

Review

Microalgal Bioremediation of Microplastics: Current Advances, Challenges and Environmental Applications

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Abstract

The world is facing a triple global crisis: climate change, loss of biodiversity, and pollution. Plastics, man-made polymers from primary fossil fuel sources, have pervasively entered almost every sector and thereby caused huge environmental pollution. Microplastic (MPs) sizes range between 1 μm and 5 μm , and nanoplastics are less than 1 μm in size, respectively. Behaviour, accumulation and movement of plastics in soil, water and air depend on their size. Smaller sizes of microplastics and nanoplastics can easily enter cells, tissues, and finally, the food chain, and pose growing ecological and health concerns due to their persistence. It also acts as an adsorbent and has the ability to penetrate food webs. Their diverse shapes, especially fibres, increase their dispersal and bioavailability in aquatic ecosystems. Recent findings indicate that microalgae contribute to the mitigation of microplastic pollution. Microalgae, diverse photosynthetic microorganisms ranging from 0.5 to 200 μm , interact with microplastics through processes such as adsorption, aggregation, and potential biodegradation mechanisms, including toxin systems or enzymes produced by the microalgae, utilising plastic polymers as carbon sources. The filamentous morphology of some species, such as *Spirulina* sp., increases the entrapment and potential degradation of microplastic fibres. It is essential to understand these interactions to construct sustainable means of mitigating microplastic pollution and recovering the aquatic ecosystem health. Microalgae produce enzymes such as lipases, esterases, and cellulases, which facilitate the biodegradation of plastics. Microalgae form biofilm on the surface of microplastics. They also secrete sticky extracellular polymeric substances (EPS) that cause the microplastic to sink to the bottom of the water body, which helps to remove microplastics from surfaces. This review summarises knowledge on microalgae–microplastic interactions, with a focus on their potential for bioremediation of microplastics and also sustainable conservation of the environment.

Keywords: microplastics; human health; bioremediation; algae; sustainable conservation



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1. Introduction

The world is currently facing a significant triple crisis: climate change, loss of biodiversity, and pollution. This crisis directly impacts the welfare of individuals, particularly the most vulnerable, as well as our planet and ecosystems. Plastic manufacturing and consumption, especially single-use plastics, have increased in recent decades. The resulting rise in pollution and plastic waste reinforces system-level risks and presents a serious and increasing threat to biodiversity, human rights, public health, and climate change. All plastics consist of polymers formed from monomers such as ethylene, propylene, styrene, phenol, formaldehyde, ethylene glycol, vinyl chloride, and acetonitrile. These monomers are predominantly derived from crude oil, which provides the fundamental organic hydrocarbon framework [1]. U.N.E.P. data indicate that the annual production of plastic exceeds 460 million metric tonnes. Plastics are used daily by consumers and industrial processes, including electronics, agriculture, and automobiles [2]. The National Oceanic and Atmospheric Administration (NOAA) defined microplastics as plastic particulates that are less than 5 mm in size during a 2008 workshop [3]. Parkesine is regarded as being the first synthetic plastic, but it was not derived from fossil fuels. It is a cellulose-derived thermoplastic (malleable at elevated temperatures) that was patented by Parkes in 1856 [4].

Microplastics are synthetic polymeric matrices or solid particles, exhibiting either regular or irregular forms, with sizes varying from 1 μm to 5 mm, originating from primary or secondary production, and are insoluble in water. Invisible subdivision of microplastics, smaller than 1 μm , was more recently discovered and called “nanoplastics” [5]. These are now believed to be even more abundant in the environment than the bigger particles. Microplastics can be present in many different shapes, though the most commonly found in the environment are fibres, which can be more than 5 mm long, but meet the definition as being under 5 mm in diameter [6–8]. Other definitions of microplastics have also been provided, and even a very idiosyncratic one (<1 cm) can be found in a recent paper published in a major journal [9]. Microplastics have a specific set of origins, distribution, and characteristics that make them potentially harmful to all ecosystems and their inhabitants. They can adsorb toxic chemicals, serve as vectors for disease-causing agents, and be ingested by a variety of organisms, possibly entering the human food chain [4,10,11]. The filamentous structure of the alga likely played a vital role in retaining microplastic fibres, given its high surface area, which facilitates the capture of tiny particles [10,11]. The current study considers a significant number of published but underutilised studies on how microalgae reduce microplastics.

Plastic pellets, microbeads in personal care products, and other sources, such as wastewater and degraded larger plastics, are major contributors to environmental microplastics [12]. Microbeads, initially introduced in the 1970s, have evolved into significant pollutants [13]. Secondary microplastics arise from the breakdown of larger plastic waste, exacerbated by poor waste management [14]. Without efforts to remove macroplastic debris, the prevalence of microplastics in oceans may increase dramatically by 2050 [14]. Plastics permeate modern life, found in electronics, packaging, and disposable items, leading to their frequent disposal and entry into ecosystems as microplastics [15].

Microplastics are prevalent in terrestrial, freshwater, and marine environments, originating from various sources such as wastewater treatment plants, industrial waste, and atmospheric deposition [16]. They accumulate in ecosystems, pose risks to organisms, and can reach humans through the food chain. Nanoplastics, smaller than 100 nm, may be released from disintegrated microplastics, presenting greater threats due to their larger surface area for toxic substance attachment [17]. Microplastics dominate ocean pollution, comprising over 90% of ocean particles, with significant accumulation in deep-sea environments [18]. Their presence disrupts soil health and affects plant and microbial life,

necessitating initiatives for pollution reduction and ecosystem preservation [19]. Additionally, airborne microplastics behave differently from those in soil and water [20]; their concentration varies with environmental conditions, impacting human health through potential toxicity and contamination [21,22]. Overall, rising plastic production, inefficient disposal, and environmental persistence exacerbate the microplastic crisis [23].

Chemicals included in plastics, such as flame suppressants like PBDEs and plasticisers like phthalates, can cause lung problems and cancer. Over 80% of plasticisers used worldwide are phthalates, which are especially dangerous since they can be released from flexible polymers like PVC [24]. Furthermore, synthetic fabrics are major sources of airborne microplastics (MPs) associated with respiratory irritation, and polypropylene MPs can cause inflammatory reactions in human cells [25]. Human faecal samples and frequently consumed items like fruits have been found to contain microplastics, with apples exhibiting particularly high levels of contamination [26].

Microplastics possess the capacity to adversely affect health and may enter the body via the oral or nasal routes. Microplastics' ability to penetrate skin, gastrointestinal, and airway epithelial barriers must be understood to reduce uncertainty in human risk assessment. Studies on human cells in vitro, rodents, and aquatic animals have demonstrated that microplastics < 10 µm may diffuse from the gut cavity to the lymphatic and circulatory systems, leading to systemic exposure and accumulation in organs such as the liver, kidney, and brain [27]. MPs adversely affect human health through mechanisms such as oxidative stress, neurotoxicity, immunological responses, metabolic disorders, impaired organ function, DNA damage, and reproductive and developmental toxicity [28]. This review compiles understanding of microalgae–microplastic interactions, with an emphasis on their potential for both sustainable environmental conservation and microplastic bioremediation.

2. Algal-Based Degradation and Reduction of Microplastics

“Biodegradation” denotes any alteration, either chemical or physical, induced by biological processes. Biological agents typically use organic polymers as substrates for growth and energy, with microbial biomass as the final product of complete biodegradation. Algae can intercept, trap, and entangle microplastics found in wastewater. Moreover, they can create heterogeneous aggregates with algae, thus reducing the concentration of microplastics in the aqueous suspension [29]. Microalgae have a major advantage over bacterial and fungal strains that produce endotoxins in water treatment applications because they can photosynthesise without the need for an organic carbon source. Algae can directly or indirectly regulate the destiny of MPs in aquatic environments. Currently, retention, flocculation, deposition, and degradation are the confirmed mechanisms (Figure 1).

2.1. Retention of Microplastics by Algae

Efforts to reduce plastic use can be initiated at the production stage through the adoption of recycled or biodegradable materials, enhanced product design for longer lifespan and recyclability, and restrictions on certain single-use plastics [30]. Although some plastics, like those used in food packaging, are essential, a total ban on others, such as microbeads, is beneficial [13]. Industries must ensure the safety of plastic products and replace hazardous materials with safer alternatives [30]. Challenges related to food safety and convenience may hinder waste reduction, but consumer education and accurate labelling can promote eco-friendly choices [31]. The four R's of waste management—Reduce, Reuse, Recycle, Recover—emphasise the need for an Integrated Waste Management System [32].

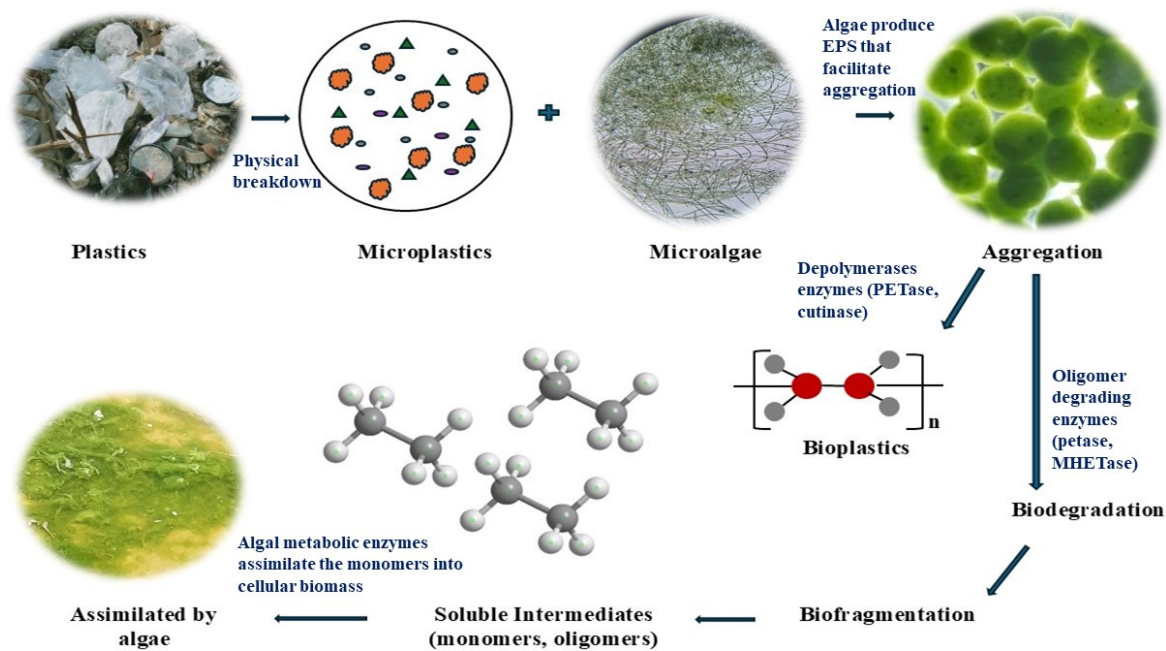


Figure 1. Microplastics degradation and reduction using algae.

Two potential methods have been suggested to elucidate how MPs become trapped on algal surfaces. One method is that microplastics can adhere to algae through sticky biofilms [33]. In marine environments, biofilms may form on microplastics, and the spatial and temporal variations in biofilm communities might influence their adhesiveness [34,35]. An additional mechanism arises when heterotrophic epibiont species can “capture” microplastics from the water column, ultimately engulfing them due to their proliferation [33]. Due to the regional and seasonal variability in epibiont species composition [33,35], certain epibiont communities may exhibit greater proficiency in trapping microplastics than others. It is important to notice that MPs with particle sizes less than 1 mm can be encapsulated within the air sacs of certain macroalgae, such as *U. prolifera*, which possess tubular algal structures [36]. In fact, various mechanisms may operate concurrently to capture MPs from the surrounding environment.

Li et al. (2022) observed that *Gracilaria lemaneiformis*, *Chondrus ocellatus*, *U. lactuca*, *U. prolifera*, and *Saccharina japonica* may capture PS and PET microplastics, predominantly fibre microplastics measuring 1–5 mm, through mechanisms of entanglement and adhesion [37]. Both macroalgae and microalgae are present in the environment. The simultaneous presence of microalgae could boost the absorption of microplastics by macroalgae [37]. It is unclear how MPs and algae bind together in actual environments when a variety of factors are at play [37].

2.2. Algae-Induced Flocculation and Following Deposition of Microplastics

In aquatic environments, microplastics can swiftly and directly cluster around algae [38]. The aggregates may consist of a combination of algae-MPs or algae-EPS-MPs [39]. The primary constituents of EPS include proteins, polysaccharides, and nucleic acids. These different polymers possess complicated shapes and physicochemical properties, and microalgae can produce them externally to provide a protective role [40,41]. The presence of MPs can enhance the secretion of EPS by algae.

Möhlenkamp et al. (2018) noted that microplastics from cosmetic items can clump with algae, allowing even elevated concentrations of microplastics to be swiftly removed from the water column [42]. The aggregation of particles is associated with the presence

of particular functional groups, including carboxyl, sulfonate, hydroxyl, and amine, in algal cell walls, enabling the algae to attract positively charged microparticles, thereby facilitating coagulation and flocculation processes [43,44]. Algae can colonise the surfaces of microplastics, particularly the larger ones, and form biofilms, hence increasing the density of microplastics [45–47]. This may occur from the alteration in the buoyancy of microplastics following the formation of biofilms by algae on their surfaces. According to Cheng and Wang (2022) and Nava and Leoni (2021), the EPS of algae can also cause cells, including algae and other microbes, to migrate from the surrounding environment to the aggregates [35,48]. Consequently, the volume of the aggregates was expanded. Su et al. (2022) discovered that EPS was the primary cause of the heterogeneous aggregation of MPs and *Chlorella vulgaris*, and that the MPs in the aggregates had accelerated withering [49]. The EPS produced by freshwater algae can vary depending on the type of MP that stimulates them [43].

2.3. Algae-Induced Biodegradation of Microplastics

The algae-mediated biodegradation of microplastics in aquatic ecosystems typically involves three successive phases: colonisation, fragmentation, and assimilation [50,51]. Initially, algae adhere to the surfaces of microplastics and establish resilient biofilms. The metabolic processes of the algae produce ligninolytic and exopolysaccharide enzymes that initiate the biodegradation of plastics, rendering microplastics brittle and compromising their structural integrity. Ultimately, water and microbial filaments infiltrate the polymer matrix, promoting the microbial breakdown of microplastics. The degrading enzymes produced by biofilms on microplastics can interact with the macromolecules of microplastics, resulting in their biodegradation [52]. Rozman and Kalčíková (2022) recorded the swift formation of biofilms on microplastics at the air-water interface, modifying the characteristics of the microplastics and validating the initiation of surface degradation visible as fissures [53].

Kim et al. (2020) detected a novel PETase in *C. reinhardtii* CC-124, a strain of green algae, in a lab environment, validating the enzymatic activity of PETase by observing the degradation of PET to terephthalic acid (TPA) [54]. Research has highlighted the potential function of Diatoms in promoting microplastic breakdown within aquatic ecosystems [55–57]. Diatoms possess extracellular enzymes, including lipases and proteases, that facilitate the disintegration of microplastics and alter their surface characteristics [56,57]. Moog et al. (2019) illustrated the enzymatic degradation of PET and polyethylene terephthalate glycol (PETG) in a saline environment utilising marine diatoms as a framework [58].

The decomposition of microplastics is a joint endeavour involving several algae, and this synergistic interaction amplifies the degradation process [59,60]. Sarmah and Rout (2018) observed the effective biodegradation of LDPE microplastics by *Phormidium lucidum* and *Oscillatoria subbrevis* without any pretreatment or pro-oxidants, leading to significant grooves on the surface of LDPE microplastics [61]. Similarly, in the coexistence system of *Anabaena spiroides* (Cyano-bacteria), *Navicula pupula*, and *Scenedesmus dimorphus*, Kumar et al. (2017) found that the induction of algal EPS led to the breakdown of both LDPE and HDPE MPs and the formation of pitted cross sections [62]. Moreover, EPS can diminish the hydrophobicity of polymers and enhance their hydrophilicity. Hadiyanto et al. (2021) observed the emergence of novel hydrophilic functional groups (carbonyl, carboxyl, hydroxyl) on the surface of microplastics during 30 days of interaction with algae (*Spirulina* and Cyanobacterial proteins), along with the formation of cracks [59]. The biodegradation of microplastics is affected by several aspects, including the intrinsic characteristics of the microplastics, the algal species involved, the presence of chemical agents, and the

prevailing environmental conditions [38,63]. While the direct biodegradation of certain microplastic polymers by algae is improbable due to the absence of hydrolysable functional groups in their polymeric structure, biodegradation may occur for those microplastics that have undergone physical or chemical treatments, resulting in the fragmentation of polymeric structures [64]. Extensive colonisation of microplastic surfaces by algae can impede the photodegradation of microplastics by shielding them from UV radiation [51].

Genetic manipulation increases the ability of microalgae to digest plastics by inducing the emergence of pores and cavities on their surface. *Chlamydomonas reinhardtii* can be genetically modified to synthesise PETase [65]. Moreover, the widely employed polymer bisphenol A (BPA) in the plastics industry can be efficiently degraded by algae into molecules lacking oestrogenic characteristics [66]. Subsequently, microalgae adopt endocytosis to internalise microplastic particles within their cells. This sequesters microplastics within cells and reduces their prevalence, functioning as a survival mechanism for microalgae in response to microplastic threats [67]. Danso et al. (2018, 2019) identified at least 27 enzymes that may degrade synthetic oligomers or polymers, predominantly including cutinase, lipase, and esterase [68,69]. The decomposition of plastic typically requires many enzymes and metabolic pathways, rather than depending on a solitary enzyme (Figure 2 & Table 1) [70].

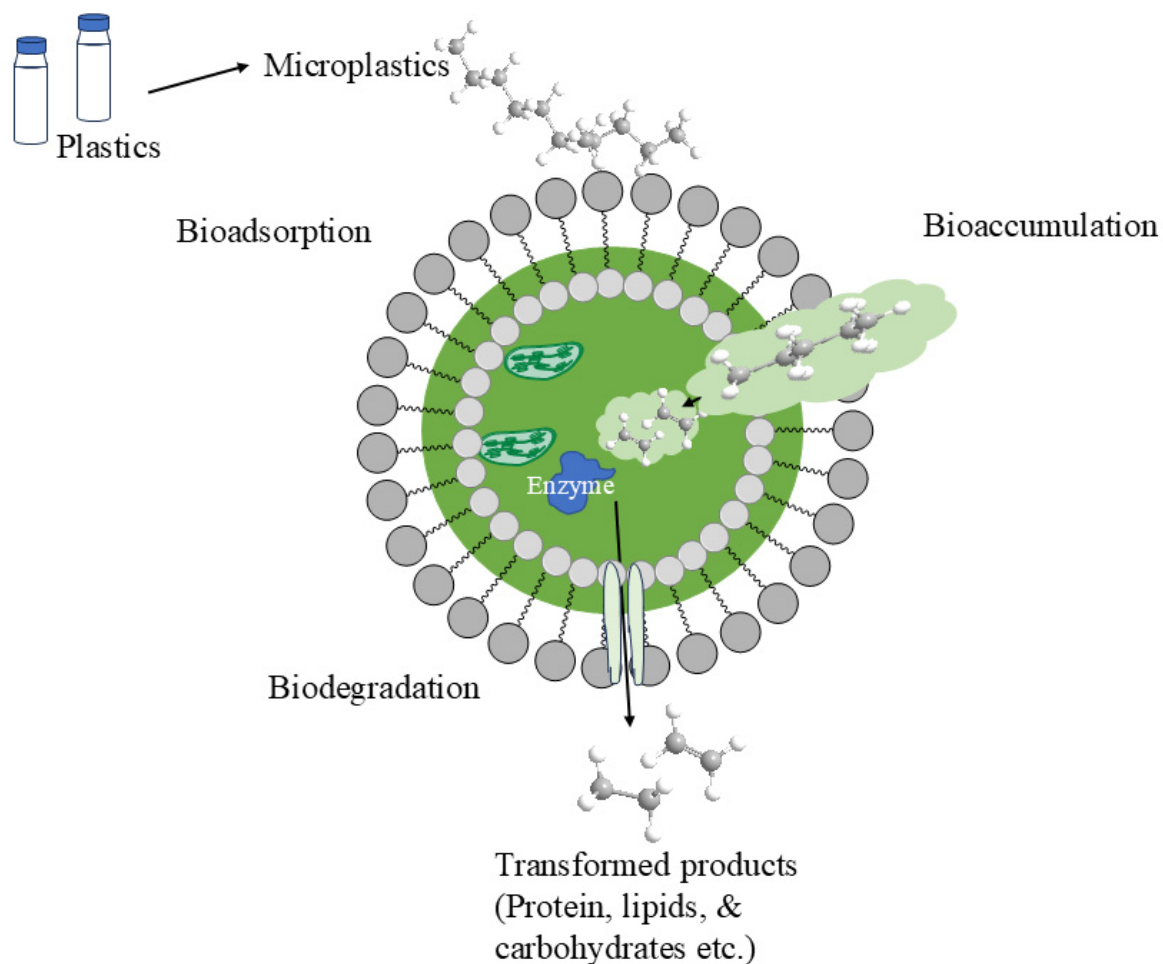


Figure 2. Mechanism of Bioremediation of microplastics by microalgae.

Table 1. Algal species in plastic degradation.

Algal Species	Plastic Form	Environment	Mechanism	References
<i>Anabaena spiroides</i> (Cyanophyceae)	Polyethylene sheet from dumped waste	Waste water in Chennai, Tamil Nadu, India	Rupturing the surface of a polythene sheet	[62]
<i>Phormidium lucidum</i> (Cyanophyceae)	Polythene bags	Sewage water, Assam, India	Grooves on the surface (biodegradation)	[61]
<i>Spirulina</i> sp. (Cyanophyceae)	Fishing nets	Lab conditions	EPS-based bioremediation	[71]
<i>Chlorella vulgaris</i> strain (abdf 21144) (Chlorophyceae)	Polyethylene sheet	Lab conditions	Absorption and bridging mechanism	[72]
<i>Navicula pupula</i> (Bacillariophyceae)	Polyethylene sheet	Dumped waste, Tamil Nadu, India	Erosion	[73]
<i>Cyanothece</i> sp. (Cyanophyceae)	Polyethylene sheet	Lab condition	Aggregation and flocculation	[74]
<i>Chlorella vulgaris</i> (Chlorophyceae)	Polyethylene	Lab condition	Coagulation and flocculation mechanism	[75]
<i>Oedogonium oocystis</i> (Chlorophyceae)	Polythene	Lucknow, Uttar Pradesh, India	Profuse crack (biodeterioration)	[76]
<i>Synechocystis</i> sp. (Cyanophyceae)	Polystyrene	Lab conditions	Pits erosion	[77]
<i>Nostoc carneum</i> (Cyanophyceae)	Polythene bag	Lab conditions	Formation of holes and cavities	[78]
<i>Uronema africanum</i> (Chlorophyceae)	LDPE (low-density polyethylene)	Dumping of domestic waste near Chennai Railway Station, Chennai, Tamil Nadu, India	Corrosion, abrasions, grooves and ridges	[54]
<i>Chlamydomonas reinhardtii</i> (Chlorophyceae)	PET (polyethylene Terephthalate)	Lab condition	Grooves and perforation	[79]
<i>Phaeodactylum tricornutum</i> (Bacillariophyceae)	PET (polyethylene Terephthalate)	Lab condition	Holes, dents, furrows and cavities by enzyme PETase	[58]
<i>Dunaliella salina</i> (Chlorophyceae)	HDPE (high-density polyethylene)	Lab condition	Biofilm formation	[79]

3. Conclusions and Future Prospective

The widespread prevalence of microplastics in aquatic systems, air, and land poses a threat to human health, biodiversity, and the global environment. Microalgae are excellent biological resources that can be utilised to reduce microplastics because of their high growth rates, ecological adaptability, and photosynthetic efficiency. Microalgae, including *Spirulina* sp., *Phormidium* sp., and *Chlorella* sp., facilitate the elimination of microplastic particles from aquatic environments by adsorbing, aggregating, and potentially biodegrading these particles. The increased retention of microplastics due to filamentous algae shape raises the possibility of their application in bioremediation technologies. The efficacy of algal perfor-

mance and deterioration is significantly influenced by environmental conditions, including light intensity, nutrient availability, and microplastic concentration. The development of photobioreactors, wastewater treatment systems, and algae-based biofilters that can efficiently capture and break down microplastics is an example of future applications. By promoting the expression of plastic-degrading enzymes, genetic engineering and synthetic biology techniques may enhance algae degradation capabilities even more. The majority of current research is still focused on laboratory-scale observations, despite these promising findings. Furthermore, a closed-loop sustainable solution to plastic pollution might be offered by integrating algal bioremediation with circular bioeconomy techniques, such as turning algal biomass into biofuels, fertilisers, or bioplastics. It is also unclear which specific metabolic and enzymatic processes microalgae use to break down microplastics. Therefore, to clarify the methods and prerequisites for ideal large-scale applications, comprehensive research integrating molecular biology, environmental engineering, and ecological modelling is needed. In order to move from experimental research to practical application and eventually contribute to global efforts in restorative aquatic ecosystem health and environmental sustainability, this field will require interdisciplinary cooperation and policy support.

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Abbreviations

EPS	Extracellular polymeric substances
NOAA	National Oceanic and Atmospheric Administration
UNEP	United Nation Environment Programme
PVC	Polyvinyl Chloride
PBDEs	Polybrominated Diphenyl Ethers
PETG	Polyethylene terephthalate glycol
LDPE	Low-density polyethylene
PET	Polyethylene Terephthalate
HDPE	High-density polyethylene

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