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Review Article

Emerging biotechnological and eco-remediation strategies for the biodegradation and removal of micro/nanoplastics from the environment: A comprehensive review

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Abstract

The proliferation of microplastics (MPs) and nanoplastics (NPs) in the aquatic and terrestrial ecosystems have proven to be a major menace to biodiversity, ecosystems, and environmental sustainability. The sources of these intractable contaminants are the fragmentation of macroplastic waste, primary particles like tire wear, synthetic fibers, personal care products, and discharges of industries. The minuscule size of MPs and NPs, their great mobility as well as resistance to degradation make them avoid traditional filtration and wastewater treatment systems. This enables them to be concentrated along food webs and causes great threats to the human health and the wildlife. Concentrating on the most innovative biotechnological and eco-remediation methods, this paper gathers the latest advances in the method of the biodegradation and elimination of MPs and NPs. The connection between environmental adaptability and microbial degradation of polymer-specific processes and microalgae, as well as synthetic microbial consortia, is explored. It also brings to the forefront progresses in enzyme mediated depolymerization, including the discovery of oxidative enzymes, and hydrolases that degrade plastic. Moreover, the biosorption, phytoremediation, and bio-based or green nanomaterials potential is evaluated as the promising, environment-friendly, approaches to capture and transformation of pollutants. The technical and analytical challenges of determining, quantifying, and predicting the movement, aging, and ecological fate of MPs and NPs in complex environmental matrices are also discussed in the paper, and how metabolic engineering, systems biology, omics technologies and nanobioremediation could enhance the effectiveness, selectivity and field implementation.

Keywords: Bioremediation technologies, Environmental risk assessment, Enzyme engineering, Plastisphere microbial communities, Sustainable remediation

INTRODUCTION

The proliferation of microplastics (MPs) and nanoplastics (NPs) is an important Anthropocene environmental issue. Owing to their persistence in the air, water, soils, food systems and biota, alternative control strategies other than conventional treatment technologies, which are not always effective against smaller fractions of particles, are essential. This situation requires integrated biotechnological and eco-remediation methods based on enzymatic catalysis, microbial metabolism, and nature-based designs in the framework of circular economy (Singh and Kumar, 2024). MPs and NPs are both source of primary and secondary sources. Abrasives, cosmetic microbeads and industrial pellets are discharged directly to the environment, and macroplastics are discharged by partial biodegradation, photooxidation, and thermomechanical stress. Other inputs are textiles, tires, packaging, paints, and agricultural films. Later fate of the particles released depends on the weathering status, additive and morphology, crystallinity and polymer chemistry (e.g. PET, PE, PP, PS and PVC). These properties determine ecological process and transport pathways by affecting the behavior of buoyancy, aggregation and sorption. The formation of biofilms on the plastic surface, the so-called, plastisphere, is also an important phenomenon altering the dynamics of contaminant movement and settling. Biofilms can mobilize or entrap particles in the hydrodynamic situation in rivers and treatment systems. NPs can adsorb metals, antibiotics, and hydrophobic contaminants, since it has reactive aging layers and its surface area is vast, in a multitude of ways, exposing them and enhancing their bioavailability. Restrictions in the process of analysis hinder the advancement of management (Kaundal and Singh, 2025). Although large MPs can be removed through wastewater treatment plants, the removal of the small particles smaller than 100 mm. is highly inefficient, and advanced instruments such as Raman and FTIR imaging, pyrolysis-GC/MS, and new single-particle methods are sensitive, but the lacking comparability and regulation is caused by irregular QA/QC, size-specific threshold, and absence of uniform procedures. There is still slow growth in policy development and exposure assessment due to lack of uniformity. The situation is even more urgent in terms of implications to human health and the environment. The plastisphere communities introduce plastics into food webs, redistribute contaminants, and change nutrient cycle. The ways of exposure to MPs and NPs in humans include inhalation, dust and contaminated food and beverages which are found indoors. Long-term effects of oxidative stresses are increasingly associated with inflammatory effects, however, the risks and the exact combination effects of the long-term effects of oxidative stress remains a question, particularly on the nanoscale (Keshta *et al.,* 2025).

Besides removing them physically, biotechnological and natural procedures are gaining popularity. Biofilm-based surfaces, algal ponds, and constructed wetlands promote aggregation and retention. Microbial consortia consisting of bacteria and fungus and algae can attack the weak polymer bonds especially in polyesters such as the PET. Since consortia are more resistant to dynamic, non-sterile environments, mixed communities have become the preference of scientists over individual strains. Directed evolution and computational design have improved the activity and thermostability of PEpt hydrolyzing hydrolases and scalable implementation platforms are achieved by whole-cell systems, including the co-expression of large numbers of enzymes by yeasts or microorganisms. Such real challenges, however, are diffusion restrictions, polymer crystallinity, partial depolymerization, and control of breakdown products. Hybrid trains are being manufactured to enhance their performance. These decrease secondary fragmentation through a mixture of the biological processes with membrane operations, filtration, coagulation-flocculation, dissolved air flotation, and well-monitored oxidation (Zhou *et al.,* 2025). Despite the positive results on removal ranges provided by field studies, there are still issues like concentrate disposal and particle generation due to the wear of membranes. Nevertheless, with these developments, gaps that remain vital in the translation to massive deployment of the research remain. In the case of benchmarking, some standard methods of sampling, polymer identification and size classification are desperately required especially in the nanoscale regime. The routes of transformation occurring in biodegradation are yet to be characterized particularly in terms of the toxicity of additives and intermediates. Also, microbial systems have to work under the condition of changing environmental pressures and a complex combination of pollutants, which require greater predictability and stability. A reliable monitoring is important as well. Its low throughput and high cost of existing analytical platforms restricts long-term validation and life cycle analysis that may indicate reduced risk measurably. Such data is still lacking and the investment and regulatory approval remains reluctant. Nevertheless, it is gaining momentum (Shiu *et al.,* 2025). The various advances in reactor engineering, plastisphere ecology and enzyme design are converging to provide next-generation field deployable solutions. It will require confirmation in complex environmental matrices and not simple laboratory demonstrations to make a difference in the real world. Interdisciplinary interprofessional collaboration among microbiologists, engineers, material scientists, analytical chemists, and legislators will be necessary with the assistance of established regulations and common data infrastructures (LaRue *et al.,* 2024).

In this review, the limitations and the possibilities of the existing biotechnological and eco-remediation therapies of MPs and NPs are critically evaluated. It aims at establishing the existing levels of preparedness and research priorities necessary to generate scalable and sustainable solution to plastic pollution, integrating the results of microbial, enzymatic, and hybrid processes.

DETECTION AND QUANTIFICATION TECHNIQUES

Microplastics (MPs) are novel contaminants for the environment with complex physicochemical properties and important ecological implications. A first and crucial step towards understanding the distribution of these particles, their fate and their associated risks is their detection (Fig. 1) and measurement. Despite the prevalent optical and chemical observation of MPs, NPs pose particular challenges for their analysis as a result

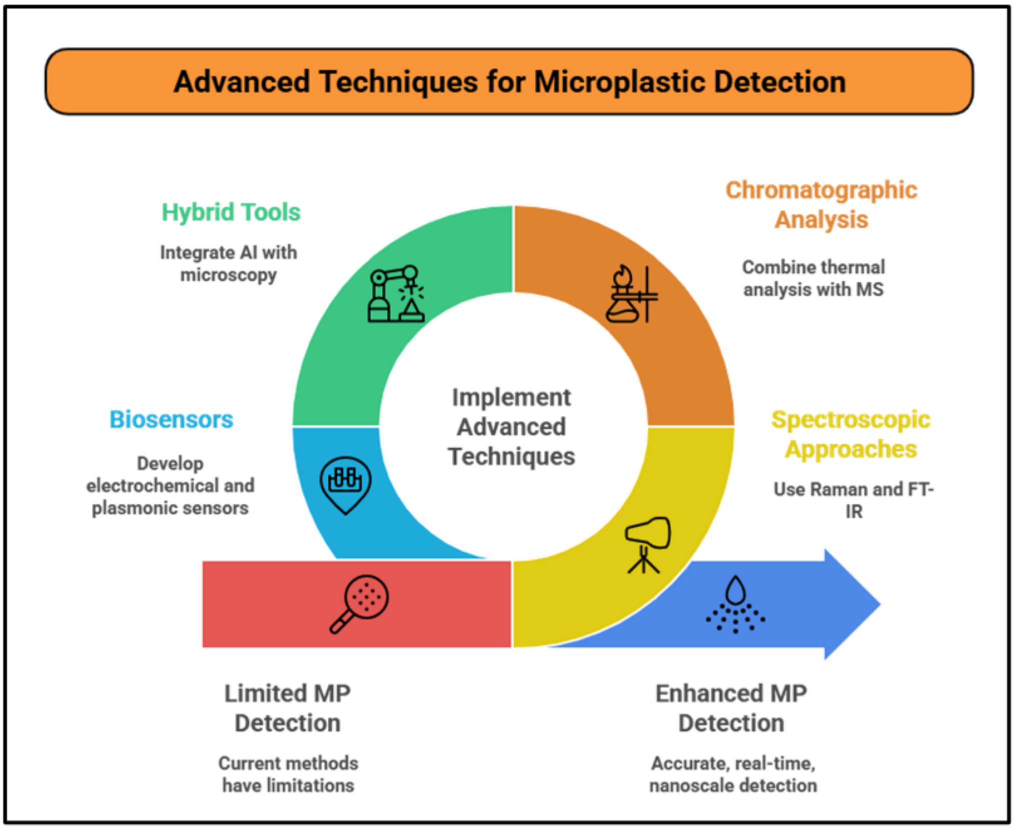

Fig. 1. *Advanced techniques for the detection of microplastics*

of their small size, different morphologies, surface functionalization and reactions with organic matter.

Analytical methods for MPs/NPs

Spectroscopic and microscopic approaches

The foundation of MP detection is nevertheless Raman spectroscopy and Fourier transform infrared spectroscopy (FT-IR). Differently from the case of vibrational scattering (applied in Raman), FT-IR is based on the infrared radiation absorption by polymer functional groups. Both offer non-destructive polymer identification from the use of unique spectra. They are limited in resolution by the limits of diffraction (typically 10-20 mm for FT-IR, and 1-2 mm for Raman) (Xie *et al.,* 2024). Samson *et al*. (2024) showed the application of focal plane array (FPA) detectors in micro-FT-IR imaging, which allowed for the simultaneous recording of thousands of spectra with an increased throughput. The technique has been successfully proven in water samples and can be applied to reliably identify MPs down to 10 mm. Confocal Raman microscopy extended the depth profiling to enable 3D mapping of polymer fragments in sediments. The nanoscale limitation has been overcome easily by surface enhanced Raman scattering (SERS). Surface enhanced Raman spectroscopy (SERS) enables the interactions with metallic nanostructures to achieve a significant enhancement of Raman signal by several orders of magnitude through localized surface plasmon resonance (LSPR) (Fang *et al.,* 2024). Yang *et al*. (2025) covered the silver with a silver film decorated for detecting the polystyrene nanoparticles with a diameter of 50 nm. This means that the nanoscale regime is attainable using Raman-based techniques and there is a problem for uniformity from one substrate to another.

Chromatographic and thermal analysis techniques

Another useful method for identifying polymers is to use both thermal analysis and mass spectrometry and chromatography. In pyrolysis-gas chromatography mass spectrometry (Py-GC-MS), the polymers are decomposed to yield volatile fragments, which are highly separable and identifiable. Unlike spectroscopy, py-GC-MS is not hampered by the size of the particle and polymers of any shape could also be detected. Fakayode *et al*. (2024) used Py-GC-MS and the simultaneous detection of polyethylene, polypropylene and polyethylene terephthalate (PET) at low levels (less than 1ug g-1) was reported in soils to which plastic mulch residues were applied. This is only an indication of how useful it is when working with complex matrices. However, the method is damaging and therefore cannot gather size or morphological information.

Advanced hybrid and Machine-learning-integrated tools

The shape of particles can be described only by using a microscopic method. At the nanoscale, shape, sur-

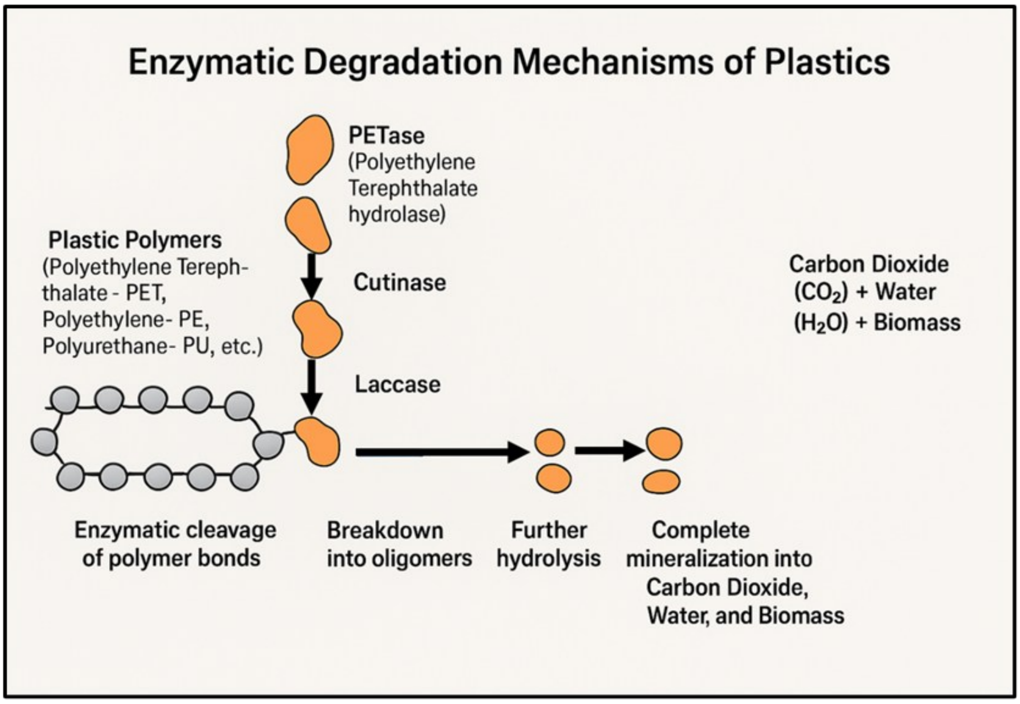

Fig. 2. *Enzymatic degradation mechanisms of micro/nano-plastics*

face texture and aggregation can be visualized using transmission electron microscopy (TEM) and scanning electron microscopy (SEM). Physical inspection, however, is time-consuming and subject to observer error. In recent years, artificial intelligence (AI) has been used for the imaging workflow (Kumari *et al.,* 2025). Khanam *et al*. (2025) carefully selected a set of SEM images that mimics aquatic habitats, has simplified deep learning methods for performing automatic classification. Convolutional neural networks (CNNs) have also been used in the past by Zeng *et al*. (2024), who were able to obtain an accuracy of over 90 percent when classifying different types of polymers. Nevertheless, the total accuracy may be misleading, in case the model is optimized to one of the majority classes whereas it is poor in some of the minority classes of interest in environmental micro/nanoplastic classification tasks, where datasets are often unbalanced (e.g., certain types of polymers or deteriorated conditions are under-represented). To test real performance on minority classes within those domains, more balanced measures of performance than F1-score, precision-recall curve, or AUC-ROC tend to be more precise. To guarantee generalizability and minimize overfitting, similar research on the spectral or image-based microplastic recognition typically reports or adds accuracy to these measures, as well as validates them through stratified k-fold cross-validation or independent test sets of more diverse environmental conditions. This may be viewed as an essential step to high-throughput NP identification. In this way, it is possible to map the distribution of MP in sediments from the accumulation of spectra of each pixel at different wavelengths (Serranti *et al*., 2024).

Biosensors and plasmonic techniques

Biosensors are the next generation tool for MP/NP detection due to their portability, low cost and real-time capabilities. Electrochemical sensors are designed to take advantage of the interaction that occurs between functionalized electrodes and polymers. In contrast, plasmonic detection such as localized SPR (LSPR) and surface plasmon resonance (SPR) can be used for the determination of binding events in a label-free manner. Nano also unveiled a prism-based SPR device that simultaneously can measure in-situ the type, size, and shape of polymers, even colored plastics, which would not be detected by optical spectroscopy. Similarly, surface-enhanced infrared absorption (SEIRA) sensors have been used to achieve the nanoscale detection limit of femtograms (Kamel *et al*., 2024).

Challenges in detection at the nanoscale

Less than 100 nm in size is problematic when it comes to separating NPs from dissolved organic matter and natural colloids. Even when improved Raman or FT-IR techniques are used, there is a propensity for weak signals which lead to an underestimate. In addition, organic waste and biofilms are among the main causes of the issue, especially in water (Ding *et al.,* 2025). According to Nene *et al*. (2025), the sensitivity of tools coated with organic was significantly reduced and aging of the particles should be considered during tool validation. One of the most acute problems is the failure to implement specific procedures during the collection, processing, and analysis of the sample. Unintentional

Table 1. Biodegradation of micro- and nanoplastics: microbial, enzymatic, and genetic solutions

Biodegradation principle	Primary agents / Pathways	Experimental evidence	Experimental conditions	Metric and initial load	Key outcomes	References
Bacterial consortia and Synergistic interactions	*Pseudomonas* and *Bacillus* mixed consortia	62% PET film degradation	avg. temp 23 °C, humidity 75%	Weight loss; 0.5 g PET film; 30 days	Synergistic breakdown of PET intermediate; SD ±4%	Nazeer *et al.* (2024)
	Marine *Rhodococcus* and *Alcanivorax* communities	PS nanosphere degradation enhanced by 48%	Controlled: 25–30 °C, 45 days	Weight loss; 1 mg/mL PS nanospheres	Biofilm-mediated depolymerization; SD ±5%	Li *et al.* (2025)
	Anaerobic sludge consortia	PP powder degraded under anoxic conditions	Anoxic, pH 10.38–10.70	Weight loss; 0.5 g PP powder; 20 days	Expands degradation to anaerobic niches	Bhandari *et al.* (2024)
Fungal decomposers	*Phanerochaete chrysosporium*	40% PS bead mineralization	Controlled: 30 °C	Mineralization (CO_2 evolution); 1 g PS beads; 60 days	Strong oxidative attack; SD ±3%	Nisha and Joshi, (2024)
	Aspergillus niger	Synergistic with bacteria-degraded PU foams	Incubated at 30 °C	Weight loss; 0.2 g PU foam; 35 days	Enhanced consortium degradation	Puranik *et al.* (2024)
	Trichoderma harzianum	LDPE film surface erosion in soil systems	Soil microcosm, 25 °C	Surface erosion; 5 cm² film pieces; 40 days	Effective soil colonization; SD ±2%	Ahmed *et al.* (2025)
Enzymatic pathways	PETase–MHETase cascades	Hydrolyzed PET into TPA + EG at 90% conversion	Lab: 25–45 ° C, pH 7.5, 10 days	Monomer release; 0.1 g PET film	Complete monomer recovery; SD ±2%	Wang *et al.* (2024)
	Cutinase cocktails	Engineered cutinase stable at high temperature/ alkaline pH	Temp: 40–90 °C, pH 6–8	Monomer release; 0.2 g PET film	High catalytic activity	El Darai *et al.* (2024)
	Immobilized PETase on MOFs	stability increased to four times	70 °C, ambient pressure, 96 h	Monomer release; 0.15 g PET	Reusable catalytic system; SD ±3%	Abdelhamid *et al.* (2024)
Protein engineering advances	PETase variants (directed evolution)	Activity doubled vs. wild type	60–70 °C	Monomer release; 0.1 g PET	Improved hydrolysis	Choi *et al.* (2024)
	Thermostable lipases	Lipase variants active at 70°C degraded microplastics in compost	70 °C, 70 days	Weight loss; 2 g plastic mix	Expands usable conditions; SD ±4%	Shrinidhi *et al.* (2024)
Synthetic biology approaches	CRISPR-edited E. coli expressing PETase–MHETase	Rapid degradation of PET sheets	30 °C, ambient	Weight loss and monomer release; 0.2 g PET sheets; 14 days	Controlled flux of intermediates	Liu *et al.* (2025)

NP alteration/degradation mechanisms such as oxidative digestion or enzyme treatment may also fool NPS. It proposed the development of reference materials that have been approved for use, interlaboratory comparisons, and procedures that meet the requirements of ISO. AI leads to faster throughput but is associated with new problems. Deep learning also requires large sets of training data and the quality of labelled data is low. Moreover, in underfunded laboratories, the facilities cannot be easily understood on account of the need for computing. To be more specific, the hyperspectral Raman datasets took multiple hours to process and thus did not allow for real-time monitoring. The process of detecting the MPs/NPs is too complicated and cannot be simplified to a single method. A hybrid (Py-GC-MS/AI-controlled classification, microfluidics) will continue to gain significance as an efficient monitoring system (Daoutakou and Kintzios, 2025).

BIODEGRADATION PATHWAYS OF MPS/NPS

To develop effective remediation methods, a person must understand how micro/nanoplastics (MPs and NPs) biodegrade. Some of the various players in biological degradation pathways include microbial communities, enzymes (Fig. 2) that catalyze the degradation of polymers, and new genetic and metabolic engineering strategies aimed at enhancing degradation capabilities. Even though MPs and NPs are often used interchangeably, it is important to keep in mind that nanoplastics are not similar to larger microplastics in regard to their environmental fate and remediation processes because of their colloidal behavior such as Brownian motion, large surface-area-to-volume ratios, and elevated surface reactivity.

Microbial biodegradation

Bacterial consortia and synergistic interactions

Since the metabolism and metabolic process of different bacteria are complementary, and the degradation of MPs by multi-species co-cultured bacteria has been shown to be synergistic, the ability of microbial consortia composed of multiple bacterial species to degrade MPs may be enhanced. It should be noted, however, that most MPs/NPs degradation efficiencies have been documented in optimal laboratory conditions e.g., controlled temperature, nutrient concentrations and pre-treated polymer substrates rather than ambient environmental conditions (Yadav *et al.,* 2026). A new review identifies the strains of bacteria which are most efficient in breaking down Polyethylene (PE); *Rhodococcus ruber* was able to break down PE in a matter of a week under controlled laboratory conditions, compared to around 40 days for *Bacillus cereus*. when compared to around 40 days for Bacillus cereus. Moreover, compared to monomicrobial cultures, mixed species consortia (such as a mixed culture of *Bacillus* and *Paenibacillus*) have been shown to have a faster rate of polyethylene degradation (Hossain *et al.,* 2024). There are contradictory outcomes of plasmid biofilms, even though the microbial diversity and cooperation are crucial in the biodegradation of MP/NP. Although adult extracellular polymeric surfaces have the potential to exclude access to substrates and prevent diffusion, early adhesion enhances cell-polymer proximity and specific enzyme local activity. The efficiencies often promise to be decreasing in natural environments and this may be attributed to ecological succession which may further concentrate non-degrading organisms that consume released metabolites (Hernández-Huerta *et al.,* 2025). Interestingly, microbial consortia perform various interactions with MPs and NPs. NPs are colloidal entities which remain suspended in aqueous conditions and are minimally physically retained in microbial aggregates or biofilms but are predominantly colonized on surfaces and depolarized by biofilm. The small size of NPs allows them to escape the conventional trapping mechanisms, and surface adsorption and direct contact with enzymes are considered more significant to NP degradation than trapping in biofilms. This has been further improved by the design of preconditioning treatments; for example, if MPs are exposed to UV light as a pre-treatment, microbial degradation is more readily achieved, highlighting the role of artificial aging in accelerating degradation kinetics (Kraus *et al.,* 2025).

Microbial breakdown of polymers by bacteria, fungus, microalgae, and artificial consortia is studied with an emphasis on the polymer-specific degradation processes and the environmental adaptation. Among the advances in enzyme-mediated depolymerization, there are oxidative enzymes and hydrolyzing enzymes that decompose plastic. Nano- materials of green origin, biosorption and phyto remedial all promise as environmentally friendly approaches to pollutant capture and transformation. The key analytical challenges of determining, quantifying, and predicting the migration, aging, and fate of MPs and NPs are also discussed. To permit efficient, scalable, and selective approaches to plastic pollution reduction, future efforts include the combination of metabolic engineering, systems biology, and omics approaches (Das and Mitra, 2024).

Role of fungal decomposers in polymer breakdown

Fungi are responsible in particular for polymer degradation through penetration by hyphae and extracellular oxidative enzymes. *Aspergillus flavus* was the most significant degrader, reducing the molecular weight of the MP, while *Zalerion maritimum* was the most significant in reducing the size and mass of the PE particles. Chigwada *et al.* (2025) suggested that the white rot fungus *Phanerochaete chrysosporium* and *Engyodontium album* can decompose PP; weight losses were approximated to be about 9.4% and 18.8% at the end of

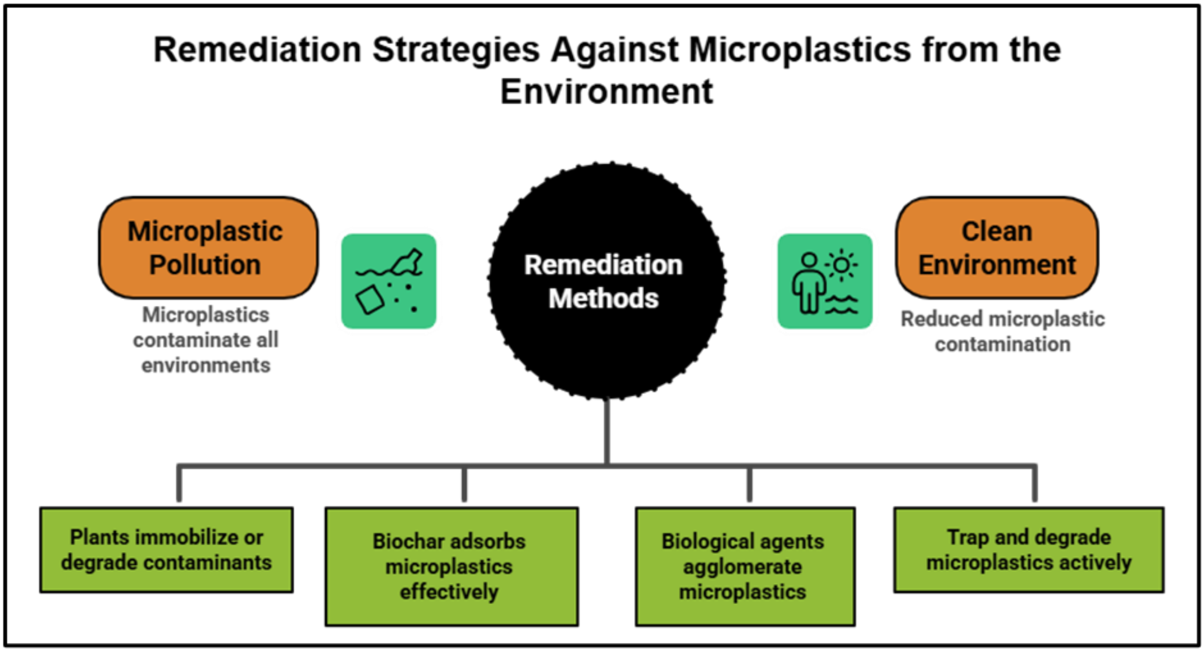

Fig. 3. *Eco-remediation strategies for removing microplastics from the environment*

one year of the UV irradiation conducted under controlled conditions. Nevertheless, they must be considered as descriptive tendencies, but not statistically verified changes in degrading efficiency since the original research did not indicate the application of statistical significance testing (e.g., p-values or confidence intervals). Maddala *et al.* (2025) has shown the importance of the filamentous fungi and *Aspergillus* species for aquatic environments. Methylparaben (MP) could be effectively degraded in aqueous mediums by *Aspergillus flavus* and *Aspergillus versicolor*. *Aspergillus tubingensis* and *Pestalotiopsis microspora* are part of the broader plastisphere - the microbial communities that make a home for themselves on plastics. Both enzymes can break down polyurethane (about 90% in two to three weeks under optimized laboratory conditions with pre-treated substrates). Other fungal degraders are *Galleria mellonella* caterpillars which degrade 13% of polyethylene in 14-hours at 37 °C under laboratory conditions, and *Bacillus pseudofirmus* and *Salipaludibacillus agaradhaerens* for LDPE (Baldelli *et al.,* 2025). Whereas the microbial and fungal systems can degrade MP/NP, most of the reported efficiencies are due to highly controlled laboratory systems that employ high temperatures, long incubation periods and pre-treatment polymers- conditions that accelerate the rate of degradation, but not reflect natural environments. Consequently, a lot of the findings remain evidence-of-concept, and inter-study comparisons often lack statistical rigor and estimates of variance and are informative, but not definitive. The hierarchy of carbon and the rivalry between the substrates also make ecological validity even more constrained; in the real world, the presence of labile organic carbon may prevent the utilisation of plastic. Future improvements in the field of adaptive consortia, mixed-substrate experiments and designed pathways are required to enhance performance and predictability (Rashid *et al.,* 2025).

Enzymatic degradation mechanisms: Key enzymes and catalytic pathways

Enzymes such as hydrolases, cutinases, laccases, peroxidases, mono-/dioxygenases, and carboxylesterases play the most important roles in biodegradation of plastic. These enzymes are first degraded extracellularly to oligomers and monomers followed by mineralization intracellularly to CO_2, water and/or biomass. However, not every detoxification is a synonym of polymer chain scission and mineralization efficiency. Besides the release of imbedded plastic additives such as plasticizers, dyes, stabilizers and flame retardants, partial biodegradation can result in the formation of low-molecular -weight oligomers that could be left in the environment or become more toxic and bioactive. There are not many studies that measure the destiny and toxicity of degradation intermediates and leached additives, but most biodegradation experiments are on weight loss, surface erosion, or monomer release. Thus, to ensure that the degradation mechanisms lead to actual risk management, in lieu of secondary contamination, the extensive analysis of the biodegradation scope must include chemical characterisation of the by-products and ecotoxicological tests (Akash *et al.,* 2025). More importantly, much of the literature on the so-called elimination of micro and nanoplastics relies on such criteria as the loss of mass, erosion of surfaces, or the decrease of the size of particles, which do not necessarily lead to detoxification of the environment. Partial enzymatic or microbial degradation can be used to produce low-molecular-weight oligomers, monomers, and

Table 2. Recent developments of Eco-Remediation and Removal strategies of MPs/NPs

Strategy	Representative microorganism/material/plant	Experimental conditions and Initial load	Duration	Key findings	References
Phytoremediation	*Lemna minor* (duckweed)	500 mL aqueous MPs solution; 0.5 mg/L MPs; 7 days	-	Reduced aquatic MP load; ~58 ± 3% removal	Pawaiya and Suthar, (2025)
	Salvinia molesta (floating fern)	Wetland mesocosm; 1 g plant per L water; 10 days	10 days	Enhanced removal due to large surface area; ~65 ± 4%	Gecheva *et al*. (2025)
Biosorption and Biochar	Corn-stalk biochar	50 mg BC in 50 mL water; MPs 100 mg/L; 24 h	24 h	High adsorption (~92 ± 3%).	Kumar *et al*. (2025)
	Algal-derived biochar (*Chlorella vulgaris*)	50 mg BC in 50 mL water; MPs 0.1 g/L; 24 h	24 h	Functional groups enhanced adsorption (~85 ± 4%)	Quang *et al*. (2025)
Biocoagulation/ Flocculation	EPS-producing *Bacillus subtilis*	1 L MPs solution; 0.5 mg/L; 12 h	12 h	Biofloc entrapped MPs; ~72 ± 4%	Hasan *et al*. (2024)
	Fungal EPS (*Aspergillus niger*)	0.5 mg/L MPs; 24 h	24 h	Enhanced binding; ~68 ± 3%	Hadiyanto *et al*. (2025)
Nanomaterial-assisted	TiO_2 nanoparticles	50 mg/L MPs; visible light; 6 h	6 h	Photocatalysis yielded ~60 ± 5% breakdown	Khan and Ong, 2025)
	ZnO–biochar nanocomposite	50 mg/L MPs; 12 h	12 h	Photocatalysis yielded ~60 ± 5% breakdown	Goyal *et al*. (2025)

Note: Whereas degradation means changes in form of the chemical or biological nature, removal is the physical movement or immobilization of MPs/NPs (e.g. adsorption, trapping, uptake). Biomass or sorbents that have polluted needs to be handled after removal with the use of one or more of the above-mentioned techniques.

leached additives (e.g. phthalates, bisphenols, flame retardants, etc.) with a potentially higher bioavailability and acute toxicity than the parent polymer itself. Several studies support the idea that fragmented plastics and soluble degradation intermediates are more likely to enter biology via the biological membrane and affect targets of the cellular components, which is known to increase ecotoxicological risks. Hence, the biodegradation should be evaluated on the basis of the mineralization activity along with the environmental outcome and toxicity of the intermediate products. Fragmentation should not be mixed up with remediation (Dey *et al.,* 2024). Specifically, there is a need to monitor the fate of such leached additives as dyes, flame retardants, and phthalate plasticizers. Since these molecules tend to be more mobile and have more acute toxicity than the parent polymer, actual cleanup must break down these chemical additions simultaneously lest it results in the development of a potentially lethal soup of small-molecule contaminants. Thus, chemical characterization of by-products should be combined with ecotoxicological tests in order to obtain the appropriate remediation potential of enzymatic and microbiological degradation of plastics (Giyahchi and Moghimi, 2025).

Structural insights and protein engineering advances

Structural improvements have resulted in improved PET-degrading enzymes. Site-directed mutagenesis of PETase generates mutants with higher activity (22% with Arg280-Ala); higher stability through glycosylation or through addition of disulfide bonds; and higher thermal stability through b1-b2 loop modifications. These modified enzymes have more affinity for high crystallinity PET which is otherwise biodegradation resistant. In addition, biotechnological approaches, such as recombinant expression in yeast and *E. coli*, have been adopted to improve the plastic degradation efficiency by producing enzymes like laccase and manganese-dependent peroxidase (Bombaywala *et al.,* 2024).

Genetic and metabolic engineering approaches: Synthetic biology for enhanced degraders

Synthetic biology can be used to enhance or create new degradation mechanisms. *Pseudomonas aeruginosa* genetically engineered to alter the synthesis of exopolymeric substances is capable of "capturing and releasing" MPs. Furthermore, the PET biodegradation by the photosynthetic system was reached by cloning PETase in microalgae (*Phaeodactylum tricornutum*). The world-first technology developed by IISER Bhopal's scientists called XenoBug is a blend of machine learning and neural networks that screens millions of enzyme sequences from metagenomes and bacterial genomes to find the potential enzymes that can degrade pollutants such as plastics. The tool can speed up the discovery of the potential strains and biodegradation pathways (Zahra *et al.,* 2025).

CRISPR and omics-based tools in microplastic degradation

CRISPR-Cas mediated gene editing (CRISPR-Cas9) for improving litter-use of lignin-rich biocomposite plastic degraders by over-expression of laccase and peroxidase in *Phanerochaete chrysosporium* using PlastiCRISPR system. Apart from degradation, CRISPR is also being used for metabolic pathway engineering for the production of biodegradable polymers such as PHAs (Kumar *et al*., 2025). The *E.coli* was engineered to make more PHA by deleting competing pathways and over expressing pntAB. The mapping of functional knowledge on metabolic pathways in Pseudomonas putida and other species (glyoxylic acid-route, PET-derived terephthalate converted into TCA cycle- intermediates (pyruvate, oxaloacetate has enabled the targeted metabolic engineering. Moreover, in a bid to enable PET degradation in a salt water environment, the PETase I. sakaiensis genes are undergoing expression in a marine-compatible Vibrio natriegens (Sarkar and Bhattacharjee, 2025).

Table 1 is a summary of underlying mechanisms, microbial or enzymatic systems engaged, technological solutions and correlates with its implications on the sustainable remediation to provide a concise picture of the recent improvements in microbial, enzymatic and genetic approaches to micro- and nanoplastic degradation.

It is important to note that the degradation efficiencies in the Table 1 are primarily associated with the transformation's metrics of the polymers, and most of the available literature has not yet conducted a systematic evaluation of additive leaching and intermediate toxicity. Although some of remedial methods used in Table 1 are applicable to MPs, the NPs can evade physical traps because of their colloidal structure and Brownian motion. Consequently, NP remediation requires an approach that relies on surface adsorption/aggregating instead of a simple physical filtration.

ECO-REMEDIATION AND REMOVAL STRATEGIES

Good environmental remedial practices are essential because the MPs can be found in every environment. Four primary approaches are common, which are nanomaterial assisted systems, biosorption/biochar, biocoagulation-flocculation, and phytoremediation (Fig. 3). Nevertheless, disposal often causes secondary wastes through the repositioning of contaminants to biomass or sorbents, but complete sustainability should be achieved through mineralization or safe post-treatment of the same.

Phytoremediation of MPs/NPs-contaminated environments

Phytoremediation (PR) is the use of plants for the immobilization, sequestration, or degradation of contaminants, usually of organics but also of heavy metals and has gained momentum as a possible remediation option for MPs and NPs (Karnwal *et al*.. 2024). Mohanty *et al*. (2024) showed that the floating macrophyte, Lemna minor (i.e. common duckweed), could readily bind MPs to plant biomass to a concentration of up to 79% after 15 cycles. It was found that the adoption of biomass replacement models, which are founded on Freundlich adsorption, produced quite feeble and repeatable MP binding. In controlled conditions, removal of MPs out of the water column may take approximately 53 cycles according to the theoretical extrapolation of the Freundlich model. But, expanding kinetic regressions far outside the 15-cycle experiment range leads to catastrophic error propagation, and this prediction is subject to inherent statistical error. The adsorption constants and stochastic environmental influences, such as hydraulic oscillations and changing biomass health, which are not present in the idealized laboratory setting, but which are contained in the 95% confidence ranges, can lead to the actual number of cycles in the field applications to vary significantly despite the fact that this value is a theoretical cutoff. Lemna is able to provide passive and cost-effective remediation for ponds or storm water installation for use in artificial wetlands and/or floating filtration systems. Slow elimination kinetics, the potential for interference in water flow, and safe disposal of contaminated biomass etc., are some of the disadvantages. There has also been some investigation into how NPs interact with marsh plants when exposed to other pollutants at the same time.

Biosorption and biochar-based technologies

Due to high surface area, porosity, abundance, and functional surface chemistry, biochar (BC) has been considered as one of the best biosorbents for the removal of MPs and NPs. The following is an overview of BC applications for MPs/NPs removal from aqueous media. BC adsorbs by electrostatic binding, aggregation and filtering in a pH and temperature-dependent way and affected by competing pollutants, the activity of BC can be increased in conjunction with coagulation or anaerobic sludge units. In addition, the assessment warns that improperly manufactured contaminated BC could be a source of pollutants (such as heavy metals and polycyclic aromatic hydrocarbons or PAHs) (Banica *et al.,* 2024). Kaur *et al*. (2025) used jujube litter (*Ziziphus jujube* L.) biochars with 300 °C and 700 °C treatment in a fixed bed column experiment for the removal of the nylon and polyethylene (PE) microplastics from the water. The removal of Pb (II) and Cd (II) was significantly enhanced on the BCs with adsorbed MP (suggesting the possibility of combined MP/heavy metal removal). Bashir *et al.* (2024) removed the PVC microplastics from aqueous solutions using pine bark biochar (BC) and modified BC (MBC). MBC worked better than raw BC (131.5 mg/g) for adsorption (up to 156.08 mg/g, 78% elimination) with the optimum pH value (10) and concentration (200 mg/L). Ion exchange, van der Waals interaction and electrostatics were some of the mechanisms while adsorption process was modelled using a PSO kinetic model and the Temkin equation. Biochar and other sorbents rapidly form an eco-corona of naturally present organic matter under real-life conditions, in aquatic situations, which is then colonized by biofilms which may alter electrostatic interactions, surface chemistry, and available porosity. This type of biofouling, especially with smaller micro- and nanoplastics can decrease adsorption capacity, hinder long-term performance, and influence particle retention. Consequently, the large removal efficiencies observed in the laboratory tests might be exaggerated in natural waters. Besides environmental conditions, such as, pH, ionic strength, and other competing contaminants, a knowledge of such dynamics is critical in scaling biosorption and membrane technologies. Future research ought to incorporate long-term field trials or pre-fouled conditions that would be more accurate in predicting the outcome of the cleanup (Qin *et al.,* 2024).

Biocoagulation and bioflocculation

In biocoagulation, the MPs/NPs are separated by agglomeration by means of biological agents i.e. algae, biopolymers or microbial exopolymers. Based on the research done on electrocoagulation, polystyrene nanoparticles were removed in synthetic wastewater with optimal voltage, electrode separation and salt concentration using aluminum electrodes at a pH value of 7.2 ± 0.3. The research reported an average removal of 88.5 (± 6.2), and maximum removal of over 95 percent only happened at optimum parameter settings. This variation means that the technology though where its peak performance is very high, its continuous reliability is prone to variations in operating conditions (dos Santos *et al.,* 2025). Bioflocculation caused by algae or phytoplankton can be utilized for improving MP aggregation. This sensitiveness is further evidenced when recent studies by Zhang *et al*. (2025) show that bio-mediated flocculation requires an exopolymer particle (TEP) concentration of 0.42mg/L or higher to maintain floc stability; beyond this level, the removal performance is not very consistent. Filamentous algal systems in conjunction with magnetic BCs offer hybrid opportunities, but specific algal systems for the removal of MP are in their infancy. The microbial EPS will operate similarly to MP capture using the general bioflocculation.

Nanomaterial-assisted bioremediation approaches

The elimination of MPs may occur through physical procedures (e.g., filtration and adsorption) and/or be degradable through chemical and enzymatic processes; they indicate various outcomes of remediation. de Rosset *et al*. (2025) have investigated the use of PVDF nanofiber membranes that have been modified with biosurfactants, TiO_2 and CuO nanoparticles as a treatment for oil-water emulsions containing 0.5 mm microplastics. The membranes exhibited almost total rejection of microplastics (99.99%) with excellent water permeability, antifouling property, and 95% oil rejection, for long-term period. This performance demonstrates its physical extraction (filter) instead of chemical degradation of the plastic polymer. Thus, MPs could be targeted by engineered membrane systems in industrial/ municipal wastewater treatment plants. Such phase-transfer methods concentrate microplastics into a secondary waste stream and require further treatment or safe disposal. In contrast to the membrane-based filtering, de Brito *et al*. (2024) demonstrated the real chemical degradation of PET microplastics by using lipase-immobilized polydopamine-functionalized magnetic Fe3O4 nanoparticles. For real-time monitoring of the degradation, hyperspectral Confocal Raman microscopy was used. These techniques of phase-transfer focus microplastics into a second waste stream, which should be treated or disposed of safely. Recent advances in integrated systems like synthetic biology, microbial electrochemical methods and hybrid bioreactors are presented in Table 2. Consequently, the removal-based techniques and the degradation-based approaches should be discussed separately to avoid making the environmental recovery process as efficient as possible.

Life cycle and energy considerations of nanomaterial-based remediation

Even though the processes of capturing and dismantling micro and nanoplastics with the help of electrochemical and nanomaterials are incredibly efficient, their sustainability ratings should be scrutinized closely.

Table 3. Emerging and novel strategies and combined systems for micro/nanoplastic biodegradation and removal

Approach	**Mechanism of action**	**Target plastic (s)**	**Key findings**	**Experimental conditions**	**Advantages**	**Key limitations**	**References**
Microbial electrochemical Systems (MESs)	Electroactive biofilms degrade MPs while generating electricity	PE, PS, mixed MPs	35% higher PE degradation; 14 days	0.5 g/L PE in batch MES	Energy-positive, multifunctional	Scale-up challenges: electrode fouling	Sanaei *et al.* (2025)
Hybrid bioreactor designs	Microbial + enzymatic + physical–chemical integration in continuous reactors	PET, PS, PVC, mixed MPs	fungal–bacterial hybrid to 60% PS degradation; 21 days	0.5 g/L MPs, continuous-flow	Scalable, controllable	Microbial instability; costly	Zhou *et al.* (2025)
Nanomaterial-assisted systems	Functionalized nanomaterials (TiO_2, Fe_3O_4, graphene oxide) for catalysis/ adsorption	PET, PE, PS, PP	80% MPs adsorption; 12 h	50 mg/L MPs in batch system	High efficiency, multifunctional	Nanotoxicity; costs	Usman *et al.* (2025)
AI, IoT and Digital twins	Predictive modelling, sensors, and digital twins for process simulation and decision support	Universal	Proof-of-concept studies demonstrated improved prediction of bioreactor performance and process behavior under simulated conditions	Simulated reactors	Supports predictive analysis and virtual optimization	Limited field validation; data scarcity; infrastructure-intensive	Flores *et al.* (2024)
Algal-bacterial consortia	Algae provide O□; bacteria degrade MPs; mutualistic interaction	PE, PS, mixed MPs	52% MPs' removal; 10 days	0.5 mg/L MPs in freshwater microcosm	Sustainable CO□ sequestration	Limited to aquatic systems	Jin *et al.* (2025)
Enzyme immobilization and Nanocarriers	Enzymes fixed on MOFs, silica, magnetic NPs → improved activity/reusability	PET, PU, PLA	nano-carrier lipase hydrolyzed PU; 7 days	0.1 g/L MPs, immobilized enzyme system	Higher stability, reusability	Carrier toxicity; costs	Wang *et al.* (2024)
Photo-bioelectrochemical systems	Photocatalysts + microbes/ electrodes for synergistic degradation	PET, PE, PS	70% PET degraded in 15 days	0.5 g/L MPs, solar-simulated light	Uses sunlight, synergistic	Complex setup	Zhou *et al.* (2024)

Contd…..

Table 3. Contd…...

Biostimulant-enhanced biodegradation	Adding organic stimulants (e.g., humic acids, biosurfactants) to boost microbial activity	PE, PS, PET	biosurfactant-enhanced microbial consortia accelerated PE degradation; 10 days	0.5 g/L MPs + 10 mg/L humic acids	Inexpensive, eco-friendly	Efficiency varies by pollutant	Liu *et al.* (2025)
Magnetically assisted bio-systems	Magnetic nanoparticles coupled with microbes/ enzymes for targeted MPs removal	PE, PVC, PET	The magnetic-bio hybrid removed 75% MPs in wastewater in 12 h	50 mg/L MPs in water	Easy recovery, efficient	Nanoparticle toxicity	Esanakula *et al.* (2025)
Fungal mycoremediation platforms	White-rot and ligninolytic fungi secrete oxidative enzymes to degrade MPs	PS, PU, PE	fungal consortia degraded PU; 21 days	0.5 g/L MPs in soil microcosms	Produces strong oxidative enzymes	Slow kinetics	Ali *et al.* (2025)
Plastisphere engineering	Manipulating plastic-colonizing microbial communities (plastisphere) to accelerate degradation	Mixed MPs	engineered plastisphere consortia degraded mixed MPs in seawater; 14 days	0.5 g/L MPs in seawater microcosm	Mimics natural succession	Risk of invasive species	Zhai *et al.* (2023)
Enzyme cocktail synergies	Using combinations of enzymes (PETase + MHETase, cutinases + lipases) for synergistic breakdown	PET, PU, PLA	dual enzyme cocktails hydrolyzed PET to TPA/EG faster than single enzymes; 7 days	0.1 g/L MPs, enzyme cocktail	Higher efficiency	Enzyme incompatibility	Yaqoob *et al.* (2025)
Electro-fenton bio-systems	Coupling Fenton oxidation with microbial degradation for enhanced MPs breakdown	PS, PVC	The electro-Fenton bio-hybrid achieved 85% MPs degradation in 10 days	0.5 g/L MPs, electrochemical setup	High removal rates	Energy intensive	Xu *et al.* (2023)
Co-culture and Synthetic consortia	Multi-species engineered consortia with complementary pathways for MPs degradation.	PET, PE, PS	Pseudomonas + Bacillus co-culture degraded 62% PET films; 30 days	0.5 g/L PET in lab reactor	Synergy, resilience	Community instability	Chen *et al.* (2024)

The production of functional nanoparticles (e.g. TiO_2, CuO and Fe_3O_4) and engineered membranes commonly requires the use of energy-intensive processes, high purity chemical stocks and solvents, heightening greenhouse gas emissions and environmental impact. As in this case, microbial electrochemical systems and electro-Fenton systems need constant supply of electricity, which could be sourced by non-renewable grids, contributing to the overall carbon footprint (Enyoh *et al.,* 2025). Recent research shows that failing to consider lifecycle implications could make cost of total energy and amount of material used to do cleanup of trace-level plastic of greater benefit than the environmental benefit. Although they are not popularly employed in the literature of today, the life cycle assessment (LCA), as well as energy balance assessments, is essential in the calculation of net environmental benefits and hotspots in the manufacturing, utilization, and disposal of nanomaterials. The effects can be reduced through green synthesis methods, renewable energy sources and recycling of the system, but these are just mere conceptual or experimental solutions. Thus, in order to ensure that such solutions provide a real net benefit in practice applications, such promises as ecologizing (or green-friendly) and sustainability should be justified by quantifiable indicators of LCA and energy efficiency (Yue *et al.,* 2025).

Distinction between pollutant removal and degradation: fate of sorbents and secondary waste

In evaluating eco-remediation methods, one should be able to tell the difference between removal and degradation. Removal processes such as biosorption, algal flocculation and biochar adsorption quickly relocate pollutants between phases (such as aqueous) to another (such as solid sorbent or biomass) without substantially altering their chemical structure. Such techniques are able to reduce the content of pollutants in the earth or water, however, the biomass and sorbents generated in these processes are likewise contaminated and must be handled further to prevent secondary contamination (Akhtar *et al.,* 2024). Degradation routes, in its turn, minimize environmental hazards in a more lasting manner, converting the pollutants to harmless end products either through biochemical or physical processes. This paradox is evidenced by the current trends in microplastics and nanoplastics elimination. Hybrid and bio-inspired technologies have attained high efficiencies of microplastic removal using adsorption and separation methods. Nevertheless, these processes tend to freeze plastics instead of breaking them down and creating concentrated plastic-impregnated sorbents, which require to be discarded or further processed.

Biochar effectively reduces the load of pollution through physical sorption but not conversion; therefore, it has to be regenerated, safely disposed, or compressed with the biodegradation processes. They can be complemented with phytoremediation or bioaugmentation, potentially based on the effect they have on the biomass of soil microorganisms, which can alter the degradation rates in the future. The future of confined pollutants remains uncertain, however, and this has led to interest in systems that make use of nanomaterials that couple adsorption with oxidative or photocatalytic degradation (Mao *et al.,* 2025). It is important to calculate sorbent fate and secondary waste formation since, as can be seen in Table 2, most eco-remediation methods mostly eliminate MPs/NPs through physical sequestration or phase transfer, as opposed to complete degradation.

INNOVATIVE APPROACHES AND INTEGRATED SYSTEMS

An integrated and scalable effort is being driven by the increasing perception of MPs and NPs as ubiquitous threats. New methods are gradually incorporating synthetic biology, electrochemical, omics and hybrid bioreactors and digital optimization convergent to multidisciplinary biodegradation platforms to enable effective environmental management, as conditions in the field limit conventional approaches.

Synthetic biology and omics-driven biodegradation platforms

Synthetic biology and omics technologies are revolutionizing the field of plastic biodegradation by making it possible to rationally engineer microorganisms and enzymes. Synthetic biology is an emerging field of biomolecular engineering, which makes use of genome engineering, metabolic redesign, and pathway optimization to produce designer biocatalysts that are capable of efficiently degrading polymers such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET). This is compared to traditional microbial systems that rely on naturally occurring (slow-degrading) microbial strains (Sharma *et al.,* 2024). Sethi and Nag, (2024) shown the utility of metagenomics, transcriptomics, and proteomics to help identify previously unknown genes and regulatory networks involved in plastic degradation. Hu *et al*. (2024) discovered new PET hydrolases from marine microbial consortia using shotgun metagenomic sequencing, which showed that there are more catalytic residues with a higher hydrolytic potential in a saline environment. Mubayi *et al*. (2024) quantified the metabolic fate of degraded PET monomers, correlated plastic degradation to the production of value-added bioproducts using metabolomics and transcriptomics. They demonstrated how terephthalic acid is directed into bio-based polymers by designed microbial consortia. CRISPR-Cas9, CRISPRa/i, and base editors are examples of new synthetic biology tools that allow precise control of groups of genes involved in polymer hydrolysis. Liu *et al*. (2025) engineered the bacterium *Ideonella sakaiensis* using synthetic promoters to drive the production of PETase and MHETase at the same time, and achieved 4.2-fold higher PET degradation than the wild strain. Further, the catalytic repertoire of plastic-degrading enzymes is being expanded using directed evolution and protein engineering.

Microbial electrochemical and bioelectrochemical systems

METs are an important development for energy-associated biodegradation schemes that exploit the electron transfer properties of electroactive microorganisms. Bioelectrochemical systems (BESs) utilize the combination of electrochemical redox reactions with microbial degradation to produce energy from contaminants in a process called bioremediation with energy recovery (Bioremediation). More broadly, METs offer two advantages to MPs/NPs: (i) they enhance microbial metabolism by providing electron acceptors and donors, and (ii) they allow monitoring and controlling degradation processes in real time (Feng *et al.,* 2025). According to Wang and Zhou, (2024) the extracellular electron shuttling of a bioanode loaded with *Shewanella oneidensis* increased the oxidative degradation rate of polystyrene microplastics. Emerging microbial electrolysis cells (MECs) utilize a small externally applied voltage to promote reductive depolymerization pathways for the degradation of polyethylene and polypropylene. The focus of the current work is on improving the electron transport and surface colonization in BES architectures through the incorporation of nanomaterials. Graphene-coated electrodes give a conductive surface for biofilm formation, and the FeO4 nanoparticles enhance the redox cycling. Importantly, BESs enable co-recovery of resources and energy as well as degradation of MPs and NPs. One of the options for combining remediation and renewable energy is to use the volatile fatty acids that are formed from the plastic monomers to generate biohydrogen or biogas (Rovira-Alsina *et al.,* 2024).

Hybrid bioreactor designs for large-scale applications

The bottleneck remains the scale-up from bench to field of bioremediation. The most efficient means of bridging this gap is by using hybrid bioreactors where biological, chemical, and physical modules are integrated. In contrast to classical single-stage systems, hybrid designs make use of multimodal synergies in order to improve stability, process resilience, and degradation rates. Fluidized bed bioreactors (FBBRs) coupled with plastic-degrading consortia have been used for the continuous microbial attenuation of MP in wastewater effluents (Singh *et al.,* 2025). Gusmao *et al*. (2024) proved a 62% degradation of polystyrene microbeads in a bench-scale FBBR in 14 days with co-cultures of *Rhodococcus* and *Aspergillus*. In addition, membrane bioreactors (MBRs) with enzymatic modules are promising for selective capture and degradation of MPs, to allow the treated effluents to meet regulatory requirements. Anaerobic hybrid digester and sequencing batch reactor (SBR) systems are under investigation for the co-treatment of MPs with organic wastes. The parallel degradation of plastics and the production of biogas constitute an interesting bioeconomic model. Kong, L., and Shi, X. (2025) observed an 11% increase in methane production from microbial co-metabolism upon the addition of PET microplastics at low concentrations. The two-stage hybrid bioreactor is an extremely innovative design. In the first step, polymers are partially depolymerized to oligomers by oxidative enzymes or electrochemical pretreatment, and in the second step, these intermediates are metabolized by engineered microbes.

Artificial intelligence (AI), Internet of things (IoT), and Digital twins for process optimization

In addition to progress in the fields of biology and engineering, the integration of digital technology is increasingly recognized as critical to increasing the scale of plastic biodegradation. New tools that might enhance the monitoring, optimization, and scale-up of bioprocesses, which are being explored more and more, include the Internet of Things (IoT), the digital twin platforms, and artificial intelligence (AI). AI algorithms, particularly machine learning models and deep learning models have demonstrated the potential in controlled or simulation-based studies to predict the enzyme-substrate interactions, assist in reactor parameter optimization and predict the degradation kinetics in different environmental conditions (Phillip and Chauhan, 2024). Ömer and Balcı, (2023) reported a deep learning framework that can accurately predict the PET degradation efficiency (>90%) by designed hydrolases, which will reduce the cost of experimental screening. Nonetheless, general accuracy or efficiency limits (>90) can be misleading when poorly balanced measures are not employed in biodegradation forecast exercises where potentially unbalanced datasets are common, and efficient degradation results are often rare in comparison to those that never degrade. Such machine learning tasks aimed at the PET degradation and the environmental processes are better evaluated by the use of balanced performance indicators such as F1-score (harmonic mean of precision and recall), AUC-ROC, or precision-recall curves, particularly on minority classes that represent a successful degradation process or specific hydrolase interactions. . Although the most common forms of direct quantification of MPs/NPs remain based largely on periodic offline methods, other novel methods of sensing involve IoT-based systems to monitor proxy parameters such as pH, redox potential, turbidity, particle count distributions, and microbial activity in real-time reactors. Even though these techniques are currently limited to a laboratory-scale or pilot-scale, such data streams can in theory be used together with AI analytics to provide predictive information regarding biodegradation mechanisms. It must be mentioned that the existing in-situ sensing systems of micro- and nanoplastics are not reliable and continuous, so there are no such systems that can be deployed to the field consistently and on a regular basis, particularly on a nanoscale (Obidi and Bayless, 2025). Table 3 enumerates advances in the integrated platforms that might improve the process of removing MP/NP, like the hybrid bioreactors, microbial electrochemical systems, and synthetic biology. However, AI and digital twin are still new and can be primarily used in simulation or laboratory studies. These technologies cannot serve as scalable remedial systems because there are no valid field datasets to do so, and make them unable to be vetted.

ENVIRONMENTAL FATE AND TOXICOLOGICAL CONCERNS

Transport, Transformation, and Persistence in ecosystems

Physical, chemical, and biological processes over the lifecycle of materials at varying scales (e.g., micrometer, nanometer) are known to play increasingly complex roles in the transport, transformation, and persistence of MPs across ecosystems. MPs have several physicochemical properties that influence their long-term fate and mobility in the environment, such as size, shape, polymer composition, surface functionalization, etc. The hydrodynamic processes, such as turbulence, sedimentation, and resuspension, are thought to be responsible for the horizontal and vertical dispersal (Khaki and Kumar, 2025). Photodegradation, mechanical abrasion, and oxidative fragmentation of MPs are enhanced by UV irradiation, temperature changes, and mechanical shear stresses. These modifications increase environmental persistence and ecological risk by creating secondary MPs and NPs and reducing particle size. Chemically weathered mineral particles/nanoparticles (MPs/NPs) can efficiently transform contaminants into vectors by changing surface properties and promoting heavy metal, polycyclic aromatic hydrocarbon (PAH), and persistent organic pollutant (POP) adsorption. Additionally, biofouling can be both a good thing and a bad thing: as fouled plastics are eaten by filter feeders and passed upwards in the food chain, microbial colonization can increase the concentrations of particles, which can lead to sedimentation, but also can enhance dispersal through trophic interactions (Sun *et al*., 2024). Transport processes in terrestrial ecosystems are affected by agricultural practices, soil texture, and moisture content. According to the studies, MPs are introduced in agricultural soils by irrigation with treated wastewater, while vertical transport is enhanced by earthworm and arthropod bioturbation. Wind erosion will increase the horizontal mobility of lightweight fibres and fragments, especially in dry and semi-arid regions where cross-border dispersal is facilitated. Reduced soil fertility and crop contamination are further concerned by the presence of MPs absorbed into soils for decades, resulting from limited rates of degradation under anaerobic/low-UV conditions (Heinze, 2024).

Bioaccumulation, biomagnification, and food web transfer

The bioaccumulation and trophic transfer of MPs/NPs through biotic webs are some of the most critical questions. While biomagnification describes the stepwise increase in particle concentration at successive trophic levels, bioaccumulation describes the absorption and retention of plastic particles into individual organisms. Plankton, invertebrates, fish, amphibians, birds, and mammals are among the many animals shown to ingest MPs/NPs in recent controlled studies and field surveys . Uptake mechanisms include adhesion to gill surfaces, direct ingestion, filter feeding, and inadvertent ingestion through prey items. Since NPs are small and similar in size to food particles, it has been shown that they are internalized by phytoplankton and zooplankton, the base of aquatic food webs. It has been experimentally shown that NPs of 50 nm size can penetrate across the algal cell wall and disturb the photosynthetic efficiency (Zhang *et al*., 2024). Collectively, our results suggest that zooplankton exposed to MPs suffered from low feeding efficiency and diminished reproductive performance, highlighting the existence of potential cascading effects at a higher trophic level. Vertical transmission is possible by ingestion of infected plankton by fish and crustaceans in the aquatic environment. In particular, the accumulation rates of bivalves (e.g., mussels and oysters) consumed by humans are high, and thus human exposure to environmental contamination is directly connected to human consumption (Ma *et al.,* 2025). In land ecosystems, MPs become part of food chains mainly by soil-plant uptake and by ingestion of forage by animals. There is increasing evidence that plants can accumulate NPs from roots and especially under hydroponic conditions, and that NPs are found in the aerial tissues . Subsequent incorporation into the terrestrial trophic system is caused by herbivores feeding on contaminated plants and detritivores such as earthworms. This food web transfer has been supported by stable isotope tracing studies, which confirm the trophic magnification of MPs from prey to predator. Further integration into terrestrial trophic systems is possible through detritivores (e.g., earthworms) and herbivores feeding on infected plants. This trophic transfer of MPs from prey to predator has been confirmed by stable isotope labelling experiments (Gao *et al.,* 2024). The possibility of biomagnification of related pollutants is a major source of concern. By adsorbing hydrophobic organic contaminants and heavy metals onto their surface, MPs/NPs act as "Trojan horses," releasing these substances into the digestive tracts of organisms and increasing toxicity above and beyond that of the particle itself. Recently, the in vivo exposure of fish models indicated that the NP-cadmium complicated system could cause organ damage to be markedly more than that in cadmium exposure (Mahendran and Ramaswamy, 2024).

Table 4. Critical analysis of experimental hazards vs. environmental risks

Contaminants	Observed effect (Hazard)	Lab dose (mg/L)	Environment level (ng/L - µg/L)	References
Polystyrene	Mammalian reproductive health	5 mg/L	10-80 ng/L	Camerano *et al*. (2024)
Nanoplastics	Invertebrate immunotoxicity	10 mg/L	0.1-10 µg/L	Kumar *et al*. (2025)
ZnO NPs	Molecular aquatic impact	1 mg/L	10-500 ng/L	Amin *et al*. (2025)
PFAS (Perfluorinated alkyl substances)	Lipid metabolic disruption	0.1 mg/L	1-20 ng/L	Bushong *et al*. (2024)
TiO_2 NPs	Mechanistic toxicity pathways	10-50 mg/L	1-100 µg/L	Dey *et al*. (2025)
Rare earths	Developmental neurotoxicity	0.2 mg/L	1-10 ng/L	Revel *et al*. (2025)
CuO NPs	Histomorphological damage	0.1- 1.0 mg/L	5-50 µg/L	Wang *et al*. (2025)
US nanoparticles	USNP pharmacokinetics	200 µg/L	10-50 ng/L	Tripathi *et al*. (2025)
Bisphenol A	Endocrine/metabolic disruption	0.5 mg/L	5-100 ng/L	Wang *et al*. (2025)

Toxicological risk assessment and health implications

The evaluation of toxicological concerns for MPs/NPs should incorporate exposure pathways, dose-response relationships, and a mechanistic understanding of the biological effects caused by MPs/NPs. It is remarkable that several laboratory toxicological studies administer much greater doses to define mechanistic action, ecologically relevant sizes of MPs/NPs are typically found in the ng/L to low ug/L range. Many levels of biological organization can be affected by toxicity, from cellular oxidative stress to ecosystem-scale population disruptions. At the cellular level, NP have been reported to induce oxidative stress, mitochondrial dysfunction, and apoptosis (Chen *et al.,* 2024). In the recent study, Zheng *et al*. (2024) confirmed the results that NP treatment leads to upregulation of inflammatory cytokines and stress-related proteins in zebrafish liver cells from the perspective of proteomics. Specifically, these inflammatory responses were observed at 50-200 ug/L levels of silver nanoparticles, which are a few orders of magnitude higher than the recommended levels (0.01-10 ng/L), indicating an acute hazard-based exposure scenario. MPs and NPs are emerging as new pollutants of concern in the risk assessment framework. However, there are still many methodological issues, such as a lack of standardized detection methods, uncertainty about environmentally relevant concentrations, and a lack of field extrapolation from laboratory results. Consequently, one should differentiate between actual environmental issues that are caused by long-term low-level exposure and toxicological risks that are found in the perfect laboratory conditions. Table 4 outlines the dissimilarity between laboratory hazard identification and actual exposure instances by summarizing published toxicological effects of MPs/NPs alongside the corresponding levels of experimental exposure as well as the different concentration ranges that are ecologically relevant. Recent advances in computational toxicology and physiologically based pharmacokinetic (PBPK) models have allowed prediction of the tissue distribution and long-term effects of nanoparticles (NPs) in humans (Haripriyaa and Suthindhiran, 2023).

CHALLENGES AND RESEARCH GAPS

Even with the rapid developments in biotechnological, eco-remediation, and hybrid systems of micro- and nanoplastics (MPs/NPs), there remains a major gap between lab success and practice. The same high degradation efficiencies are often reported in controlled research studies yet these findings are hardly replicated in soils or aquatic systems where microbial activities are limited by changes in temperature, pH and nutrient levels. Due to the selective metabolism of microorganisms on labile organic media, the carbon catabolite inhibition further limits performance by suppressing the synthesis of enzymes used to synthesize refractory polymers. Moreover, environmental plastics weather, chemically modify and are enriched with additives and co colonization by co-contaminants such as metals or pesticides is discouraged. Consequently, most laboratory values are overestimates of real environmental expectations, as opposed to the actual expectations on the environment. The same can be said about sorbent-based methods and phytoremediation. The complexity of economic scaling is that biochar activity depends on the feedstock and pyrolysis conditions and the plant absorption is dependent on the features of a species, hydrodynamics, and particle diameter. Regardless of their persistence, hybrid bioreactors struggle to maintain steady microbial communities lasting through long periods of operating. These issues are compounded by monitoring problems: the existing analytical tools are accurate, but expensive and low throughput and limit predictive modeling and long-term validation. Another hindrance is lack of methodological consensus. Since fragmentation, biofilm formation or additive leaching can occur without mineralization, biodegradation may be overestimated by other metrics such as that of weight loss or surface erosion. There is an increasing recommendation to employ some of the newer verification methodologies, such as as respirometry and use of isotopic tracing (i.e. 13C) to confirm true conversion to CO2 and biomass. In the meantime, the use of engineered microorganisms or nano-enabling technologies remains dubious, as the datasets are not equal, and there are no standards as well as regulatory frameworks that heavily focus on risk assessment instead of authorization. All these barriers work against the creation of ecologically sound, scalable repair.

Conclusion

With their wide-ranging ecological and human health impacts, microplastics have become a major global pollutant infiltrating terrestrial, marine and atmospheric systems. They represent major challenges for detection, measurement, and risk assessment because of their persistence, wide range of physicochemical properties and complex and intricate interactions with environmental matrices. While advanced analytical techniques such as FTIR, Raman spectroscopy, pyrolysis-GC/MS and nanoparticle tracking have helped us to better characterize MPs/NPs, exposure assessment is hindered by the lack of methodological sensitivity and standardization in the nano-scale region. The growing level of data demonstrates that the MPs and NPs are biologically absorbed from one trophic level to the next, causing oxidative stress, inflammatory responses, and potential bioaccumulation in humans. For this reason, eco-remediation and biotechnology techniques are becoming more popular as manageable alternatives for conventional physicochemical therapies. Only laboratory scale studies have been conducted so far for microbial degradation, enzymatic catalysis, phytoremediation and integrated hybrid systems, and more research is needed to incorporate these methods into an industrial scale system. Bridging the gaps between analysis, ecology and technology is of fundamental importance for future development. It will be important to establish multidisciplinary research combining state-of-the-art detection tools with environmentally friendly remediation and all under the umbrella of stringent legal regulations. Both the promotion of innovation and alignment of policies can help the scientific community promote the concepts of circular economy and reduce the risks from MPs/NPs. This comprehensive strategy is a solution to safeguarding human health and ecosystems from the growing problem of plastic pollution.

Conflict of interest

The authors declare that they have no conflict of interest.

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