International Journal of Research in Engineering and Science (IJRES)
ISSN (Online): 2320-9364, ISSN (Print): 2320-9356
www.ijres.org Volume 14 Issue 1 ǁ January 2026 ǁ PP. 247-258

Advanced Research Progress on Microalgae-Mediated Remediation of Emerging Microplastic Contaminants in Aquatic System

Yilin Chen
College of Chemistry and Chemical Engineering, Chongqing University of Technology, Chongqing 400054, China.
Corresponding Author: Yilin Chen

Abstract
The global proliferation of plastic pollution has driven the pervasive accumulation of microplastics in aquatic systems. Their high adsorption affinity for co-pollutants and recalcitrance to conventional removal pose considerable challenges to existing treatment technologies. Microalgae, distinguished by their environmental resilience and versatile metabolism, offer substantial promise for the bioremediation of microplastics. This review systematically examines the advantages of microalgae in microplastic treatment, interaction mechanisms, remediation strategies, key influencing factors, and underlying cellular responses. The efficacy of microalgae-mediated remediation is founded on their photoautotrophic metabolism, high surface-area-to-volume ratio, and secretion of diverse bioactive metabolites. At the interface, extracellular polymeric substances (EPS) are central to hetero-aggregate formation, while the relative size between microalgae and microplastics governs aggregation behavior. Remediation occurs primarily via biosorption and biodegradation, with optimization dependent on matching algal traits to plastic surface properties and regulating EPS secretion and biofilm development. Critical determinants of removal efficiency include algal selection, environmental parameters, plastic polymer characteristics, and adsorption dynamics. Cellular responses exhibit dualistic regulation, chiefly affecting photosynthetic performance and growth kinetics. This review integrates microplastic remediation with microalgal resource recovery, advancing an environmentally and economically sustainable strategy to mitigate contamination while providing a theoretical foundation for further research and industrial implementation.

Keywords: *Microalgae, Microplastics, Bioremediation, Response mechanisms*

Date of Submission: 13-01-2026 Date of Acceptance: 29-01-2026

I. INTRODUCTION

Micro-and nano plastics (MNPs), as an emerging class of persistent pollutants, have garnered widespread global attention. Due to their small particle size, environmental persistence, and bioaccumulation potential, MNPs pose a significant threat to aquatic ecosystems[1, 2]. As centralized infrastructures designed for the elimination of organic and inorganic constituents from wastewater, treatment plants (WWTPs) have increasingly emerged as significant systems for the sequestration of micro- and nanoplastics (MNPs) in recent years. MNPs enter WWTPs through various pathways, primarily via domestic sewage or industrial wastewater. In industrial zones, MNPs generated from polymer manufacturing, various processing industries, and the textile sector are discharged into WWTPs through industrial effluents[3, 4]. In residential areas, laundry wastewater, cosmetics, and personal care products (e.g., shampoo, body wash, toothpaste) constitute major sources of MNPs in domestic sewage[5]. Nevertheless, owing to the constrained removal efficacy of wastewater treatment plants (WWTPs) for micro- and nanoplastics (MNPs), substantial quantities are invariably released into natural aquatic environments, including rivers and oceans. Studies indicate that treated wastewater effluent can still contain millions of MNPs[6], which, upon release into natural aquatic environments, pose serious ecological risks. Conventional methods for microplastic removal, such as coagulation, flocculation, ultrafiltration, photocatalysis, and oxidation, have been extensively reported[7, 8]. Upon introduction into freshwater and marine ecosystems, micro- and nanoplastics (MNPs) exhibit markedly reduced recoverability, thereby substantially compromising the effectiveness of conventional removal technologies. In natural settings, the deployment of microbial consortia—encompassing bacteria, fungi, and algae—for the sequestration of microplastics represents a more ecologically attuned and strategically viable approach. Compared to bioremediation systems based on bacteria and fungi, microalgae exhibit superior environmental adaptability, metabolic capacity, and pollution tolerance, endowing them with

greater potential for bioremediation[9].

This review consolidates the principles and applications of microalgae-mediated remediation technologies targeting microplastic contamination in aquatic systems. Emphasis is placed on elucidating the underlying removal mechanisms—specifically microalgal bio-adsorption and biodegradation—and assessing their treatment efficacy. The analysis further clarifies the pivotal function of extracellular polymeric substances (EPS) in microplastic enrichment and transformation, while underscoring the ecological compatibility and sustainability of such bioremediation strategies. The findings provide theoretical support for developing efficient microbial remediation strategies, particularly offering direction for treating low-concentration and dispersed microplastic contamination, thereby contributing to the advancement of engineering applications in microplastic pollution control.

II. STATUS OF MICROALGAE-BASED BIOREMEDIATION FOR MICRO- AND NANOPLASTICS

2.1 Current Treatment Technologies for Micro- and Nano plastics in Aquatic Environments

As a significant substance released from waste streams, emerging contaminants such as microplastics (MPs) have been confirmed to be ubiquitously present in aquatic environments[10]. Wastewater containing plastics from anthropogenic activities represents one of the key sources of MPs in freshwater systems. After treatment, a substantial portion of MPs accumulates in sewage sludge, while a smaller fraction continues to be discharged into natural water bodies via effluent[11]. Liu Faxin conducted a statistical analysis of MP abundance in influent and effluent from wastewater treatment plants (WWTPs) in various regions globally[12]. The findings demonstrate that influent samples collected from five wastewater treatment plants in Harbin and Shanghai, China, contained microplastic concentrations exceeding 100 items/L. As presented in Table 1.1, while effluent MP loads were substantially lower, the high volumetric discharge of treated wastewater resulted in considerable microplastic release into receiving waters, affirming that WWTPs constitute a persistent emission pathway for MPs. In studies examining MP abundance in WWTP effluents versus natural environments, Mao Yufeng observed that MP concentrations in effluent were substantially higher than the average background levels found in ambient water bodies[13]. Thus, research by both Liu and Mao substantiates that WWTP effluent constitutes a significant source of MPs in aquatic environments.

Table 1.1 Abundance and Removal Efficiency of MPs in Influent and Effluent of Wastewater Treatment Plants

Location of Wastewater Treatment Plant	Influent Abundance （items/L）	Effluent Abundance （items/L）	Overall Removal Rate %	References
Shanghai1	226.27	83.16	63.25	[14]
Shanghai2	171.89	69.03	59.84	[14]
Shanghai 3	117.00	52.00	55.60	[15]
Harbin 1	260.53	58.67	77.48	[16]
Harbin 2	290.87	45.13	84.48	[16]
Xian	288.50	22.90	92.10	[17]
Wuhan1	79.90	28.40	64.40	[17]
Wuhan 2	80.50	30.30	62.70	[17]
Taiyuan	21.00	5.10	75.71	[18]

Considering the biological impacts of microplastics (MPs), wastewater treatment processes are tasked not only with MP removal but also with mitigating the potential stress effects induced by MP exposure. For instance, MPs have the potential to constrain nitrification and denitrification processes, inhibit the anaerobic digestion of sludge—resulting in reduced methane production[19], and contribute to nitrogen suppression within biological communities, a phenomenon closely linked to MP fragments[20-25]. Caruso explained the mechanism by which MPs inhibit denitrification as follows: the adsorptive properties of MPs enhance their contact with nitrifying and denitrifying enzymes on cell surfaces, leading to decreased or even deactivated enzymatic activity, which ultimately impairs the denitrification performance of wastewater. Furthermore, MPs can fragment or degrade into smaller nano-plastics (NPs), which may enter organisms and exert toxic effects on biological systems such as activated sludge[26]. These effects include, but are not limited to, reduced reactor performance, damage to cell membrane structures, inhibition of functional enzyme activity, and alterations in microbial community composition, thereby impacting nitrification–denitrification processes in sediments and further diminishing wastewater treatment efficiency [27-30].

Currently, there are no dedicated treatment processes specifically designed for the removal of emerging contaminants such as MPs/NPs. However, Jia et al. conducted an investigation into the abundance of MPs in the influent and effluent of conventional wastewater treatment plants[14], revealing that traditional wastewater treatment methods exhibit relatively high removal efficiency for MPs (Table 1.1). The removal efficiency of MPs is closely related to the type of wastewater treatment process employed. Generally, effluent from tertiary-treated

wastewater shows lower MPs concentrations (0–51 items/L) compared to effluent treated only with primary or secondary processes (9×10^{-4}–447 items/L)[31]. The removal efficiency of MPs also varies across different stages of wastewater treatment. For instance, screening units effectively intercept larger MPs, with removal efficiency governed by the dimensional relationship between mesh apertures and MP particle sizes. Flotation demonstrates particular efficacy in eliminating low-density polymers such as polyethylene (PE) and polypropylene (PP), along with intermediate-density materials including polystyrene (PS). Within grit chambers and primary sedimentation tanks, 60–98% of macro-scale MPs undergo co-sedimentation by adsorbing onto sand or other dense particulates, thereby achieving physical separation from the wastewater stream. Secondary treatment (biological treatment) can achieve MPs removal rates of 50%–98%, though the efficiency may fluctuate due to variations in biological process types and the toxicity of MPs to microorganisms[31]. Among these, modified processes such as activated sludge, anaerobic-anoxic-oxic (A^2/O), sequencing batch reactor (SBR), and oxidation ditches exhibit MPs removal efficiencies ranging from 3.2% to 42.9%[32-34]. Research by Mohammad indicates that the key mechanism for MPs removal in activated sludge processes lies in the aggregation of MPs with extracellular polymeric substances (EPS) secreted by microorganism[35]s, forming flocs that facilitate removal through adsorption, degradation, or aggregation. Biofilm-mediated processes for microplastic removal operate on a comparable principle, leveraging both the adsorptive properties of extracellular polymeric substances and the natural detachment phase of mature biofilms. Furthermore, the inherent metabolic activity of resident microorganisms enables the depolymerization and assimilation of plastic polymers, ultimately driving their mineralization and conversion into bioavailable carbon and energy substrates for microbial metabolism. While microplastics inherently demonstrate limited biodegradability, their degradation potential may be enhanced through physicochemical and biological processes that reduce polymer chain length and increase surface hydrophilicity. While conventional wastewater treatment processes demonstrate notable efficacy in removing microplastics, the implementation of advanced (tertiary) treatment remains essential to achieve maximal reduction of residual MP concentrations in effluent discharges. Lares et al. observed that after treatment with a membrane bioreactor (MBR), MPs concentration in wastewater decreased from 57.6 items/L to 0.4 items/L, achieving a removal efficiency of 99.4%, slightly higher than that of activated sludge processes (98.3%)[36]. Ozone, a common disinfectant used in tertiary treatment, can act on MPs made of materials such as PP and PE by increasing polymer surface tension, enhancing adhesion properties, reducing hydrophobicity, and improving solubility, thereby promoting the degradation of MP polymers. Hidayaturrahman et al. achieved a removal efficiency of up to 89.9% when treating MPs with sizes of 1–5 μm using ozone[37].

2.2 Overview of Microalgae-Based Bioremediation in Wastewater Treatment

Microalgae-based bioremediation technology has garnered widespread attention in the context of carbon emission reduction due to its low-carbon footprint and high biomass value. This technology involves the assimilation of inorganic pollutants in wastewater—such as ammonium nitrogen (NH_4^+-N), nitrate nitrogen (NO_3^--N), phosphate (PO_4^{3-}-P), nitrite nitrogen (NO_2^--N)—and organic pollutants like nitrogen and phosphorus from urea, which are utilized by microalgae to synthesize organic compounds necessary for cellular growth[38]. These compounds, despite their status as wastewater contaminants, simultaneously function as vital nutrients for microalgal proliferation. As photoautotrophs, microalgae sequester atmospheric CO_2 and release O_2, thereby obviating the need for external carbon supplementation while concurrently elevating dissolved oxygen levels in aquatic systems. Furthermore, microalgae exhibit considerable commercial promise, with viable applications spanning the food, pharmaceutical, cosmetic, and bioenergy sectors. For example, certain microalgal species contain 15–300 times higher oil content compared to traditional oil-producing materials such as corn, soybeans, and oil palm [39]. Therefore, microalgae-based wastewater bioremediation is distinguished by its straightforward process design, efficient pollutant removal, and robust environmental resilience, establishing it as a highly promising technology for sustainable water treatment.

The coupling of wastewater treatment with microalgae cultivation fundamentally illustrates the contextual valuation of pollutants across ecological systems—a circular process of resource recovery often termed "waste-to-wealth." Within this framework, the metabolic pathways governing carbon, nitrogen, and phosphorus assimilation in microalgae constitute the principal mechanisms underlying pollutant uptake and biotransformation. In microalgae, carbon metabolism centers on photosynthetic carbon fixation—primarily through the dark reaction—where atmospheric CO_2 or dissolved HCO_3^- serves as the inorganic carbon substrate. Upon uptake, CO_2 is assimilated via the Calvin cycle, utilizing energy and reducing equivalents generated during the light reaction (ATP and NADPH) to synthesize organic compounds. The dark reaction also includes C4 and CAM pathways, which together constitute the CO_2 concentrating mechanisms (CCMs) in microalgae to cope with insufficient CO_2 in the growth environment. Certain algal species can also absorb sugars (e.g., glucose), alcohols (e.g., glycerol and ethanol), and acids (e.g., acetic acid) as organic carbon sources to achieve heterotrophic growth[40]. Based on the availability of organic carbon sources and light, microalgal carbon metabolism can be classified into three distinct trophic modes: autotrophic, heterotrophic, and mixotrophic. Kamalanathan et al. cultivated microalgae

under autotrophic conditions, resulting in larger cell volumes, higher growth rates, and greater biomass concentrations compared to heterotrophic modes[41]. In contrast, Xia et al. argued that heterotrophic and mixotrophic modes can circumvent the drawbacks of photoinhibition and light limitation in photosynthesis, offering microalgae the potential for higher growth efficiency and biomass yields[42]. Since the organic carbon present in wastewater cannot be completely assimilated through autotrophic metabolism alone, heterotrophic metabolic pathways assume a more substantial role in carbon removal within wastewater treatment systems. Accordingly, selecting an appropriate carbon metabolism mode based on wastewater composition is crucial for enhancing overall treatment performance[43]. Inorganic nitrogen forms available to microalgae—including NH_4^+-N, NO_2^--N, and NO_3^--N—are assimilated into organic nitrogen compounds necessary for biomass synthesis, thereby promoting nitrogen removal from wastewater. Among these, NH_4^+-N serves as the preferential nitrogen source and is directly incorporated into amino acids primarily through the glutamine synthetase-glutamate synthase (GS-GOGAT) pathway, supplemented by the glutamate dehydrogenase (GDH) pathway in microalgal cells. NO_2^--N and NO_3^--N require reduction to NH_4^+-N by nitrite reductase (NiR) and endogenous nitrate reductase (NR) before further processing through the GS-GOGAT pathway[44]. Phosphorus, as another essential nutrient present in wastewater, can be assimilated via phosphorylation into organic compounds such as lipids and nucleic acids. However, under conditions of inorganic phosphorus scarcity, phosphorus stored in organic esters can be remobilized and converted back into inorganic phosphate to sustain essential phosphorylation processes in microalgae.

2.3 Advantages of Microbial Remediation Technologies for Microplastic Removal

In recent years, microalgae have gained recognition as significant bioindicators of aquatic ecosystem health, with their capacity to colonize microplastic surfaces in freshwater and polluted wastewater environments drawing increasing scientific attention. Compared to bacteria and fungi, microalgae exhibit unique advantages in degrading microplastics. They do not require substantial carbon sources, possess intrinsic photosynthetic and autotrophic metabolic capabilities, and demonstrate stronger adaptability to aquatic environments. Current research indicates that microalgae such as cyanobacteria, green algae, and diatoms can be applied in the degradation of microplastics[45, 46]. The degradation of microplastics by microalgae involves multiple mechanisms, including the secretion of toxins and enzymes that directly catalyze plastic depolymerization, as well as the production of extracellular polymeric substances (EPS), which facilitate microplastic aggregation and enhance their aqueous solubility and subsequent biodegradability. Integrating microalgae production with wastewater treatment[47]. utilizing wastewater to cultivate algae while simultaneously removing microplastics, represents a relatively novel bioremediation approach for wastewater. This technology offers the following advantages:

2.3.1 Photoautotrophic Metabolism

Microalgae assimilate CO_2 via the Calvin cycle, harnessing light energy to drive pollutant degradation without the need for exogenous organic carbon inputs. In contrast to heterotrophic microorganisms—which typically require supplemental carbon sources such as glucose—this photoautotrophic strategy lowers treatment costs by an estimated 60–70%. The oxygen released during photosynthesis can directly participate in the oxidative degradation of plastics. MPs/NPs themselves possess stable chemical structures and are difficult to be rapidly utilized as carbon sources. Photoautotrophic metabolism avoids the "carbon source competition" dilemma faced by microorganisms—where easily degradable organic matter is prioritized over plastic pollutants—ensuring that energy is consistently and directionally allocated to the degradation of MPs/NPs. When treating wastewater containing MPs/NPs, the operational cost is only \$0.15–0.25/m³, while biomass sales revenue can reach \$0.20–0.35/m³, achieving a balanced budget or even profitability[48]. By contrast, fungal remediation necessitates continuous external supplementation of organic substrates—a factor constituting over 40% of total operational costs—rendering the autotrophic metabolism of microalgae substantially more economically viable and competitive.

2.3.2 High Specific Surface Area

Microalgal cells typically range from 3 to 10 μm in diameter, with a specific surface area of 10–100 m²/g—significantly higher than that of conventional activated sludge (~1 m²/g). A single cell of *Scenedesmus* can adsorb between 500 and 800 nanoplastic particles, achieving an adsorption capacity of up to 120 mg per gram of biomass. This suggests that, per unit biomass, microalgae offer a significantly greater number of active binding sites.

2.3.3 Diversity of Secreted Metabolites

The diversity of metabolites secreted by microalgae constitutes their central advantage over conventional remediation microorganisms such as fungi and bacteria. These secretions include extracellular polymeric substances (EPS), degradative enzymes, reactive oxygen species (ROS), organic acids, signaling

molecules, and other bioactive compounds. EPS serves as the primary component of microalgal secretions, constituting 30–50% of dry weight and consisting of polysaccharides, proteins, nucleic acids, and humic substances. Per gram of EPS contains 3–5 mmol of carboxyl or hydroxyl groups, which capture MPs/NPs through electrostatic attraction and hydrogen bonding. Microalgae secrete a diverse array of enzymes that collectively function within three primary catalytic systems—polysaccharide-active, esterase-mediated, and redox-related—enabling synergistic degradation of microplastics and their breakdown products. Under photosynthetic electron leakage or high-light stress conditions, microalgae generate reactive oxygen species (ROS) such as hydroxyl radicals (·OH), singlet oxygen ($^1O_2$), and hydrogen peroxide (H_2O_2), promoting non-enzymatic oxidative degradation of micro- and nanoplastics. Low-molecular-weight organic acids, including citric acid, oxalic acid, and malic acid, excreted by microalgae, play roles in pre-oxidation and detoxification during MPs/NPs remediation. Signaling molecules, such as N-acyl homoserine lactones (AHLs) and diketopiperazines (DKPs), regulate community behavior and enhance the systematic efficiency of remediation. The secretions of microalgae constitute a dynamic system integrating physical, chemical, biological, and informational functions, whereas the secretions of fungi and bacteria are relatively limited in scope and typically require artificial supplementation to achieve comparable effects[49].

III. MECHANISMS AND APPLICATION ADVANCES IN MICROALGAE-BASED REMOVAL OF MICROPLASTICS

Microalgae-based bioremediation involves two primary pathways: biosorption and biodegradation, both of which collectively contribute to the structural weakening and molecular weight reduction of microplastics through surface chemistry and metabolic byproducts[50]. Microalgae demonstrate the capability to form heterogeneous aggregates with microplastics and facilitate the degradation of polymer molecules into simpler, safer compounds[51].

3.1 Biosorption

3.1.1 Extracellular Polymeric Substances (EPS)-Mediated Adsorption

The formation mechanism of microalgae–microplastic heterogeneous aggregates involves sequential processes of colonization, aggregation, and adsorption. When microalgae come into contact with microplastic particles, they initiate surface colonization. Under the toxic stress induced by microplastics, microalgae secrete extracellular polymeric substances (EPS), thereby promoting biofilm formation[52]. During the biosorption of microplastics, extracellular polymeric substances (EPS) mediate initial contact between microorganisms and microplastic surfaces via their adhesive properties, thereby promoting biofilm formation and establishing a microenvironment favorable for subsequent degradation processes. Concurrently, its active components directly interact with microplastic surfaces via mechanisms such as electrostatic interactions and hydrogen bonding, significantly improving adsorption efficiency[53].

3.1.2 Bio-flocculation and Co-sedimentation

Algal cells form heterogeneous aggregates with micro- and nanoplastics through extracellular secretions such as EPS, resulting in "algae–EPS–plastic" composite structures. As the density and particle size of these aggregates increase, they undergo accelerated co-sedimentation, enabling efficient solid–liquid separation and paving the way for subsequent resource recovery. MPs/NPs act as "crystal nuclei," promoting the formation of microalgal flocs. Following the development of microalgae–microplastic composite flocs, significant changes occur in the overall density and morphology of the particles, leading to a substantial increase in settling velocity.

3.2 Biodegradation

3.2.1 Photochemical Pre-oxidation

Photochemical pre-oxidation serves as the "first step" in the degradation of MPs/NPs by microalgae. Driven by visible-to-near-infrared radiation ($\lambda \geq 400$ nm), algal cells continuously generate reactive oxygen species (ROS), including hydroxyl radicals (·OH), singlet oxygen ($^1O_2$), and superoxide anions (O_2^-), through mechanisms such as photosynthetic electron leakage, pigment sensitization, and synergistic interactions with extracellular semiconductor nanoparticles (e.g., TiO_2, ZnO, g-C_3N_4). These reactive oxygen species non-selectively oxidize the C–H and C–C backbone structures on plastic surfaces, introducing hydrophilic functional groups such as carbonyl and hydroxyl moieties, thereby generating cleavage sites for subsequent enzymatic degradation or mineralization. This process operates without the addition of chemical oxidants or external carbon sources and aligns synchronously with photosynthetic carbon fixation, positioning it as a cutting-edge approach in green remediation technologies.

3.2.2 Enzymatic Degradation

Microbial-secreted enzymes play a critical role in the transformation of microplastics, requiring the synergistic action of extracellular and intracellular enzymes for effective degradation. Extracellular enzymes break down microplastics into monomers or smaller units, including hydrolases such as lipases, carboxylesterases, cutinases, and proteases, which are involved in the decomposition of microplastics[54]. As a class of biocatalytic macromolecules produced by microorganisms and other organisms, enzymes can specifically recognize and bind to microplastic surfaces. Through their active sites, they catalyze the cleavage of chemical bonds within the polymer chains of microplastics, thereby initiating and accelerating their degradation, ultimately converting microplastics into small-molecule substances[55].

3.2.3 Biofilm

Biofilms play a significant role in the degradation of microplastics. Their attachment not only increases the contact area between cells and microplastics but also alters the morphological structure of microplastics by forming pits and micropores on the surface, thereby providing additional reactive sites for microbial colonization and enzymatic activity[56]. Concurrently, biofilm formation reduces the hydrophobicity of microplastics, increases their density, and—through the enrichment of surface oxygen-containing functional groups and the adherence of polysaccharide-rich substances—promotes microplastic oxidation and decomposition. Biofilm development is predominantly regulated by environmental factors, with its formation and structural characteristics being modulated by conditions such as temperature, nutrient availability, and hydrodynamic forces. Therefore, in bioremediation systems, mixing intensity and circulation-induced shear forces must be carefully balanced to maintain effective mass transfer while avoiding the disruption of floc structures[57].

3.3 Synergistic Enhancement Mechanisms in Symbiotic Systems

3.3.1 Microalgae-Bacteria Co-culture

Compared to cultivating microalgae or bacteria individually, co-culturing microalgae with specific bacterial strains can enhance the efficiency of wastewater treatment. In such co-culture systems, microalgae and bacteria continuously exchange organic and inorganic substances. Microalgae produce oxygen through photosynthesis, providing electron acceptors for oxygenase enzymes (e.g., laccase, alkane hydroxylase) secreted by bacteria, while simultaneously fixing CO_2. Concurrently, phosphate generated through bacterial respiration serves as an essential nutrient for microalgal growth[58]. Bacteria mineralize MPs, releasing organic additives (e.g., phthalates, BHT) and generating CO_2, which in turn sustains microalgal growth, achieving a closed-loop system with "zero external carbon input." The extracellular polymeric substances (EPS) composed of polysaccharides, proteins, and nucleic acids from both algae and bacteria form a "capture-enzymolysis" composite layer on plastic surfaces, increasing the removal efficiency of nano plastics (54–125 nm) from 45% to 78%[59].

3.3.2 Microalgae-Fungi Co-culture

Photosynthetically derived metabolites from microalgae can provide fungi with organic carbon substrates, oxygen, and other critical nutrients. Concurrently, fungal hyphae provide shading for microalgae, mitigating potential damage from high light intensity, while also supplying secondary metabolites, inorganic salts, mineral nutrients, and other growth-required components to enhance the metabolic activity of microalgae[60]. This symbiotic interaction establishes a more stable environment for microalgal growth. The distinctive structure of fungal-microalgal aggregates facilitates microplastic removal from wastewater via mechanisms similar to those in standalone microalgal systems, primarily encompassing biosorption, bioaccumulation, and biodegradation, complemented by indirect photodegradation, to achieve efficient microplastic elimination.

IV. KEY FACTORS INFLUENCING MICROPLASTIC REMOVAL

4.1 Selection of Microalgal Species

Contact between *Chlorella* and microplastics can induce surface aging and crack formation within tens of days. Changes in Fourier-transform infrared spectra indicate enhanced hydrophilicity and exposure of functional groups on microplastics, which not only facilitate the subsequent removal of co-contaminants but also improve adhesion strength[61]. Scenedesmus can achieve efficient removal of multiple types of microplastics through two pathways: cell wall adsorption and heteroaggregation. Prolonged exposure shifts the dominant mechanism from pure adsorption to EPS-mediated aggregation and sedimentation[53]. In certain systems, non-conventional microorganisms such as cyanobacteria, green algae, and protozoans can, through symbiotic interactions, promote preliminary degradation and surface erosion of polyethylene, thereby substantially mitigating particle resuspension during long-term operation.

4.2 Environmental Factors

Environmental parameters play a crucial role in influencing the removal process. pH regulates electrostatic interactions by altering the surface charge characteristics of both the adsorbent and the microplastics[62, 63]. Within an appropriate range, temperature can accelerate the adsorption process, though extreme temperatures may disrupt the structure of the adsorbent[64]. Ionic strength influences the thickness of the electrical double layer, thereby altering interfacial interactions. Concurrently, co-existing substances may compete for adsorption sites, ultimately affecting overall removal efficiency. The combined interplay of these environmental factors underlies the complex kinetic behavior observed in microbial adsorption systems.

4.3 Molecular Structure of Microplastics

In terms of biodegradation, the molecular structure of microplastics is the most critical influencing factor. Plastics containing ester or amide bonds typically exhibit faster degradation rates due to the susceptibility of these bonds to enzymatic hydrolysis, whereas polyolefins, primarily composed of carbon-carbon bonds, are more resistant to degradation due to their stable structure[65, 66]. The physical morphology of microplastics also plays a significant role: smaller particle sizes and rougher surfaces facilitate microbial attachment and enzymatic action[66]. Environmental conditions substantially regulate the degradation process: temperature modulates degradation efficiency by influencing microbial activity and enzyme reaction rates; pH not only affects microbial growth but also directly determines enzymatic activity; and the availability of nutrients governs the metabolic vitality of microbial communities[67].

4.4 Adsorption Characteristics

Regarding adsorbent properties, specific surface area, pore structure, and the composition and distribution of surface functional groups play decisive roles. Adsorbents with greater specific surface areas, more developed pore structures, and a higher density and variety of surface functional groups offer increased contact interfaces and a greater number of binding sites for microplastics, thereby enhancing adsorption efficiency. The physicochemical characteristics of microplastics themselves also significantly influence adsorption, including particle size, shape, surface charge distribution, and hydrophobicity[68].

V. RESPONSE MECHANISMS OF MICROALGAE TO MPS/NPS

Microalgae respond to MPs/NPs mainly through two key aspects: photosynthetic activity and biomass growth. Photosynthesis is a fundamental physiological process in microalgae, and research indicates that MPs/NPs can suppress photosynthetic efficiency, potentially associated with the downregulation of genes involved in photosynthetic pathways. Bhattacharya et al. observed that nano-sized PS particles could hinder CO_2 uptake in Scenedesmus, thereby impairing photosynthetic efficiency in algal cells[69]. Microalgal growth serves as a fundamental indicator for investigating the biological effects of MPs/NPs. Some studies have reported inhibitory effects[70], promotive effects[71], or dual-phase effects of MPs/NPs on microalgal growth. In such studies, factors including the type, concentration, size of MPs/NPs, and algal species are typically set as independent variables to explore these varied outcomes. To explain these experimental observations, several studies have summarized the molecular-level response mechanisms of algae to MPs/NPs, including surface effects[69], cell membrane toxicity[72], and oxidative stress induced by intracellular reactive oxygen species (ROS). Other mechanisms, such as shading effects, physical damage, and genotoxicity, require further elucidation. Selected studies on MPs/NPs characteristics and associated mechanisms are summarized in Table 1.2.

Table 1.2 Effects of MPs/NPs on Microalgae and Corresponding Micro-scale Mechanisms

Polymer Type	Particle Size (nm)	Concentration (mg/L)	Algal Species	Observed Effect	Mechanism	References
PS	100、1000	10、50、100	*C.pyrenoidosa*	Dual-phase effect	Mechanical damage, Oxidative stress	[13]
PS	80、1000、5000	10、50、100	*M.aeruginosa*	Promotion	Increase in chlorophylla content, enhanced cellular activity	[71]
PS PS-COOH	20、50、500	250	*C.vulgaris*	Inhibition	Mechanical damage, Oxidative stress	[70]
PS-COOH	50	250	*D.tertiolecta*	Inhibition	Mechanical damage, Oxidative stress	[73]

PS-COOH	70	1000	*S.obliquus*	Inhibition	Mechanical damage, Oxidative stress	[74]
PS	1000、5000	2、10、50	*C.pyrenoidosa*	Inhibition	Shading effect, Oxidative stress Oxidative stress、Gene regulation	[75]
PS	80	5、10、20、30、40、	*C.pyrenoidosa*	Inhibition	Shading effect, Oxidative stress, Mechanical damage、Osmotic regulation	[76]

5.1 Mechanisms of Microplastic-Induced Growth Inhibition in Microalgae

Across studies reporting growth inhibition, a consistent pattern emerges: higher concentrations and smaller particle sizes of MPs/NPs are associated with stronger inhibitory effects, reflecting a clear dose- and size-dependent response. Sendra et al. confirmed that 50 nm and 100 nm PS NPs at a concentration of 50 mg/L inhibited the growth of diatoms, with the 50 nm particles showing stronger inhibition than the 100 nm ones[77]. However, the notion that the toxicity of MPs/NPs is inversely proportional to particle size is somewhat oversimplified and requires refinement. Ye further elaborated that the growth inhibition rate of microalgae increases as the relative size between algal cells and MPs/NPs becomes larger[78]. Yang et al. conducted experiments with 80 nm PS NPs at concentration gradients of 0, 5, 10, 20, 30, 40, and 50 mg/L, finding that microalgal growth inhibition increased with rising NP concentration, with the highest inhibition observed at 50 mg/L[78]. Furthermore, the inhibitory effect of high-concentration NPs (20–50 mg/L) persisted beyond 96 hours, whereas significant growth suppression in other experimental groups occurred within 24–48 hours post-exposure. Cell membrane disruption and oxidative stress induced by intracellular reactive oxygen species are considered primary mechanisms underlying the growth-inhibitory effects of MPs/NPs on microalgae. MPs/NPs can promote ROS generation and lipid peroxidation, induce oxidative stress, and exacerbate their adverse impacts. Under such conditions, the activities of antioxidant enzymes in algal cells, such as catalase (CAT) and superoxide dismutase (SOD), increase to scavenge excess ROS[79]. Lipid peroxidation refers to the oxidation of biological membranes by ROS, i.e., the reaction of ROS with phospholipids in cell membranes, which can impair membrane fluidity, cellular structure, and function. Malondialdehyde (MDA), a typical product of intracellular lipid peroxidation, serves as an indicator for assessing the extent of membrane damage[80]. The antioxidant system also includes non-enzymatic antioxidants, such as carotenoids, which enhance algal resistance to lipid peroxidation and play a crucial role in maintaining ROS balance[81].

Shading effects and mechanical damage caused by MPs/NPs may also be key factors contributing to the inhibition of microalgal growth. Cao et al. proposed the inhibitory effects of PS MPs on *C. pyrenoidosa* using oxidative stress and lipid peroxidation, introduced the concept of adhesion[75]. MPs adhering to the surface of *C. pyrenoidosa* obstruct photosynthesis and reduce electron transport rates. The decline in electron transport results in electron accumulation, which in turn exerts a positive feedback effect on oxidative stress by elevating ROS levels. Excessive ROS promotes lipid peroxidation in cell membranes, thereby increasing malondialdehyde (MDA) content. The adhesion phenomenon described in this study can be attributed to a shading effect, in which plastics and microalgae form aggregates that interfere with photosynthetic light availability. Lagarde referred to the aggregation between algae and plastic particles as hetero-aggregation of algae[82]. Moreover, he observed that heteroaggregation of microalgae and plastics could increase the density of MPs, indirectly promoting their sedimentation in water bodies. In the study by Yang[76], heteroaggregates formed between high-concentration NPs and *C. pyrenoidosa* exhibited a morphology where NPs enveloped microalgal cells. This not only reduced light absorption efficiency but also inhibited nutrient exchange and utilization, thereby accelerating cell apoptosis. Furthermore, during the initial phase of heteroaggregate formation between NPs and microalgae, alterations in cell wall structure and damage to the cell membrane occurred, resulting in mechanical injury. Numerous studies have also confirmed the prevalence of mechanical damage caused by MPs to microalgae[83]. Therefore, the growth inhibitory effect of MPs/NPs on microalgae may result from shading effects and physical disruption caused by hetero-aggregation between algal cells and plastic particles.

The toxic effects of MPs/NPs are not necessarily cumulative, meaning that microalgal growth tends to recover in later stages, and the growth inhibition rate decreases over time[13, 84]. Xiao et al. attributed the biological adaptability of algae to factors such as increased vacuolization, chloroplast deformation, and homo-aggregation of microalgae[84]. Other studies suggest that EPS plays a key role in the detoxification process by adsorbing MPs from the water, forming hetero-aggregates that reduce the concentration of suspended MPs through sedimentation[85]. Similarly, EPS can also promote homo-aggregation among algal cells. Yang et al. proposed microalgae counteract ROS accumulation by regulating cellular osmotic pressure[76]. This is attributed to the fact that lowering cellular osmotic pressure can accelerate the degradation of damaged proteins and organelles, thereby promoting cell proliferation. Numerous studies have shown that low doses of toxicants can stimulate adaptive

responses in unicellular algae, enhancing cellular or organismal resistance to stress[86]. However, reports on the detoxification mechanisms of microalgae remain scarce, and the mechanisms by which microalgae detoxify MPs/NPs require further elucidation.

5.2 Mechanisms of Microplastic-Induced Growth Promotion in Microalgae

In addition to inhibitory effects, conclusions such as growth promotion and dual-phase effects—reflecting varying responses—also exist in this field of research. Wang Ting et al. reported a growth-promoting effect of plastic microbeads on *M. aeruginosa*, with the promotive effect inversely related to concentration and particle size[71]. The study noted that chlorophyll-a content is closely linked to the light-harvesting capacity of algal cells and is therefore used as an indicator of cellular vitality[87]. Since chlorophyll-a concentration in the experimental groups surpassed that in the control group, photosynthetic activity was enhanced in the exposed groups, leading to a growth-promoting effect. However, Mao Yufeng et al. explained the slight induction observed in the second phase of the dual-phase effect of MPs on algae was not based on changes in chlorophyll-a concentration. Instead, by the second phase, *Chlorella pyrenoidosa* had adapted to the stress from MPs (experienced in the first phase), leading to enhanced photosynthetic activity, thickened cell walls, and homoaggregation of algal cells. These physiological improvements enabled the microalgae to effectively withstand external stress and increase biomass concentration[13]. Some studies have also considered MPs/NPs as nutrient sources, using this perspective to explain microalgal growth promotion.

VI. CONCLUSIONS AND FUTURE PERSPECTIVES

Microalgae-based wastewater bioremediation offers the dual benefits of carbon mitigation and resource recovery, aligning with the principles of green development as an innovative wastewater treatment strategy. However, variability in wastewater quality and flow poses challenges to its industrial-scale implementation, while the presence of emerging contaminants further tests the operational stability and pollutant removal efficiency of the system. As discussed in Section V, emerging contaminants such as MPs/NPs can disrupt the normal physiological activities of microalgae, affecting their growth performance and photosynthetic activity. While the observed inhibitory effects are often explained through mechanisms such as oxidative stress, cell membrane toxicity, shading effects, and mechanical damage, research on molecular and genetic-level response mechanisms remains limited. Moreover, the accuracy and practical relevance of current findings are influenced by discrepancies between experimental conditions and real-world scenarios. Firstly, there is a significant disparity between environmental and experimental concentrations of MPs/NPs, with experimental concentrations typically several orders of magnitude higher than environmental levels, which questions the practical applicability of such studies. Secondly, the shape, type, and concentration of MPs/NPs in actual water bodies are complex and heterogeneous, whereas most existing research conclusions are derived under idealized conditions involving single polymer types, spherical standard plastic particles, and simplified microalgal cultivation environments. Lastly, natural water bodies and real wastewater contain complex compositions, where MPs/NPs readily form complexes with hydrophobic organic micropollutants such as polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and perfluorooctanesulfonic acid.

Future research should progressively simulate realistic aquatic environments by introducing multi-species microalgal consortia, incorporating diverse co-existing pollutants, and mimicking hydrodynamic conditions (e.g., flow velocity, turbulence intensity). To advance industrialization, distribution models of microplastics across diverse aquatic systems should be established to guide the selection, inoculation, cultivation, and harvesting of suitable algal strains. Furthermore, co-conversion technologies should prioritize the development of integrated continuous-flow systems, optimization of feedstock proportions and reaction parameters, and selection of appropriate catalysts and reaction atmospheres to maximize the value-added conversion of resulting products.

REFERENCES

[1] GIGAULT J, EL HADRI H, NGUYEN B, et al. Nanoplastics are neither microplastics nor engineered nanoparticles [J]. Nature Nanotechnology, 2021, 16(5): 501-7.
[2] SAIKUMAR S, MANI R, GANESAN M, et al. Trophic transfer and their impact of microplastics on estuarine food chain model [J]. Journal of Hazardous Materials, 2024, 464: 132927.
[3] LIU X, YUAN W, DI M, et al. Transfer and fate of microplastics during the conventional activated sludge process in one wastewater treatment plant of China [J]. Chemical Engineering Journal, 2019, 362: 176-82.
[4] XU X, JIAN Y, XUE Y, et al. Microplastics in the wastewater treatment plants (WWTPs): Occurrence and removal [J]. Chemosphere, 2019, 235: 1089-96.
[5] BECUCCI M, MANCINI M, CAMPO R, et al. Microplastics in the Florence wastewater treatment plant studied by a continuous sampling method and Raman spectroscopy: A preliminary investigation [J]. Science of The Total Environment, 2022, 808: 152025.
[6] MURPHY F, EWINS C, CARBONNIER F, et al. Wastewater Treatment Works (WwTW) as a Source of Microplastics in the Aquatic Environment [J]. Environmental Science & Technology, 2016, 50(11): 5800-8.
[7] TANG W, LI H, FEI L, et al. The removal of microplastics from water by coagulation: A comprehensive review [J]. Science of The

Total Environment, 2022, 851: 158224.
[8] GIRISH N, PARASHAR N, HAIT S. Coagulative removal of microplastics from aqueous matrices: Recent progresses and future perspectives [J]. Science of The Total Environment, 2023, 899: 165723.
[9] SOUSA P M S, KINNEY K A, SOUSA C A, et al. Microalgae for microplastic removal from water and wastewater: a review [J]. Environmental Chemistry Letters, 2025, 23(2): 611-48.
[10] LI J, LIU H, PAUL CHEN J. Microplastics in freshwater systems: A review on occurrence, environmental effects, and methods for microplastics detection [J]. Water Research, 2018, 137: 362-74.
[11] KANG H-J, PARK H-J, KWON O-K, et al. Occurrence of microplastics in municipal sewage treatment plants: a review [J]. Environmental Health and Toxicology, 2018, 33(3): e2018013.
[12] LIU F, CHENG W, REN J. Research progress on the occurrece,migration and fate of microplastics in wastewater treatment plants [J]. Environmental Pollution & Control, 2022, 44(06): 793-800.
[13] MAO Y. Aggregation Kinetics of Microplastics and ItsToxicity to Chlorella pyrenoidosa [D]; Chongqing University, 2019.
[14] JIA Q, CHEN H, ZHAO X, et al. Removal of Microplastics by Different Treatment Processes in Shanghai LargeMunicipal Wastewater Treatment Plants [J]. Environmental Science, 2019, 40(09): 4105-12.
[15] BAI M, ZHAO H, PENG G, et al. Occurrence, characteristics of microplastic during urban sewage treatment process [J]. China Environmental Science, 2018, 38(05): 1734-43.
[16] XUAN L, LIU S, LUO Y, et al. Removal of microplastics in different wastewater treatment processes in Harbinmunicipal wastewater treatment plants [J]. Acta Scientiae Circumstantiae, 2020, 40(11): 3964-70.
[17] FENG Z, CHEN Z, CHEN B, et al. Discussion on Microplastic Treatment Technologies and Strategiess of Urban Water Environment based on WastewaterTreatment Plants [J]. Environmental Science and Management, 2022, 47(04): 113-7.
[18] XIE L, HAO W, ZHANG F, et al. Research on the removal efficiency of microplastics inTaiyuan dual-process municipal wastewater treatment plant [J]. Applied Chemical Industry, 2022, 51(04): 1049-54+59.
[19] WEI W, HUANG Q-S, SUN J, et al. Revealing the Mechanisms of Polyethylene Microplastics Affecting Anaerobic Digestion of Waste Activated Sludge [J]. Environmental Science & Technology, 2019, 53(16): 9604-13.
[20] TANG S, QIAN J, WANG P, et al. Exposure to nanoplastic induces cell damage and nitrogen inhibition of activated sludge: Evidence from bacterial individuals and groups [J]. Environmental pollution (Barking, Essex : 1987), 2022, 306: 119471.
[21] LI X, CHEN L, JI Y, et al. Effects of chemical pretreatments on microplastic extraction in sewage sludge and their physicochemical characteristics [J]. Water Res, 2020, 171: 115379.
[22] HE Y, LI L, SONG K, et al. Effect of microplastic particle size to the nutrients removal in activated sludge system [J]. Marine Pollution Bulletin, 2021, 163: 111972.
[23] CHEN Y, ZHANG Y, ZHANG Z. Occurrence, effects, and biodegradation of plastic additives in sludge anaerobic digestion: A review [J]. Environmental Pollution, 2021, 287: 117568.
[24] LI L, SONG K, YEERKEN S, et al. Effect evaluation of microplastics on activated sludge nitrification and denitrification [J]. Science of The Total Environment, 2020, 707: 135953.
[25] ALI I, DING T, PENG C, et al. Micro- and nanoplastics in wastewater treatment plants: Occurrence, removal, fate, impacts and remediation technologies – A critical review [J]. Chemical Engineering Journal, 2021, 423: 130205.
[26] CARUSO G, PEDà C, CAPPELLO S, et al. Effects of microplastics on trophic parameters, abundance and metabolic activities of seawater and fish gut bacteria in mesocosm conditions [J]. Environmental Science and Pollution Research, 2018, 25(30): 30067-83.
[27] SEELEY M E, SONG B, PASSIE R, et al. Microplastics affect sedimentary microbial communities and nitrogen cycling [J]. Nature Communications, 2020, 11(1): 2372.
[28] DARAEI H, RAFIEE M, YAZDANBAKHSH A R, et al. A comparative study on the toxicity of nano zero valent iron (nZVI) on aerobic granular sludge and flocculent activated sludge: Reactor performance, microbial behavior, and mechanism of toxicity [J]. Process Safety and Environmental Protection, 2019, 129: 238-48.
[29] WANG X, HAN T, SUN Y, et al. Effects of nano metal oxide particles on activated sludge system: Stress and performance recovery mechanism [J]. Environmental pollution (Barking, Essex : 1987), 2021, 285: 117408.
[30] YAZDANBAKHSH A R, RAFIEE M, DARAEI H, et al. Responses of flocculated activated sludge to bimetallic Ag-Fe nanoparticles toxicity: Performance, activity enzymatic, and bacterial community shift [J]. Journal of Hazardous Materials, 2019, 366: 114-23.
[31] SUN J, DAI X, WANG Q, et al. Microplastics in wastewater treatment plants: Detection, occurrence and removal [J]. Water Research, 2019, 152: 21-37.
[32] EGEA-CORBACHO A, MARTíN-GARCíA A P, FRANCO A A, et al. Occurrence, identification and removal of microplastics in a wastewater treatment plant compared to an advanced MBR technology: Full-scale pilot plant [J]. Journal of Environmental Chemical Engineering, 2023, 11(3): 109644.
[33] MASON S A, GARNEAU D, SUTTON R, et al. Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent [J]. Environmental Pollution, 2016, 218: 1045-54.
[34] CARR S A, LIU J, TESORO A G. Transport and fate of microplastic particles in wastewater treatment plants [J]. Water Research, 2016, 91: 174-82.
[35] AHMED M B, RAHMAN M S, ALOM J, et al. Microplastic particles in the aquatic environment: A systematic review [J]. Science of The Total Environment, 2021, 775: 145793.
[36] LARES M, NCIBI M C, SILLANPää M, et al. Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology [J]. Water Research, 2018, 133: 236-46.
[37] HIDAYATURRAHMAN H, LEE T-G. A study on characteristics of microplastic in wastewater of South Korea: Identification, quantification, and fate of microplastics during treatment process [J]. Marine Pollution Bulletin, 2019, 146: 696-702.
[38] WHITTON R, OMETTO F, PIDOU M, et al. Microalgae for municipal wastewater nutrient remediation: mechanisms, reactors and outlook for tertiary treatment [J]. Environmental Technology Reviews, 2015, 4(1): 133-48.
[39] SHAH S H, RAJA I A, RIZWAN M, et al. Potential of microalgal biodiesel production and its sustainability perspectives in Pakistan [J]. Renewable and Sustainable Energy Reviews, 2018, 81: 76-92.
[40] MORALES-SáNCHEZ D, MARTINEZ-RODRIGUEZ O A, KYNDT J, et al. Heterotrophic growth of microalgae: metabolic aspects [J]. World journal of microbiology & biotechnology, 2015, 31(1): 1-9.
[41] KAMALANATHAN M, CHAISUTYAKORN P, GLEADOW R, et al. A comparison of photoautotrophic, heterotrophic, and mixotrophic growth for biomass production by the green alga Scenedesmus sp. (Chlorophyceae) [J]. Phycologia, 2018, 57(3): 309-17.
[42] XIA A, MURPHY J D. Microalgal Cultivation in Treating Liquid Digestate from Biogas Systems [J]. Trends in Biotechnology, 2016, 34(4): 264-75.
[43] SU Y. Revisiting carbon, nitrogen, and phosphorus metabolisms in microalgae for wastewater treatment [J]. Science of The Total

Environment, 2021, 762: 144590.
[44] TAYLOR M W, BARR N G, GRANT C M, et al. Changes in amino acid composition of Ulva intestinalis (Chlorophyceae) following addition of ammonium or nitrate [J]. Phycologia, 2006, 45(3): 270-6.
[45] SANNIYASI E, GOPAL R K, GUNASEKAR D K, et al. Biodegradation of low-density polyethylene (LDPE) sheet by microalga, Uronema africanum Borge [J]. Scientific reports, 2021, 11(1): 17233.
[46] DING J, LIU X, CHEN X, et al. Biodegradation mechanisms and biological enhancement of microplastics in the environment [J]. Earth Science Frontiers, 2025, 32(03): 248-62.
[47] CUNHA C, FARIA M, NOGUEIRA N, et al. Marine vs freshwater microalgae exopolymers as biosolutions to microplastics pollution [J]. Environmental Pollution, 2019, 249: 372-80.
[48] GIORDANO M, WANG Q. Microalgae for Industrial Purposes [M]//VAZ JR S. Biomass and Green Chemistry: Building a Renewable Pathway. Cham; Springer International Publishing. 2018: 133-67.
[49] KUMAR N, SHUKLA P. Microalgal-based bioremediation of emerging contaminants: Mechanisms and challenges [J]. Environmental Pollution, 2023, 337: 122591.
[50] REMPEL A, GUTKOSKI J P, NAZARI M T, et al. Current advances in microalgae-based bioremediation and other technologies for emerging contaminants treatment [J]. Science of The Total Environment, 2021, 772: 144918.
[51] SARMAH P, ROUT J. Efficient biodegradation of low-density polyethylene by cyanobacteria isolated from submerged polyethylene surface in domestic sewage water [J]. Environmental Science and Pollution Research, 2018, 25(33): 33508-20.
[52] DEMIR-YILMAZ I, YAKOVENKO N, ROUX C, et al. The role of microplastics in microalgae cells aggregation: A study at the molecular scale using atomic force microscopy [J]. Science of The Total Environment, 2022, 832: 155036.
[53] CHENG Y-R, WANG H-Y. Highly effective removal of microplastics by microalgae Scenedesmus abundans [J]. Chemical Engineering Journal, 2022, 435: 135079.
[54] SáNCHEZ C. Lignocellulosic residues: Biodegradation and bioconversion by fungi [J]. Biotechnology Advances, 2009, 27(2): 185-94.
[55] SAHU S, KAUR A, KHATRI M, et al. A review on cutinases enzyme in degradation of microplastics [J]. Journal of Environmental Management, 2023, 347: 119193.
[56] CHEN X, XIONG X, JIANG X, et al. Sinking of floating plastic debris caused by biofilm development in a freshwater lake [J]. Chemosphere, 2019, 222: 856-64.
[57] TOYOFUKU M, INABA T, KIYOKAWA T, et al. Environmental factors that shape biofilm formation [J]. Bioscience, biotechnology, and biochemistry, 2016, 80(1): 7-12.
[58] LI D, LIU R, CUI X, et al. Co-culture of bacteria and microalgae for treatment of high concentration biogas slurry [J]. Journal of Water Process Engineering, 2021, 41: 102014.
[59] LI C, PING W, GE J, et al. [Advances in the co-culture of microalgae with other microorganisms and applications] [J]. Sheng wu gong cheng xue bao = Chinese journal of biotechnology, 2022, 38(2): 518-30.
[60] WU Q, TENG Y, WANG W, et al. Carbon source regulation of microalgal-fungal system for the resource recovery of wastewater: A review [J]. Chemical Engineering Journal, 2024, 488: 150851.
[61] KIKI C, QIU Y, WANG Q, et al. Induced aging, structural change, and adsorption behavior modifications of microplastics by microalgae [J]. Environment International, 2022, 166: 107382.
[62] SALAMA E-S, KURADE M B, ABOU-SHANAB R A I, et al. Recent progress in microalgal biomass production coupled with wastewater treatment for biofuel generation [J]. Renewable and Sustainable Energy Reviews, 2017, 79: 1189-211.
[63] FABRIZIO, CAPRIOA D, ALTIMARIA P, et al. T. obliquus Cultivation Under Heterotrophic Conditions: Determination of Growth Parameters, F, 2019 [C].
[64] ZHOU W, MIN M, LI Y, et al. A hetero-photoautotrophic two-stage cultivation process to improve wastewater nutrient removal and enhance algal lipid accumulation [J]. Bioresource Technology, 2012, 110: 448-55.
[65] YUAN Y, ZHOU W, FENG Q, et al. Advances in biodegradation of polyolefin plastics [J]. Chinese Journal of Biotechnology, 2023, 39(05): 1930-48.
[66] YANG F, HOU M, SONG L, et al. Fate and effects of MPs/NPs in agricultural soils [J]. China Plastics, 2025, 39(04): 52-8.
[67] LI S. Degradation Effect and Mechanism of Fungicide Carboxin byDelftia sp. HFL-1 [D]; Anhui AgriculturalUniversity, 2024.
[68] KOU S, GUAN Z, LU X, et al. Migration of Microplastics in Soil and Its Effect on Organic Pollutants: A Review [J]. Soils, 2024, 56(03): 457-70.
[69] BHATTACHARYA P, LIN S, TURNER J P, et al. Physical Adsorption of Charged Plastic Nanoparticles Affects Algal Photosynthesis [J]. The Journal of Physical Chemistry C, 2010, 114(39): 16556-61.
[70] HAZEEM L J, YESILAY G, BOUOUDINA M, et al. Investigation of the toxic effects of different polystyrene micro-and nanoplastics on microalgae Chlorella vulgaris by analysis of cell viability, pigment content, oxidative stress and ultrastructural changes [J]. Marine Pollution Bulletin, 2020, 156: 111278.
[71] WANG T. The distribution characteristics ofmicroplastics in river water bodiesof Shanghai and the toxicologicalstudy of plastic microbeads onMicrocystis aeruginos [D]; Shanghai Ocean University, 2021.
[72] DéNIEL M, LAGARDE F, CARUSO A, et al. Infrared spectroscopy as a tool to monitor interactions between nanoplastics and microalgae [J]. Analytical and Bioanalytical Chemistry, 2020, 412(18): 4413-22.
[73] SJOLLEMA S B, REDONDO-HASSELERHARM P, LESLIE H A, et al. Do plastic particles affect microalgal photosynthesis and growth? [J]. Aquatic Toxicology, 2016, 170: 259-61.
[74] BESSELING E, WANG B, LüRLING M, et al. Nanoplastic affects growth of S. obliquus and reproduction of D. magna [J]. Environ Sci Technol, 2014, 48(20): 12336-43.
[75] CAO Q, SUN W, YANG T, et al. The toxic effects of polystyrene microplastics on freshwater algae Chlorella pyrenoidosa depends on the different size of polystyrene microplastics [J]. Chemosphere, 2022, 308: 136135.
[76] YANG W, GAO P, LI H, et al. Mechanism of the inhibition and detoxification effects of the interaction between nanoplastics and microalgae Chlorella pyrenoidosa [J]. Science of The Total Environment, 2021, 783: 146919.
[77] SENDRA M, STAFFIERI E, YESTE M P, et al. Are the primary characteristics of polystyrene nanoplastics responsible for toxicity and ad/absorption in the marine diatom Phaeodactylum tricornutum? [J]. Environmental Pollution, 2019, 249: 610-9.
[78] YE S, RAO M, XIAO W, et al. The relative size of microalgal cells and microplastics determines the toxicity of microplastics to microalgae [J]. Process Safety and Environmental Protection, 2023, 169: 860-8.
[79] NAM S-H, LEE J, AN Y-J. Towards understanding the impact of plastics on freshwater and marine microalgae: A review of the mechanisms and toxicity endpoints [J]. Journal of Hazardous Materials, 2022, 423: 127174.
[80] DEL RIO D, STEWART A J, PELLEGRINI N. A review of recent studies on malondialdehyde as toxic molecule and biological marker of oxidative stress [J]. Nutrition, Metabolism and Cardiovascular Diseases, 2005, 15(4): 316-28.

[81] REZAYIAN M, NIKNAM V, EBRAHIMZADEH H. Oxidative damage and antioxidative system in algae [J]. Toxicology Reports, 2019, 6: 1309-13.
[82] LAGARDE F, OLIVIER O, ZANELLA M, et al. Microplastic interactions with freshwater microalgae: Hetero-aggregation and changes in plastic density appear strongly dependent on polymer type [J]. Environmental Pollution, 2016, 215: 331-9.
[83] ZHANG C, CHEN X, WANG J, et al. Toxic effects of microplastic on marine microalgae Skeletonema costatum: Interactions between microplastic and algae [J]. Environmental Pollution, 2017, 220: 1282-8.
[84] XIAO Y, JIANG X, LIAO Y, et al. Adverse physiological and molecular level effects of polystyrene microplastics on freshwater microalgae [J]. Chemosphere, 2020, 255: 126914.
[85] LIU Z. Investigation of Interaction Mechanismbetween Typical Microplastics andMicroalgae [D]; Tianjin University, 2020.
[86] CALABRESE E J. Hormesis Mediates Acquired Resilience: Using Plant-Derived Chemicals to Enhance Health [J]. Annual review of food science and technology, 2021, 12: 355-81.
[87] ZHAO L S, LI K, WANG Q M, et al. Nitrogen Starvation Impacts the Photosynthetic Performance of Porphyridium cruentum as Revealed by Chlorophyll a Fluorescence [J]. Scientific reports, 2017, 7(1): 8542.