeodactylum tricornutum MASCC-0025. Front Microbiol. 2022;13:840562.
66. Li H, Li H, Meng F, Zhang B, Lin Y, Wu J, et al. The biodegradation of Para-xylene in seawater by a newly isolated oceanic microalga *Rhodomonas* sp. JZB-2. J Water Proc Eng. 2020;36:101311.
67. Li H, Tan J, Sun T, Wang Y, Meng F. Acclimation of *Isochrysis galbana* Parke (*Isochrysidaceae*) for enhancing its tolerance and biodegradation to high-level phenol in seawater. Ecotoxicol Environ Saf. 2021;207:111571.
68. Khan MI, Shin JH, Kim JD. The promising future of microalgae: current status, challenges, and optimization of a sustainable and renewable

industry for biofuels, feed, and other products. Microb Cell Fact. 2018;17:1–21.

69. Dias C, Santos JA, Reis A, Lopes da Silva T. The use of oleaginous yeasts and microalgae grown in brewery wastewater for lipid production and nutrient removal: a review. Waste Biomass Valori. 2023;14(6):1799–822.
70. Cicci A, Scarponi P, Cavinato C, Bravi M. Microalgae production in olive mill wastewater fractions and cattle digestate slurry: Bioremediation effects and suitability for energy and feed uses. Sci Total Environ. 2024;932:172773.
71. Aziz MMA, Kassim KA, Shokravi Z, Jakarni FM, Liu HY, Zaini N, et al. Two-stage cultivation strategy for simultaneous increases in growth rate and lipid content of microalgae: a review. Renew Sustain Energy Rev. 2020;119:109621.
72. Arashiro LT, Ferrer I, Pániker CC, Gómez-Pinchetti JL, Rousseau DP, Van Hulle SW, et al. Natural pigments and biogas recovery from microalgae grown in wastewater. ACS Sustain Chem Eng. 2020;8(29):10691–701.
73. Saxena A, Singh PK, Bhatnagar A, Tiwari A. Growth of marine diatoms on aquaculture wastewater supplemented with nanosilica. Bioresour Technol. 2022;344:126210.
74. Lin JY, Ng IS. Thermal cultivation of halophilic *Cyanobacterium aponinum* for C-phycocyanin production and simultaneously reducing carbon emission using wastewater. Chem Eng J. 2023;461:141968.
75. Jiao K, Xiao W, Xu Y, Zeng X, Ho SH, Laws EA, et al. Using a trait-based approach to optimize mixotrophic growth of the red microalga *Porphyridium purpureum* towards fatty acid production. Biotechnol Biofuels. 2018;11:1–11.
76. Yeung T, Wotton A, Walsh L, Aldous L, Conibeer G, Patterson R. Repurposing commercial anaerobic digester wastewater to improve cyanobacteria cultivation and digestibility for bioenergy systems. Sustain Energy Fuels. 2019;3(3):841–9.
77. Senatore V, Rueda E, Bellver M, Díez-Montero R, Ferrer I, Zarra T, et al. Production of phycobiliproteins, bioplastics and lipids by the cyanobacteria *Synechocystis* sp. treating secondary effluent in a biorefinery approach. Sci Total Environ. 2023;857:159343.
78. Mariotto M, Egloff S, Fritz I, Refardt D. Cultivation of the PHB-producing cyanobacterium *Synechococcus leopoliensis* in a pilot-scale open system using nitrogen from waste streams. Algal Res. 2023;70:103013.
79. Lin JY, Tan SI, Yi YC, Hsiang CC, Chang CH, Chen CY, et al. High-level production and extraction of C-phycocyanin from cyanobacteria *Synechococcus* sp. PCC7002 for antioxidation, antibacterial and lead adsorption. Environ Res. 2022;206:112283.
80. Simonazzi M, Pezzolesi L, Galletti P, Gualandi C, Pistocchi R, De Marco N, et al. Production of polyhydroxybutyrate by the cyanobacterium cf *Anabaena* sp. Int J Biol Macromol. 2021;191:92–9.
81. Mathiot C, Ponge P, Gallard B, Sassi JF, Delrue F, Le Moigne N. Microalgae starch-based bioplastics: Screening of ten strains and plasticization of unfractionated microalgae by extrusion. Carbohydr Polym. 2019;208:142–51.
82. Lubis M, Harahap MB, Ginting MHS, Sartika M, Azmi H. Production of bioplastic from avocado seed starch reinforced with microcrystalline cellulose from sugar palm fibers. J Eng Sci Technol. 2018;13(2):381–93.
83. Chong JWR, Tan X, Khoo KS, Ng HS, Jonglertjunya W, Yew GY, et al. Microalgae-based bioplastics: future solution towards mitigation of plastic wastes. Environ Res. 2022;206:112620.
84. Rueda E, García-Galán MJ, Ortiz A, Uggetti E, Carretero J, García J, et al. Bioremediation of agricultural runoff and biopolymers production from cyanobacteria cultured in demonstrative full-scale photobioreactors. Process Saf Environ Prot. 2020;139:241–50.
85. Jaeschke DP, Teixeira IR, Marczak LDF, Mercali GD. Phycocyanin from *Spirulina*: a review of extraction methods and stability. Food Res Int. 2021;143:110314.
86. Palanisamy KM, Bhuyar P, Ab Rahim MH, Govindan N, Maniam GP. Cultivation of microalgae *Spirulina platensis* biomass using palm oil mill effluent for phycocyanin productivity and future biomass refinery attributes. Int J Energy Res. 2023;1:2257271.
87. Chini Zittelli G, Lauceri R, Faraloni C, Silva Benavides AM, Torzillo G. Valuable pigments from microalgae: phycobiliproteins, primary carotenoids, and fucoxanthin. Photochem Photobiol Sci. 2023;22(8):1733–89.
88. Mamdouh AZ, Zahran E, Mohamed F, Zaki V. *Nannochloropsis oculata* feed additive alleviates mercuric chloride-induced toxicity in Nile tilapia (*Oreochromis niloticus*). Aquat Toxicol. 2021;238:105936.
89. Devi ND, Sun X, Hu B, Goud VV. Bioremediation of domestic wastewater with microalgae-cyanobacteria co-culture by nutritional balance approach and its feasibility for biodiesel and animal feed production. Chem Eng J. 2023;454:140197.
90. de Moraes LBS, Santos RFB, Gonçalves Junior GF, Mota GCP, Dantas DMDM, de Souza BR, et al. Microalgae for feeding of penaeid shrimp larvae: an overview. Aquac Int. 2022;30(3):1295–313.
91. Hempel F, Bozarth AS, Lindenkamp N, Klingl A, Zauner S, Linne U, et al. Microalgae as bioreactors for bioplastic production. Microb Cell Fact. 2011;10:1–6.
92. Moog D, Schmitt J, Senger J, Zarzycki J, Rexer KH, Linne U, et al. Using a marine microalga as a chassis for polyethylene terephthalate (PET) degradation. Microb Cell Fact. 2019;18:1–15.
93. Carbó M, Chaturvedi P, Álvarez A, Pineda-Cevallos D, Ghatak A, González PR, et al. Ferroptosis is the key cellular process mediating Bisphenol A responses in *Chlamydomonas* and a promising target for enhancing microalgae-based bioremediation. J Hazard Mater. 2023;448:130997.
94. Tang Y, Zhang B, Li Z, Deng P, Deng X, Long H, et al. Overexpression of the sulfate transporter-encoding SULTR2 increases chromium accumulation in *Chlamydomonas reinhardtii*. Biotechnol Bioeng. 2023;120(5):1334–45.
95. Naduthodi MIS, Südfeld C, Avitzigiannis EK, Trevisan N, van Lith E, Alcaide Sancho J, et al. Comprehensive genome engineering toolbox for microalgae *Nannochloropsis oceanica* based on CRISPR-Cas systems. ACS Synth Biol. 2021;10(12):3369–78.
96. Slattery SS, Diamond A, Wang H, Therrien JA, Lant JT, Jazey T, et al. An expanded plasmid-based genetic toolbox enables Cas9 genome editing and stable maintenance of synthetic pathways in *Phaeodactylum tricornutum*. ACS Synth Biol. 2018;7(2):328–38.
97. Yin W, Hu H. CRISPR/Cas9-mediated genome editing via homologous recombination in a centric diatom Chaetoceros muelleri. ACS Synth Biol. 2023;12(4):1287–96.
98. Feng S, Xie X, Liu J, Li A, Wang Q, Guo D, et al. A potential paradigm in CRISPR/Cas systems delivery: at the crossroad of microalgal gene editing and algal-mediated nanoparticles. J Nanobiotechnol. 2023;21(1):370.
99. Chuai GH, Wang QL, Liu Q. In silico meets in vivo: towards computational CRISPR-based sgRNA design. Trends Biotechnol. 2017;35(1):12–21.
100. Dong D, Guo M, Wang S, Zhu Y, Wang S, Xiong Z, et al. Structural basis of CRISPR–SpyCas9 inhibition by an anti-CRISPR protein. Nature. 2017;546(7658):436–9.
101. Rauch BJ, Silvis MR, Hultquist JF, Waters CS, McGregor MJ, Krogan NJ, et al. Inhibition of CRISPR-Cas9 with bacteriophage proteins. Cell. 2017;168(1):150–8.
102. Kong W, Kong J, Feng S, Yang T, Xu L, Shen B, et al. Cultivation of microalgae–bacteria consortium by waste gas–waste water to achieve CO2 fixation, wastewater purification and bioproducts production. Biotechnol Biofuels Bioprod. 2024;17(1):26.
103. Tandon P, Jin Q, Huang L. A promising approach to enhance microalgae productivity by exogenous supply of vitamins. Microb Cell Fact. 2017;16:1–13.
104. Patidar SK, Kim SH, Kim JH, Park J, Park BS, Han MS. *Pelagibaca bermudensis* promotes biofuel competence of *Tetraselmis striata* in a broad range of abiotic stressors: dynamics of quorum-sensing precursors and strategic improvement in lipid productivity. Biotechnol Biofuels. 2018;11:1–16.
105. Zhao X, Zhang T, Dang B, Guo M, Jin M, Li C, et al. Microalgae-based constructed wetland system enhances nitrogen removal and reduce carbon emissions: performance and mechanisms. Sci Total Environ. 2023;877:162883.
106. Gerardo ML, Oatley-Radcliffe DL, Lovitt RW. Integration of membrane technology in microalgae biorefineries. J Membrane Sci. 2014;464:86–99.

107. Wang H, Jing Y, Yu J, Ma B, Sui M, Zhu Y, et al. Micro/nanorobots for remediation of water resources and aquatic life. Front Bioeng Biotechnol. 2023;11:1312074.
108. Okedi TI, Fisher AC, Yunus K. Quantitative analysis of the effects of morphological changes on extracellular electron transfer rates in cyanobacteria. Biotechnol Biofuels. 2020;13:1–14.
109. Jiao N, Luo T, Chen Q, Zhao Z, Xiao X, Liu J, et al. The microbial carbon pump and climate change. Nat Rev Microbiol. 2024;22:408–19.

Publisher's Note